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Developing context-specific frameworks for integrated sustainability assessment of agricultural intensity change: An application for Europe

Vasco Diogo [a,*], Julian Helfenstein [b], Franziska Mohr [a,c], Vinisha Varghese [d], Niels Debonne [a,e], Christian Levers [e], Rebecca Swart [e], Gabi Sonderegger [c,f], Thomas Nemecek [g], Christian Schader [h], Achim Walter [i], Guy Ziv [j], Felix Herzog [b], Peter H. Verburg [a,e], Matthias Bürgi [a,c]

[a] *Land Change Science Unit, Swiss Federal Research Institute WSL, Switzerland*
[b] *Agricultural Landscapes and Biodiversity Group, Agroscope, Switzerland*
[c] *Institute of Geography, University of Bern, Switzerland*
[d] *Institute of Environmental Engineering, Department of Civil, Environmental and Geomatic Engineering, ETH Zürich, Switzerland*
[e] *Environmental Geography Group, Institute for Environmental Studies (IVM), VU Amsterdam, the Netherlands*
[f] *Centre for Development and Environment, University of Bern, Switzerland*
[g] *Life Cycle Assessment Group, Agroscope, Switzerland*
[h] *Research Institute of Organic Agriculture (FiBL), Switzerland*
[i] *Institute of Agricultural Sciences, Department of Environmental Systems Science, ETH Zürich, Switzerland*
[j] *School of Geography, Faculty of Environment, University of Leeds, United Kingdom*

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ABSTRACT

Agriculture plays a central role in achieving most Sustainable Development Goals (SDGs). Sustainable intensification (SI) of agriculture has been proposed as a promising concept for safeguarding global food security, while simultaneously protecting the environment and promoting good quality of life. However, SI often leads to context-specific sustainability trade-offs. Operationalising SI thus needs to be supported by transparent sustainability assessments. In this article, we propose a general systematic approach to developing context-specific frameworks for integrated sustainability assessment of agricultural intensity change. Firstly, we specify a comprehensive system representation for analysing how changes in agricultural intensity lead to a multitude of sustainability outcomes affecting different societal groups across geographical scales. We then introduce a procedure for identifying the attributes that are relevant for assessment within particular contexts, and respective indicator metrics. Finally, we illustrate the proposed approach by developing an assessment framework for evaluating a wide range of intensification pathways in Europe. The application of the approach revealed processes and effects that are relevant for the European context but are rarely considered in SI assessments. These include farmers' health, workers' living conditions, cultural heritage and sense of place of rural communities, animal welfare, impacts on sectors not directly related to agriculture (e.g., tourism), shrinking and ageing of rural population and consumers' health. The proposed approach addresses important gaps in SI assessments, and thus represents an important step forward in defining transparent procedures for sustainability assessments that can stimulate an informed debate about the operationalisation of SI and its contribution towards achieving SDGs.

1. Introduction

Agriculture is pivotal for achieving most of United Nations Sustainable Development Goals (SDG) targets (Ehrensperger et al., 2019; FAO, 2018). This interconnectedness means that complex interactions may emerge among different development priorities, possibly leading to synergies, but also to competing demands (Kroll et al., 2019; Pham-Truffert et al., 2020). Coherent solutions are therefore required to enable sustainability transformations in agriculture capable of fostering SDG co-benefits and navigating their potential trade-offs (Caron et al., 2018).

A large number of approaches for sustainable agricultural production have emerged in recent decades, proposing diverse pathways to

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* Correspondence to: Zuercherstrasse 111, CH-8903 Birmensdorf, Switzerland.
E-mail address: vasco.diogo@wsl.ch (V. Diogo).

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reconcile the requirements for safeguarding global food security with preserving the environment and promoting good quality of life (Oberč and Schnell, 2020). The concept of sustainable intensification (SI) proposes three underlying principles to tackle these challenges: i) increasing agricultural productivity; ii) improving resource-use efficiency and reducing the use of harmful inputs; and iii) halting expansion in important biodiversity hotspots by confining food production to existing farmland (Godfray et al., 2010). SI originally revolved around identifying and promoting farming practices allowing for productivity gains while keeping adverse environmental impacts at a minimum (Pretty, 1997). Such alleged win-wins have subsequently been widely endorsed by scientists, governments and international organisations, particularly in the context of smallholder farming in developing countries (FAO, 2011; Pretty et al., 2011). However, the concept of SI has been increasingly criticised for being too weakly and narrowly defined to merit the term "sustainable", leading to calls for extending its scope beyond productivity and environmental objectives (Cook et al., 2015; Loos et al., 2014; Struik and Kuyper, 2017). Current perspectives emphasise that SI needs to equally engage with the social and economic dimensions of sustainability, and be fully embedded within the multiple dimensions of food systems (Rockström et al., 2017; Struik and Kuyper, 2017). This implies that intensification impacts on biodiversity, climate change and food availability must be considered along with a range of sustainability outcomes on rural livelihoods and social cohesion (Helfenstein et al., 2020).

Different societal groups often have disparate preferences in terms of which outcomes should be prioritised or avoided (Bennett et al., 2021; Pérez-Soba et al., 2018). Given that sustainability outcomes are not independent of each other, agricultural intensification will almost inevitably lead to trade-offs and to different sets of winners and losers (Egli et al., 2018; Kanter et al., 2018). Hence, SI requires the development of a shared system of values and norms (Struik et al., 2014). The operationalisation of SI should thus not be simply regarded as the adoption of a set of prescribed farming practices, but instead as a process of social negotiation, institutional innovation and adaptive management (Schut et al., 2016; Struik et al., 2014). In this sense, SI can be interpreted as a "boundary object" (*sensu* Franks, 2014) or a guiding principle (Smith, 2013), about which stakeholders can negotiate problems and conflicts, to iteratively and incrementally arrive at solutions drawing on the full range of SI approaches. Such a process should ideally be informed and supported by a comprehensive and transparent trade-off assessment of alternative SI pathways (Helfenstein et al., 2020; Struik and Kuyper, 2017).

Assessing the extent to which changes in agricultural intensity affect sustainabiliy outcomes is, however, highly challenging (Struik et al., 2014). It involves appraising and anticipating several indirect and long-term effects beyond the farm level, including environmental spill-overs and cascading effects on ecosystems and biogeochemical cycles (Campbell et al., 2017; Tilman et al., 2002; Vignieri, 2019), changes in social relationships and norms (Janker et al., 2019), and market-related dynamics (García et al., 2020). Moreover, such processes and outcomes are highly context-specific, depending to a large extent on the historical developments, socio-economic conditions and institutional settings in which they are embedded (Tappeiner et al., 2020). Finally, conflicting sustainability outcomes may co-emerge at different geographical scales. For example, land-use redistribution (Rising and Devineni, 2020) and optimisation through international trade could in principle contribute to lower global greenhouse gas (GHG) emissions and food prices (Popp et al., 2017), but also lead potentially to irreversible localised impacts on sensitive ecosystems, rural livelihoods and indigenous communities (Lambin, 2012). Hence, changes in agricultural intensity and resulting trade-offs must be evaluated across different normative dimensions, geographical scales and contexts (Helfenstein et al., 2020; Kanter et al., 2018; Thomson et al., 2019).

Different assessment frameworks and tools have been proposed in recent years for evaluating the sustainability of alternative agricultural development trajectories. Sustainability assessment tools at the field/farm level, for example, can quantify in detail the impacts directly triggered by the practices and use of resources within those management units. However, they fail to fully account for the dynamic interactions with surrounding ecosystems and communities (Eichler Inwood et al., 2018). Furthermore, the social dimension of sustainability is often underrepresented (Mahon et al., 2017; Schader et al., 2014), usually not going beyond labour-related considerations (Janker and Mann, 2020). Musumba et al. (2017) and Smith et al. (2017) have recently proposed holistic indicator frameworks for SI assessment, covering a broad range of dimensions at multiple scales. However, these frameworks have been primarily developed for place-based assessments in the context of smallholder farming in developing countries. They do not consider, for instance, the outcomes resulting from larger scale processes, such as market linkages between distant regions and structural shifts in food consumption and production. Such processes may have critical implications for sustainability (Liu et al., 2013). For example, de-intensification of production or increased use of imported inputs (e.g., feed concentrates) at a given location may lead to production reallocation and/or intensification elsewhere (Cadillo-Benalcazar et al., 2020; Fuchs et al., 2020; Wang et al., 2017). These frameworks are therefore not fully applicable to contexts in high-income economies where agricultural production and food consumption are largely integrated in global supply chains and markets.

There is, consequently, a need for developing procedures and criteria to generate analytical frameworks for integrated SI assessment that can provide a comprehensive outlook of sustainability outcomes from local to global scales, while capturing context-specific socio-ecological processes. Such frameworks must be capable of guiding action and supporting broader societal transformations, by providing useful information for deliberation and negotiation. Hence, they need to simultaneously consider the legitimate, but potentially conflicting, normative values and perceptions of different groups of social actors operating at different scales in their specific contexts (Cadillo-Benalcazar et al., 2020). In this article, we aim to address these gaps by presenting a general systematic approach to developing context-specific, multi-scale frameworks for integrated sustainability assessment of agricultural intensity change (Section 2). Any formal assessment of sustainability entails two main steps: i) a pre-analytical step for defining what, out of many alternative and legitimate perceptions, should be considered as the relevant system to be analysed; ii) an analytical decision about how to formalise the system's representation through a finite set of relevant attributes and proxy variables for their quantification (Binder et al., 2010; Giampietro et al., 2006). Hence, we start by proposing a comprehensive system representation for analysing how changes in agricultural intensity lead to multiple sustainability outcomes affecting different societal groups (Section 2.1). We then describe the main steps for identifying the attributes of agricultural intensity and sustainability that are relevant for assessment within a specific context, and for selecting the respective methods and metrics for assessing them (Section 2.2). Finally, we illustrate the proposed approach by developing a multi-scale framework for integrated SI assessment in Europe (Sections 3 and 4), and discuss its strengths and limitations (Section 5).

2. A systematic approach for developing context-specific frameworks for integrated SI assessment

2.1. System representation

Following the conceptual framework for SI pathways proposed by Helfenstein et al. (2020), we start by defining agricultural intensity change (AIC) as the process of adjusting i) management intensity (i.e., the activities, management practices and uses of resources in the farm), and/or ii) landscape structure (i.e., the spatial configuration and composition of agricultural fields and surrounding semi-natural elements and habitats in agro-ecosystems), in order to iii) enhance agricultural productivity (i.e., output per unit of input). Sustainability outcomes (SO) are assumed to evolve relationally through pathways of compound effects resulting from individual processes of AIC (Fig. 1). A number of interrelated socio-ecological processes (SEP) are potentially affected by AIC:

- different types of socio-ecological flows, including biogeochemical cycles and emission of pollutants; people movements (e.g., seasonal/migrant workers, migration of rural population to cities); biological movements (e.g., migratory birds, pollinators, pathogens); trade of agricultural inputs and commodities, and the monetary flows associated with them (Adger et al., 2009; Hull and Liu, 2018);
- the functioning of ecosystems (Emmerson et al., 2016; Stoate et al., 2009)
- different types of socio-ecological interactions, including: social relationships among actors in the farm (e.g., family, workers), members of surrounding communities (e.g., other farmers, neighbours, government officials, collectives) and other (external) actors (e.g., service providers, tourists, consumers) (Janker et al., 2019); species-habitat interactions (Morrison and Dirzo, 2020); human-nature experiences (Soga and Gaston, 2016); and human-livestock interactions (Hostiou et al., 2017).

Changes in these SEP may, in turn, enhance or hinder the ability of agricultural landscapes to deliver bundles of ecosystem services (IPBES, 2019), including regulating (e.g., pollination, freshwater availability), material (e.g., food and feed production) and non-material services (e.g., supporting identities and experiences). The combined effect of changes in SEP and ecosystem service provision (ESP) results in multiple environmental, economic and social outcomes affecting different societal groups, both positively and negatively (Anderson et al., 2019; Blicharska et al., 2019). Feedbacks are established between ESP, SO and AIC, often mediated by concurrent developments in contextual factors (Matson et al., 1997; Meyfroidt, 2013; Meyfroidt et al., 2018). Hence, the effects of AIC on SO need to be assessed along temporal scales long enough (e.g., decades) to capture processes and pathways leading to regime shifts, systemic lock-ins and rebound effects (Giampietro and Mayumi, 2018; Ramankutty and Coomes, 2016; Tappeiner et al., 2020).

The proposed causal framework (see Fig. 1) is largely inspired by the *Driving forces-Pressures-States-Impacts-Responses* (DPSIR) model, originally proposed by the European Environmental Agency (EEA, 2007) and subsequently adopted by multiple international organisations (FAO, 2013; Patrício et al., 2016) to describe and analyse processes and interactions in human-environment systems. However, we make a few important adjustments in relation to the original DPSIR model. Firstly, we explicitly distinguish *Driving forces* in terms of the human activities leading to AIC from the contextual factors that shape them. Secondly, we extend the type of *Pressures* that are typically considered in DPSIR analysis (e.g., the release of pollutants resulting from human activities) to also consider a wider range of SEP, such as the flows of commodities, people and species, and their interactions. As mentioned in Patrício et al. (2016), *Pressures*, *States* and *Impacts* are not necessarily mutually exclusive categories despite being treated as such, with the distinction often depending on the timeframe considered and scope of the analysis. This has led to varied interpretations on what these components should represent. Rather than attempting to differentiate and characterise these categories, we instead took an outcome-oriented approach which addresses a broad range of SEP and impacts, including changes in ESP (which may or may not affect human activities and well-being) and SO (for which normative ambitions, concerns and/or targets are expressed by different societal groups). Finally, we explicitly consider *Responses* as feedback processes, which may materialise in terms of changes in contextual factors and adjustments in farm management leading to AIC.

Socio-ecological systems express multiple structures and functions in parallel, and within hierarchical levels that are both spatially nested and networked (Adger et al., 2009; Liu et al., 2015; Ostrom, 2009). They can thus be perceived and represented in several non-equivalent ways by distinct groups of social actors. This diversity of perceptions reflects the different norms, beliefs, interests and concerns of these groups, and their respective narratives (*sensu* Giampietro et al., 2006, i.e., the sets of system attributes deemed relevant, and hypothesised causal relations) about how the system should be "improved" (Cadillo-Benalcazar et al., 2020; Lomas and Giampietro, 2017). Hence, multiple scales and levels of analysis need to be simultaneously adopted to capture these

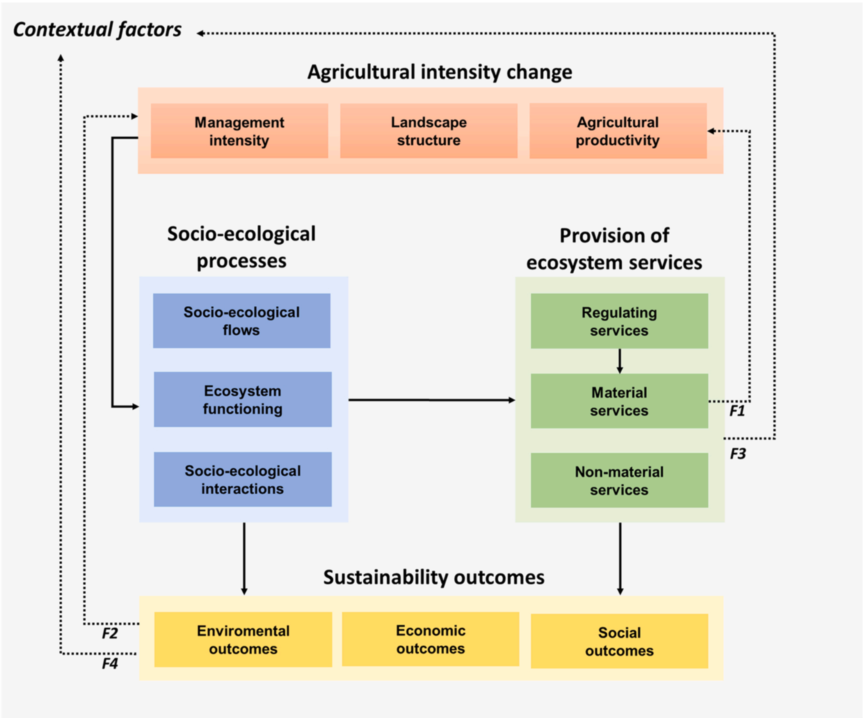

Fig. 1. Pathways of compound effects of agricultural intensity change on sustainability outcomes. Contextual factors (e.g., climate, demography, lifestyle, policy, technology, topography, soil characteristics) affect how these pathways develop over time. Feedback processes (dotted arrows) may emerge due to changes in agricultural productivity resulting from degradation/enhancement of material services (*F1*), changes in agricultural intensity as human-driven responses to sustainability outcomes (*F2*) and broader changes in contextual factors resulting from changes in the provision of ecosystem services (*F3*, e.g., through biogeochemical processes) and from societal developments triggered by sustainability outcomes (*F4*, e.g., demographic changes, policy reforms, technological change, or changes in lifestyle and consumption).

non-equivalent perceptions and narratives. On this basis, we consider the agricultural field, landscape, region and global Earth System as relevant, hierarchically nested geographical scales of analysis for SI assessment (Fig. 2). Rather than fixed entities, these scales are interpreted as constellations of temporary coherence with relatively open territorial boundaries (Wilson, 2009). The agricultural field takes a central place, as the scale at which farm managers execute decisions leading to changes in management intensity (e.g., increasing input application rate) and landscape structure (e.g., increasing field size and removing linear vegetation elements). The landscape scale is instrumental for understanding the socio-ecological context in which farm managers are embedded while making decisions, and assessing the outcomes of these decisions (Helfenstein et al., 2020). Landscapes are here defined as coupled socio-ecological systems characterised by spatially coherent and interrelated sets of natural and anthropogenic components (Angelstam et al., 2019, 2013), including different interacting, and partially overlapping, levels of organisation:

- farms, i.e., decision-making units comprising agricultural fields for crop and livestock production, in which farm managers make decisions on the use of available resources to fulfil a combination of objectives (Malek et al., 2019);
- communities, consisting of actors with different roles, and connected through institutionalised interactions, normative regulations and social relationships defined by work, business and private life (Janker et al., 2019);
- agro-ecosystems, i.e., a complex of plants, animals and microorganisms, their mutual relations, and resulting geographical patterns of landscape structure (Miguet et al., 2016; Tscharntke et al., 2005).

Regions (e.g., countries, sub- and supra-national regions) are relevant scales of analysis because these are usually the administrative units for which political ambitions and (sustainability) targets are set, and progress is monitored. Outcomes in distant “telecoupled” regions, i.e., regions which are not geographically nested but are connected by significant inbound (e.g., food and feed imports) and/or outbound flows (e.g., food exports), are also explicitly considered (Liu et al., 2013). Finally, we consider the global scale to be bounded by the Earth system, and consisting of many smaller coupled social-ecological systems, evolving through time as a set of interconnected complex adaptive systems (Adger et al., 2009; Liu et al., 2015). Assessing outcomes at the global scale is crucial, for example, to identify coordinated solutions for achieving food security without jeopardising the functioning and resilience of the Earth system as a whole (Gerten et al., 2020; Steffen et al., 2015).

2.2. *Defining context-specific frameworks for integrated SI assessment*

Developing a sustainability assessment framework entails identifying and defining the system attributes that are relevant for different groups of social actors, in order to inform and guide their actions according to their specific sets of expectations, interests and concerns (Cadillo-Benalcazar et al., 2020; Giampietro et al., 2006; Lomas and

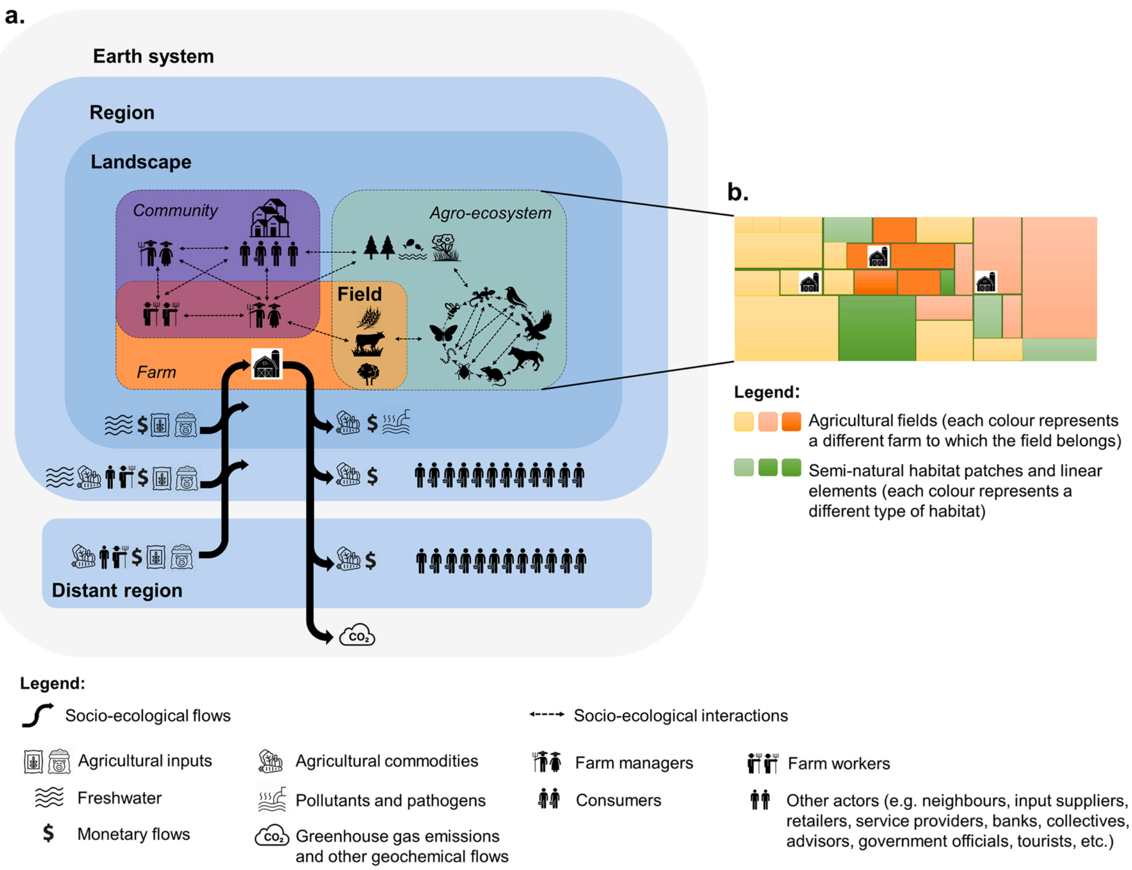

Fig. 2. Geographical scales and organisational levels of analysis for SI assessment. **a.** Socio-ecological flows and interactions operating across geographical scales (labels in bold) and embedded levels of organisation (labels in italics). Changes in agricultural intensity may trigger or affect a range of inbound and outbound flows, across nested scales from the agricultural field up to the global Earth system, and among networked distant regions. They may also trigger changes in socio-ecological interactions involving different types of actors and species across different organisational levels within the landscape (i.e., farms, communities and agro-ecosystems). b. Landscape structure of agro-ecosystems. Farms are physically composed of a collection of agricultural fields, which may include both adjacent and dispersed fields across the landscape, intertwined with semi-natural habitat patches (e.g., forests, heaths, wetlands) and linear elements (e.g., hedgerows, tree lines, stone walls).

Giampietro, 2017). While developing such frameworks, these system attributes are usually thematically organised in nested hierarchical levels, to facilitate their definition and selection in a structured way (De Olde et al., 2016; Van Cauwenbergh et al., 2007). Adopting the terminology proposed in the FAO-SAFA guidelines (FAO, 2014), we use the following hierarchical levels: dimensions, themes, sub-themes and indicators. Following the system representation presented in Section 2.1, we start by designating *Agricultural intensity*, *Ecosystem service provision* and *Sustainability outcomes* as the core dimensions for the development of the analytical framework. The lower hierarchical levels of these dimensions are then specified by identifying the attributes and metrics that enable the assessment of how AIC affects, through changes in SEP and ESP, a multitude of SO. Accordingly, we propose the following steps (Fig. 3):

- **Step 1:** Identify the mechanisms of agricultural intensity change (MAIC) that are applicable to a particular context. MAIC are defined as the adjustment of a particular set of attributes of management intensity or landscape structure that affects agricultural productivity by causing changes in the output/input ratios, i.e., agronomic productivity, resource-use efficiency and/or profitability. Based on the identified mechanisms, relevant themes, sub-themes and indicators are defined for the *Agricultural intensity* dimension that permit the assessment of these mechanisms quantitatively.
- **Step 2:** Identify the potential effects of the identified MAIC on context-specific SEP, leading to changes in ESP. Relevant themes, sub-themes and indicators are then defined for the *Ecosystem service provision* dimension.
- **Step 3:** Identify the potential effects of the identified MAIC on SEP and ESP, leading to a range of SO that are relevant to different groups of social actors. Relevant themes, sub-themes and indicators are then defined for the *Sustainability outcomes* dimension. The combined results of Steps 1, 2 and 3 allow the definition of the context-specific hierarchical structure of SI indicators.
- **Step 4:** Identify available methods and data sources to compute metrics for the SI indicators defined in the previous steps. The selected metrics enable the definition of the context-specific framework for integrated SI assessment.

3. Material and methods

We illustrate the application of the approach presented in Section 2 by developing a multi-scale indicator framework for SI assessment in Europe. In particular, we apply the approach through a stepwise literature review, for each core dimension in turn, as follows:

- **Step 1:** the *Agricultural intensity* dimension was defined by conducting a literature review, combined with inductive content analysis (Khirfan et al., 2020), to identify the main MAIC in Europe. Firstly, we searched for peer-reviewed articles describing cases with changes in agronomic productivity, resource-use efficiency and/or profitability in Europe. Appendix A describes in detail the literature search strategy and criteria for selecting articles. Based on the literature analysis, we developed a MAIC typology, and identified sets of attributes that characterise them (see Table A.1). Based on these results, we defined *Agricultural intensity* themes, sub-themes and indicators.
- **Step 2:** the *Ecosystem service provision* dimension was defined by conducting a literature review, combined with deductive content analysis (Kyngäs and Kaakinen, 2020), to identify the effects of AIC on ESP in Europe. Appendix B describes in detail the literature search strategy, criteria for selecting articles and approach for conducting the literature analysis. We used the IPBES Nature's Contributions to People (NCP) framework (Díaz et al., 2018, 2015) as a heuristic to specify the hierarchical structure of this dimension. The NCP framework has been jointly developed by academia, governments and civil society, building upon the ecosystem service concept (Millennium Ecosystem Assessment, 2005), while emphasising the importance of cultural context as a central factor for shaping human

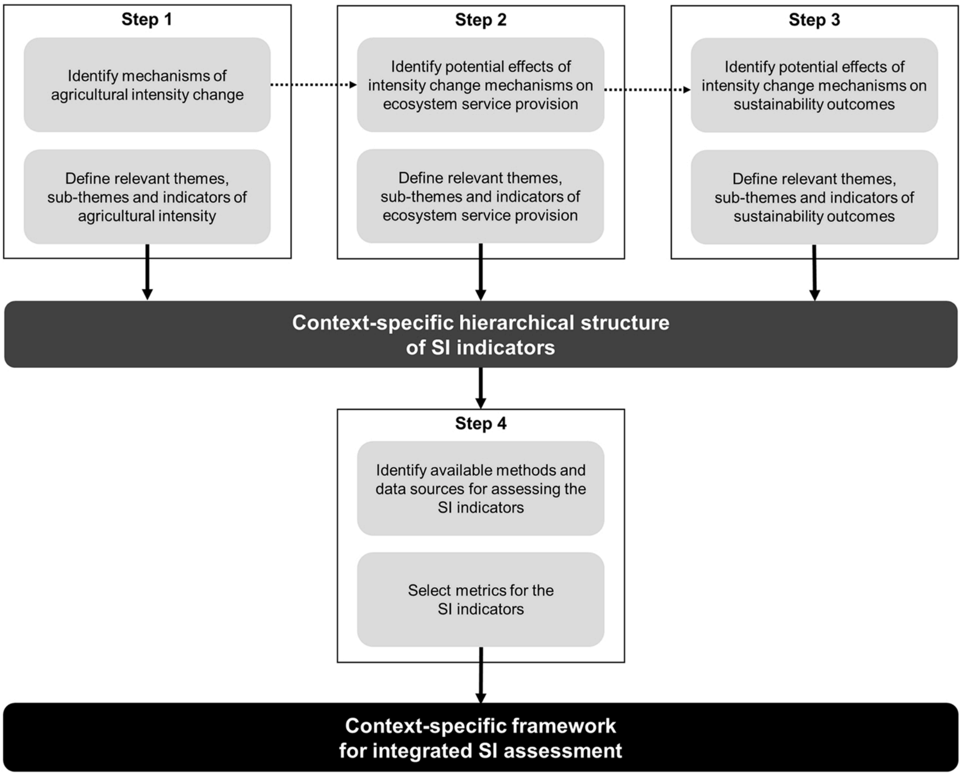

Fig. 3. Approach for developing context-specific frameworks for integrated SI assessment.

perception of nature and quality of life (Díaz et al., 2018; Peterson et al., 2018). The sets of ecosystem service categories defined by the NCP framework were used as a guiding principle for defining the *Ecosystem service provision* themes (i.e., NCP types) and sub-themes (i.e., NCP reporting categories; for their definitions, see Table B.1 in Appendix B), and accordingly guide the content analysis of the selected literature. We then identified the effects of each MAIC on each NCP reporting category (Tables B.2, B.3 and B.4 in Appendix B). Based on these results, for each sub-theme we defined a set of key attributes as *Ecosystem service provision* indicators.

- **Step 3:** the *Sustainability outcomes* dimension was defined through literature review, combined with deductive content analysis, on the effects of AIC in Europe on SO. We used the United Nations Sustainable Development Goals (SDG) framework (UN, 2015) as a heuristic to specify the hierarchical structure of this dimension. The SDG framework has been developed through a comprehensive participatory process (UN, 2014; UNDG, 2013), representing a compromise between a multiplicity of concerns and interests from different societal groups. Hence, the SDGs provide a comprehensive mapping of a broad universe of legitimate, but potentially conflicting, normative visions of sustainability (Le Blanc, 2015). This, in turn, provides an appropriate guiding principle for defining the *Sustainability outcome* themes (i.e., SDG goals) and sub-themes (i.e., SDG targets). We adapted the list of keywords of the SDG literature search queries proposed by the Aurora Universities Network (AUN, 2021) to define search strings. Appendix C describes in detail the literature search strategy, criteria for selecting articles and approach for conducting the literature review. The results of the literature analysis were used to identify the effects of each MAIC on SO related to each SDG goal (Tables C.2, C.3 and C.4 in Appendix C) and the societal groups to which they are relevant. Based on these results, for each sub-theme we defined a set of key attributes as *Sustainability outcome* indicators.
- **Step 4:** we reviewed existing literature to identify applicable methods and metrics to measure the indicators defined in the previous steps at different scales in Europe. In addition, we also reviewed online data portals from international agencies and organisations to identify available data sources with pan-European coverage. Appendix D.1 describes in detail the search strategy and criteria for the review of literature and databases.

4. Results

4.1. Assessing agricultural intensity change in Europe (Step 1)

We identified thirteen MAIC operating in Europe (Table 1; for a detailed overview and references, see Table A.1 in Appendix A). Many of these mechanisms are often observed in combination with others. For example, an increase in capital intensity typically occurs together with an increase in land management intensity, input-use intensity, farm concentration and a certain degree of farm specialisation. Some mechanisms may result in the de-intensification of other attributes. For example, increased capital intensity and improved information management through the adoption of robotics for precision farming contributes to lower input-use intensity. Product differentiation, vertical integration, income diversification and cooperation enable increased profitability and reduced risks through economies of scope and/or added-value creation, without necessarily increasing physical production.

Agricultural Intensity sub-themes and indicators were specified based on the identified attributes of management intensity, landscape structure and agricultural productivity (Table 2). Land management indicators are primarily measured at the agricultural field scale. Consumable input use and agronomic productivity indicators can be measured at the field scale (e.g., to assess relationships between field productivity and management intensity), but they are equally relevant

Table 1
Mechanisms of agricultural intensity change (MAIC) operating in European agriculture.

MAIC	Description
Land management intensity	Adjusting the intensity of land management practices (e.g., livestock density, grazing period length, crop rotation cycles, cropping density, intercropping) and frequency of field management operations (e.g., soil tilling, grassland mowing, mechanical weeding, orchard pruning, soil drainage).
Capital intensity	Adjusting investments in fixed capital assets such as buildings (e.g., silos, stables, greenhouses), infrastructure (e.g., irrigation, roads), machinery and equipment (e.g., mechanic plough, automatic feeder, milking robots, drones), permanent crops (e.g., tree orchards), livestock herd size, and land reclamation (e.g., permanent drainage of wetlands).
Input-use intensity	Adjusting the use of consumable inputs such as fertilisers, pesticides, animal feed and health inputs, seeds, water and energy.
Labour intensity	Adjusting labour inputs, including family and hired labour (permanent and seasonal).
Farm consolidation	Achieving increasing returns to scale/size through enlargement of farm size (e.g., buying/renting land from other farms), land consolidation (e.g., reallocating land to make farms more compact) and landscape simplification (increasing field size by removing semi-natural habitat patches and linear landscape elements).
Farm specialisation / diversification	Adjusting crop diversity, and/or the diversity of livestock species, breeds and stages of animal development. In the case of specialisation, resources are concentrated on a limited number of activities for which local conditions and available resources are optimal. In the case of diversification, economies of scope are achieved by engaging in complementary activities (e.g., mixed crop-livestock systems) or cultivating complementary crops (e.g., nutrient fixating crops, cover crops, different types of forage crops).
Income diversification	Diversifying the number of activities and income sources, including agro-environmental activities (particularly, when they are supported by financial compensation schemes), non-farming activities (e.g., agritourism, gastronomy, renting idle farm equipment, renting land for renewable energy production) and off-farm employment.
Regional specialisation and concentration	Achieving agglomeration benefits through clustering of similar farm activities in regions where industrial/logistic hubs for processing, transporting or marketing agricultural products exist (e.g., dairy industry, vegetable oil production, harbours, auctions).
Vertical integration	Reducing transaction costs and risks through contract farming, and/or consolidation of production, processing and marketing operations (e.g., direct marketing).
Knowledge intensity change	Acquiring knowledge and skills to improve management practices through education and training, and/or consultation with advisory/extension services.
Improved information management	Adjusting planning (e.g., seeding, harvesting), process controlling (e.g., milking operations), resource-use (e.g., fertiliser use), and/or marketing strategies (e.g., sales) using information and communications technology (ICT).
Crop/breed change and product differentiation	Switching to higher productivity varieties, high-value products or added-value niche markets (e.g., organic farming, protected designation of origin, voluntary sustainability standards).
Cooperation	Achieving economies of scale and/or scope based on social capital (e.g., jointly governing resources, infrastructure, services, knowledge, value chains, and/or marketing strategies).

Table 2
Themes, sub-themes and indicators for assessing agricultural intensity (AI) in Europe.

AI theme	AI sub-theme	AI indicators	Scale/level of measurement[a]	MAIC[b]
Management intensity	Land management	Livestock density; Grazing period length; Frequency of field operations; Cropping frequency; Fallow cycle frequency; Sowing density; Intercropping; Crop rotation	AFS	LMI; FSD
	Fixed capital assets	Irrigation area; Irrigation equipment; Machinery and equipment; Buildings and infrastructure; Permanent crop area; Permanent crop density; Herd size; Breeding livestock; Milking livestock; Livestock replacement rate; Land ownership structure;	FL	CI; IIM
	Consumable inputs	Fertiliser use; Fertiliser composition; Pesticide use; Pesticide toxicity; Feed intake; Feed composition; Animal health inputs use; Water use; Energy use; Seeds inputs;	AFS; FL	IUI
	Labour	Labour input; Family labour; Hired labour; Permanent/seasonal labour; Employee turnover	FL	LI
	Farm size	Farm area; Farm economic size		FC
	Human capital	Farmer education and training; Workers training; Consultation with advisory/extension services		KI; IIM
	Farming diversity	Crop types and varieties; Livestock species and breed varieties; Stages of animal development;		FSD; RSC; CCPD
	Income sources	Farming income; Non-farming income; Off-farm income; Subsidies; Diversity of income sources		ID
	ICT use	ICT services use frequency; Computer literacy		IIM; KI
	Value chain and product value added	Value-chain position; Contract farming; Processed products; By-products; Organic farming; Regional product certification; Voluntary sustainability standards		VI; CCPD
	Social capital	Membership in organisations;		C
Landscape structure	Landscape composition	Agricultural land-use composition; Semi-natural habitat composition;	FL; LS	FC; LMI; CI; FSD; RSC; ID
	Landscape configuration	Agricultural field size; Distance of fields to the farmhouse; Semi-natural habitat patch size; Density of landscape elements; Density of historical/cultural landmarks		FC; CI
Agricultural productivity	Agronomic productivity	Crop yield; Grassland yield; Yield variability; Animal productivity	AFS; FL	LMI; CI; IUI; LI; FC; FSD; KI; IIM; KI; CCPD
	Resource-use efficiency	Input efficiency; Nutrient efficiency; Labour efficiency; Energy efficiency; Water efficiency; Feed efficiency; Input self-sufficiency		All mechanisms
	Profitability	Economic output; Economic added-value; Total output; Total output variability;	FL	All mechanisms

[a] Scales and levels of organisation: AFS – Agricultural field scale; FL - Farm level; LS - Landscape scale.
[b] Mechanisms of agricultural intensity change: LMI - Land management intensity; CI - Capital intensity; IUI - Input-use intensity; LI - Labour intensity; FC - Farm consolidation; FSD - Farm specialisation / diversification; RSC - Regional specialisation and concentration; VI - Vertical integration; KI - Knowledge intensification; IIM - Improved information management; CCPD - Crop change and product differentiation; ID – Income diversification; C - Cooperation.

at the farm level to assess of the overall resource-use efficiency of the farm. All other management intensity and agricultural productivity indicators are primarily assessed at the farm level. Provided that the number and stratification of the sample is representative, indicators at the farm level can be aggregated at the landscape and regional scales to identify broader structural changes in agricultural intensity.

Landscape structure indicators are primarily assessed at the landscape scale, to reveal potential causal linkages between alterations in landscape structure and changes in the provision of ecosystem services (see Section 4.2). However, some indicators are also relevant at the farm level in order to distinguish the magnitude effects of intensity change processes of individual farms within the landscape.

4.2. Assessing the effects of agricultural intensity change on ecosystem service provision in Europe (Step 2)

We identified the effects of the different MAIC operating in Europe in the provision of fourteen ecosystem services (Fig. 4; for a detailed overview and references, see Tables B.2, B.3 and B.4 in Appendix B), and accordingly specified indicators to assess these effects (Table 3). Most ecosystem services are directly mediated by the provision of habitat creation and maintenance, due to the role of agricultural farmland and semi-natural vegetation in providing regulating functions (i.e., climate, water, air quality, and extreme event regulation) or habitat for the organisms facilitating them (e.g., pollinators, soil regulating biota, pest control organisms). Therefore, MAIC that alter habitat composition, biotic interactions and overall ecosystem functioning through changes in landscape structure and/or increased flows of pollutants (including surplus of nutrients) have significant effects on bundles of regulating services. These combined effects on regulating services may partially negate the positive effects of MAIC enhancing material services (i.e., energy, food and feed provision), potentially leading to further adjustments in agricultural intensity as a response. In addition, mechanisms that affect habitat creation and maintenance may also affect human-nature interactions, leading to changes in the provision of non-material services (i.e., supporting identities, experiences and learning). These may, in turn, trigger societal responses. Ecosystem service provision indicators are primarily assessed at the landscape scale, though soil regulation, detrimental organism regulation and material services are also appropriately assessed at the field scale.

4.3. Assessing the effects of agricultural intensity change on sustainability outcomes in Europe (Step 3)

Based on the SDG framework, we identified twelve themes of SO that are affected at multiple scales by the MAIC operating in Europe. In this section we provide a summary of these effects; for a detailed overview and references, see Tables C.2, C.3 and C.4 in Appendix C. The respective sustainability outcome indicators are specified in Table 4.

All MAIC affect the aggregated production and trade flows of agricultural commodities, thus influencing outcomes related to SDG2 (End hunger) and SDG7 (Access to energy), i.e., food and energy availability, affordability, self-sufficiency and supply stability. These outcomes are primarily assessed at the regional scale, including distant regions connected through trade flows. The aggregated patterns of production, trade and consumption are also pivotal for outcomes related to SDG12 (Sustainable consumption and production), which is assessed with the indicators land, water and material footprints of food consumption at regional and global scales. Land management, capital and input-use intensification in livestock production affect animal welfare and health. Such outcomes are also included in the SDG12 theme.

All mechanisms also bring about changes in monetary flows to and from the farm. Consequently, they affect outcomes at the farm level related to SDG1 (End poverty), particularly farm household income levels, and overall farm resilience (i.e., income stability, viability, adaptability and autonomy). Mechanisms that operate through economies of size and scale may also trigger rebound effects leading to structural changes at broader scales. For example, increased production within a region due to widespread capital, land management and input-use intensification may drive commodity prices down, putting additional competitive pressure on smaller farms, and potentially undermining their viability. Such processes thus affect outcomes related to SDG10 (Reduce inequality). Indicators that assess income levels and inequality at the regional scale are thus included in SDG1 and 10 themes, respectively.

Income and farm resilience, in turn, play an important role in outcomes related to SDG3 (Health and well-being), due to potential psychological distress experienced by farm households because of high levels of debt (e.g., due to high capital intensity) and irregular monetary flows (e.g., due to price volatility). In addition, long working hours can cause injuries, be mentally stressful, and reduce opportunities for social interaction, and therefore have a potential effect on farmers' and workers' physical and mental health. Input-use intensification increases health risks to farm managers and workers due to increased exposure to pesticides during handling and spraying, and to surrounding communities through spray drift. It also leads to a high concentration of pollutants in surface and groundwater resources, thus posing health risks to communities that extract drinking water directly from the environment. In addition, it may also increase consumers' exposure to toxic chemicals in food. Increased livestock density causes the degradation of air quality through emissions of particulate matter, leading to increased risks of respiratory diseases. It also increases the transmission risk and virulence of zoonotic diseases and antimicrobial-resistant bacteria to both surrounding communities and consumers. Indicators at the farm level, community level and regional scale are thus included as part of SDG3, to assess the respective health outcomes in different groups of actors.

Aggregated monetary flows and labour demand within a region have important effects on the economic output and employment of agriculture and other related sectors (e.g., input suppliers, retailers, service providers, food processing), thereby affecting regional-scale outcomes related to SDG8 (Economic growth and employment). High unemployment resulting from a structural decrease in labour intensity may drive (young) people to migrate to urban areas, leading to a shrinking and ageing population. Concurrently, labour-intensive farms (e.g., horticulture specialists) rely on low-cost seasonal workers, often of migrant origin. Human and labour rights violations, limited health protection, precarious housing conditions, and social exclusion are often reported. Such processes and the resulting changes in social interactions play an important role in the quality of life and social cohesion of rural communities. As a result, indicators that assess these aspects are included in the theme SDG11 (Sustainable cities and communities). In addition, women are often worst affected when unemployment in rural areas is high, which is then amplified by unbalanced responsibilities in terms of household caring duties. Hence, indicators that assess women's unemployment and migration are also included as part of SDG5 (Gender equality).

Mechanisms affecting non-material services, combined with capital intensification (e.g., replacing historical farm buildings with modern facilities), and specialisation/diversification (e.g., abandonment/uptake of traditional farm practices and local varieties), may affect not only the cultural heritage, sense of place, and quality of life of surrounding communities, but also the potential for tourism and gastronomy. Hence, indicators that assess these outcomes at the community level and regional scale are included in the themes SDG11 and 8, respectively.

Combinations of MAIC that cause changes in water use, flows of excess nutrients and chemicals, and the provision of water regulating services contribute to outcomes related to SDG6 (Clean water), which can be assessed with indicators of freshwater availability and quality at the landscape and regional scales. Mechanisms that contribute to changes in landscape structure and the provision of regulating services play a significant role in outcomes related to SDG15 (Sustainable terrestrial ecosystems), assessed with indicators of biodiversity, land degradation and deforestation. Several mechanisms affect SDG13 (Climate action) by contributing to direct and indirect GHG emissions at the farm level. In addition, changes in land management intensity have an impact on soil carbon content, farm consolidation affects carbon sequestration, while drainage and irrigation contribute to the release of nitrous oxide and carbon dioxide. Indicators that assess these effects at the field and landscape scales are thus also included. Finally, the overall carbon footprint of the food system can be assessed at regional and global scales, considering total GHG emissions from production to consumption.

4.4. Selecting SI indicator metrics (Step 4)

Based on the three previous steps, we defined the hierarchical structure of the indicator framework for SI assessment in Europe (i.e., Tables 2, 3 and 4 combined). Indicator metrics were then selected for each indicator at their respective scales/levels of measurement. The resulting multi-scale framework for SI assessment in Europe is presented in Appendix D.2 (Tables D.3, D.4 and D.5), including references to methods and data sources.

Most farm- and community-level indicator metrics on agricultural intensity change and socio-economic sustainability outcomes (i.e., SDG1, 3, 10, 11 and 12) can be derived through farm surveys and stakeholder interviews. Indicator metrics related to farm accounting (i.e., resource-use efficiency, profitability, SDG1 and 10) can be derived from official national surveys, such as those collected by the EU Farm Accountancy Data Network, which also provides aggregated metrics at the regional scale for different farm typologies.

Several methods are available to derive indicator metrics at the field and landscape scales for landscape structure, ecosystem service provision and environmental sustainability outcomes (i.e., SDG6, 13 and 15), including: field surveys, stakeholder interviews, remote sensing, volunteered geographic information, environmental monitoring and spatial modelling. International initiatives have recently developed harmonised indicator metrics for biodiversity assessment at the regional and global scales (BIP/CBD, 2010; GEO BON, 2017; OECD, 2019). Ecosystem service accounting is also increasingly receiving attention from both EU and global governance initiatives aiming at developing accounting systems at the country and sub-national levels (e.g., UNCEEA, 2021; Vysna et al., 2021).

Environmental sustainability outcomes related to production and consumption patterns (i.e., SDG12 and 13) can be derived at the farm level through life-cycle assessment, and at regional and global scales through environmental footprint assessment, and material and energy flow accounting methods that link remote sensing with trade data. Finally, regional- and global scale indicator metrics on sustainability outcomes related to SDG2, 7, 8 and 11 are typically made available in online data portals from official statistics offices and international agencies and organisations.

The selected indicator metrics can then be implemented within a decision-support tool with visualisation systems such as dashboards or scorecards. Ideally, these tools should enable different groups of social actors to visualise, for instance, (combinations of) interventions that render improvements from their perspective but negative consequences for concerns prioritised by other social actors (Cadillo-Benalcazar et al., 2020). Such tools should thus be equipped with a user interface open to semantic control (i.e., with the ability to flexibly select and manipulate the information relevant for a particular task), so that sub-selections of indicators can be thematically organised. This could be done, for example, in terms of the groups of actors for which the indicators are relevant, and the scales at which the outcomes are manifest. This means not only organising and distinguishing indicators for different types of

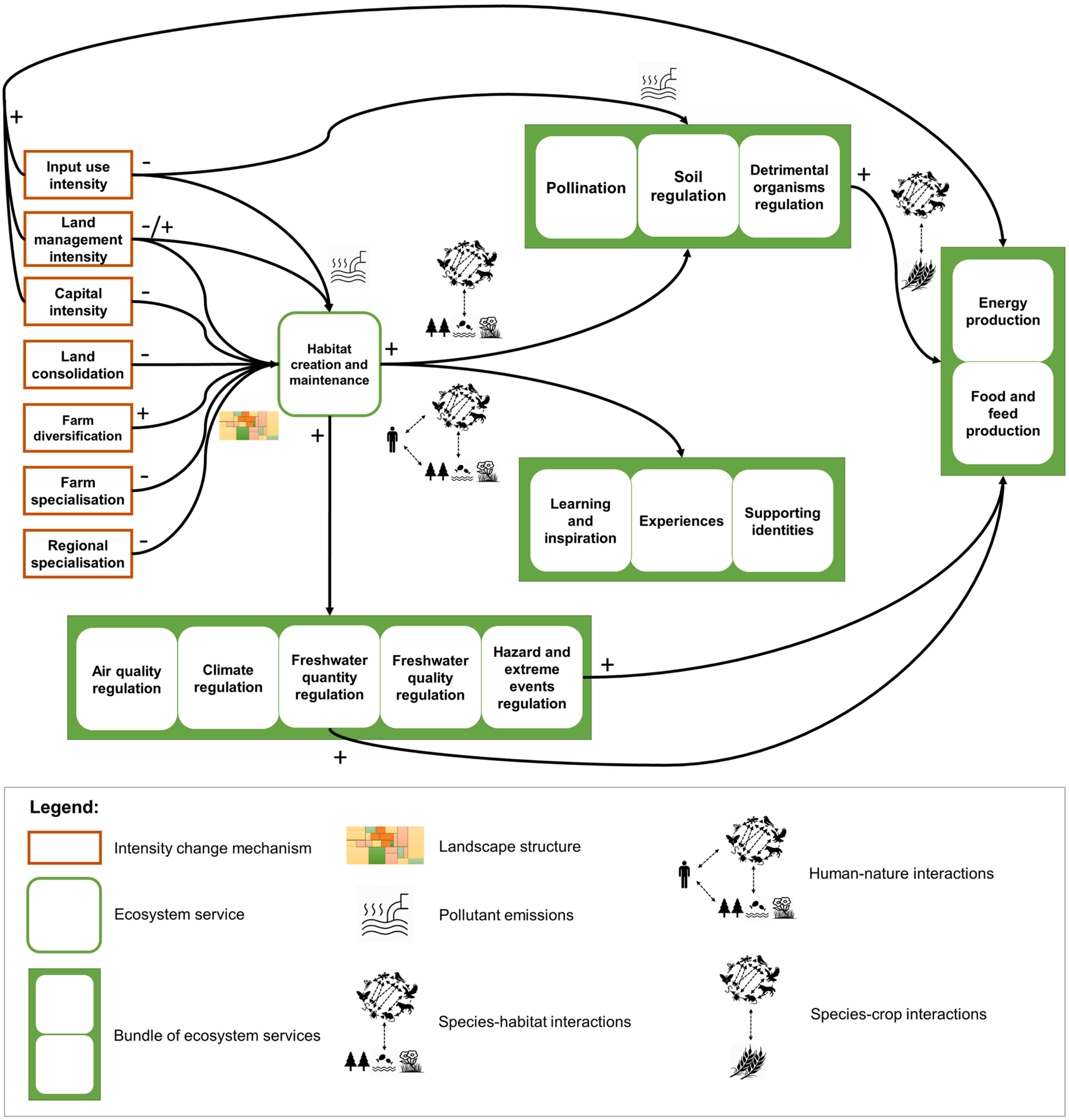

Fig. 4. Identified effects of mechanisms of agricultural intensity change on the provision of ecosystem services in Europe (feedback processes in terms of human-driven responses to changes in the provision of ecosystem services are not depicted).

actors (e.g., farmers, workers, rural communities, consumers) but also disaggregating indicator metrics for similar types of actors with different sets of characteristics (e.g., type of production system, income level, region), in order to identify how (structural) changes in agricultural intensity may affect similar types of actors in unequal ways (Broegaard et al., 2017; Dawson et al., 2019, 2016; Rasmussen et al., 2018; Suwarno et al., 2016). It is also important to allow for metrics with different units of measurement for the same indicator. Seufert and Ramankutty (2017), for example, identified contrasting findings in terms of environmental performance of organic agriculture when assessing impacts per unit of area and per unit of product. For guidelines on designing and encoding visualisations representing socio-ecological processes and outcomes, and analysing and visualising multi-scale sustainability trade-offs, we refer to Sonderegger et al. (2020) and Kanter et al. (2018), respectively.

5. Discussion and conclusions

The proposed approach provides a clear rationale for identifying attributes that are relevant for the assessment of SI in a particular context, and their respective scales of measurement, based on the explicit identification of relevant system boundaries, socio-ecological processes, groups of actors and their respective stakes. In this way, the

Table 3
Themes, sub-themes and indicators for assessing ecosystem service provision (ESP) in Europe.

ESP themes	ESP sub-themes	ESP indicators
Regulating services	Habitat creation and maintenance	Habitat availability; Habitat connectivity; Habitat fragmentation; Habitat quality; Net primary production; Temporal stability
	Pollination	Pollination potential
	Air quality regulation	Air pollution retention capacity
	Climate regulation	Carbon sequestration potential; Albedo; Evapo-transpiration; Temperature regulation; Humidity regulation
	Water quantity regulation	Water flow regulation capacity
	Water quality regulation	Water pollution filtration capacity
	Soil regulation	Soil erosion regulation capacity; Soil nutrient fixation capacity; Sediment retention capacity
	Extreme events regulation	Flood regulation capacity; Wind regulation capacity; Fire regulation capacity;
	Detrimental organisms regulation	Natural pest control potential;
Material services	Energy production	Potential crop yield for bioenergy crops
	Food and feed production	Potential crop yield for food crops; Potential crop yield for feed crops;
Non-material services	Learning and inspiration	Landscape educational value;
	Physical and psychological experiences	Landscape aesthetic value; Landscape recreational value
	Supporting identities	Cultural heritage value; Landscape spiritual value

most common shortcomings of existing SI assessment frameworks are addressed, particularly the incomplete coverage of sustainability dimensions and chains of causal effects, and arbitrariness in the definition and selection of indicators and scales of measurement (Janker and Mann, 2020; Mahon et al., 2017; Schader et al., 2014). Scown and Nicholas (2020), for example, found that the current EU Common Agricultural Policy monitoring system is unable to conduct a balanced assessment of many of its potentially competing goals because its selection of indicators is biased towards only a few objectives.

Defining agricultural intensity broadly in terms of output/input ratios enabled the identification of a diverse range of MAIC beyond land-use intensification. This is in line with the conceptual framework of SI fields of action proposed by Weltin et al. (2018), which, similarly to our framework, also accounts for intensity change strategies based on resource-use efficiency and added-value generation. Such mechanisms are highly relevant as they provide farmers with potentially viable strategies for improving their income and coping with ongoing structural changes (i.e., scale enlargement, with diminishing margins) in European agriculture (Maucorps et al., 2019; Tocco et al., 2015).

The SDG framework provided a useful heuristic for identifying normative dimensions representative of the aspirations and concerns of different groups of actors in Europe. While many of the identified sustainability themes bore similarities to existing frameworks (e.g., farm income, biodiversity, water pollution, climate change – see, for example, Van Cauwenbergh et al., 2007, FAO, 2014, Smith et al., 2017), our approach revealed a number of additional outcomes that are rarely considered in SI assessments. This included, for example, farm households' (mental) health, seasonal workers' health and living conditions, animal welfare, cultural heritage and sense of place of rural communities, impacts on economic sectors not directly related to agriculture (e.g., tourism), shrinking and ageing of rural population, energy security, and consumers' health. These sustainability themes are central to recent European-wide policy initiatives, such as the *European Green Deal* (EC, 2019) and the *Farm to Fork Strategy* (EC, 2020), and ongoing debates on the sustainability of European agriculture (e.g., Bartz et al., 2019; Navarro and López-Bao, 2018; Pe'er et al., 2020, 2019, 2017, 2014). These results underpin the usefulness of the generated framework towards informing deliberations in the context of European agriculture.

The development of the framework also revealed the importance of structural feedbacks of production and consumption that operate across nested scales and distant regions, thus reiterating the need for envisioning SI pathways that coordinate transformative changes both in the supply and demand side of food systems (Cadillo-Benalcazar et al., 2020; Fuchs et al., 2020; Poore and Nemecek, 2018; Renner et al., 2020; Scherer et al., 2018). Many of these processes and effects are also relevant in non-European contexts, thus underlining the utility of our approach for generating SI assessments generally.

The concept of multifunctionality is strongly associated to that of sustainability, particularly in relation to agricultural landscapes and their ability to sustain ecological functions, economic development and the well-being of rural communities (O'Farrell and Anderson, 2010; Stoate et al., 2009; Wilson, 2010, 2009). Although we have not explicitly addressed it here, many of the proposed indicators facilitate the evaluation of landscape multifunctionality, and respective outcomes over a wide range of sustainability themes. Analysing the multifunctionality of agri-food value chains is also relevant for sustainability, as it can expose strategic and operational misalignments within chains, misallocation of resources, and opportunities for creating not only economic, but also environmental and social value (Fearne et al., 2012; Porter and Kramer, 2011). Hence, we recognise that the present approach could benefit from a more explicit representation of value chain networks, and respective indicator metrics to measure multifunctional value along them, from farmer to consumer (e.g., Fagioli et al., 2017).

We illustrated the proposed approach by generating a framework specifically tailored to the European context. Europe as a whole was thereby considered as a "context", to the extent that it is a world region where many countries share standardised systems of laws, regulations and policy frameworks, a single common market, an advanced agricultural sector integrated into global supply chains and, to some degree, similar sets of principles, values and lifestyles. However, Europe is also characterised by a large degree of heterogeneity in terms of geographical features, cultural manifestations and historical legacies. On this basis, one could instead argue that it is actually composed of a patchwork of diverse (sub-)contexts. Two interrelated challenges would arise, if the framework were intended to be fully operationalised in a uniform way across Europe. Firstly, only a few studies may have the time, resources and/or expertise to fully evaluate such an exhaustive set of attributes for an entire continent. Thus, some degree of prioritisation may be required when selecting the attributes, processes and sustainability dimensions to be evaluated. In fact, not all indicators are necessarily relevant for quantification in every European sub-context. The framework presented here should, therefore, not be regarded as a "one-size-fits-all" assessment tool to be uniformly operationalised, but rather as a decision-support tool open to semantic control for selecting indicators in function of the goals and scope of analysis. For example, regional scale indicators can be selected to uniformly assess trends and benchmark outcomes across regions for the whole of Europe, using metrics available in public online databases or produced with large-scale models (e.g., Cerilli et al., 2020; Debonne et al., 2022). Indicators at the landscape scale and farm level should be specifically selected for sub-contexts based on their relevance (e.g., depending on the existing types of agro-ecosystem, ongoing processes of intensity change, and the priorities and concerns of different local groups of actors), and then evaluated in place-based assessments. In such settings, the generated framework can offer a structured procedure to conduct integrated multi-scale SI assessments for a variety of sub-contexts within the larger European context, and accordingly evaluate the extent to which local aspirations and developments in different locations converge/diverge towards broader regional targets, global priorities and societal visions (e.g., Helfenstein et al., 2022).

Table 4
Themes and indicators for assessing sustainability outcomes (SO).

SO themes	SO indicators	Scales/levels of measurement[a]	MAIC[b]	Socio-ecological processes	Mediating ecosystem services	Relevant actors
SDG1 – End poverty	Income level; Income stability; Farm viability; Farm adaptability; Farm autonomy	FL; RS;	All mechanisms	Commodity and monetary flows	Regulating and material services	Farm managers and households; Workers
SDG2 – Zero hunger	Food availability; Affordability; Supply stability; Self-sufficiency; Safety; Nutrition security; Food security	RS; DR	All mechanisms	Commodity and monetary flows	Regulating and material services	Consumers
SDG3 - Health and well being	Mental health; Physical injuries; Occupational exposure to pesticides; Zoonotic diseases; Respiratory illnesses	FL	All mechanisms	Private and work interactions; Livestock-human and human–nature interactions; Monetary, pollutant and pathogen flows	-	Farm managers and households; Workers
	Environmental exposure to pesticides; Exposure to nitrates in drinking water; Zoonotic diseases; Respiratory illnesses	CL	LMI; CI; IUI	Water, pollutant and pathogen flows	Air quality regulation; Water quality regulation	Communities
	Dietary exposure to pesticide residues and heavy metals; Food-borne diseases	RS	LMI; CI; IUI	Commodity flows	-	Consumers
SDG5 – Gender equality	Women unemployment; Women migration	RS	CI; LI; FC	Private and work interactions; Migration flows	-	Farm households; Communities
SDG6 – Clean Water	Freshwater availability; Freshwater quality	LS; RS	LMI; CI; IUI; FC; FSD; RSC; IIM	Water, pollutant and pathogen flows	Water and soil regulating services	Farm managers; Communities
SDG7 – Clean Energy	Energy security	RS; DR	All mechanisms	Commodity and monetary flows	Regulating and material services	Consumers
SDG8 – Work and economic growth	Economic output agriculture; Economic output tourism; Regional economic output; Regional unemployment	RS	All mechanisms	Commodity, monetary and people flows	All ES	Farm managers; Communities; Agriculture-related sectors: Tourists
SDG10 – Reduced inequality	Income inequality; Income stability; Farm adaptability; Farm autonomy; Poverty	CL; RS	All mechanisms	Commodity and monetary flows	Regulating and material services	Farm managers and households; Workers; Communities
SDG11 – Sustainable cities and communities	Social cohesion; Workers' rights; Quality of life; Sense of place; Rural population; Air quality	CL; RS	All mechanisms	Migration flows; Private, work and business interactions; Human-nature interactions; Pollutant flows	Regulating and non-material services	Communities; Farm workers
SDG12 – Sustainable production and consumption	Animal health and welfare	FL; RS	LMI; CI; IUI	Human-livestock interactions	–	Farm managers; Workers; NGOs; Consumers
	Land footprint; Water footprint; Nutrient footprint; Material footprint	RS; DR	LMI; CI; IUI; FC	Commodity flows		Consumers
SDG13 – Climate action	Carbon storage; Soil nitrous oxide emissions	AFS; LS	LMI; IUI, FC;	GHG flows	Climate regulation	Farm managers; Consumers
	Carbon footprint	FL; RS; GS	All mechanisms			
SDG15 – Sustainable terrestrial ecosystems	Land degradation	AFS; RS	LMI; CI; IUI; FC; FSD; RSC; CCPD	Ecosystem functioning; Species migration; Pollutant flows	Regulating services	Farm managers; Nature conservation
	Deforestation; Ecosystem degradation	LS; RS; DR				
	Water biodiversity; Soil biodiversity; Above-ground biodiversity	AFS; LS; RS; DR; GS				
	Functional biodiversity	LS				

[a] Scales and levels of organisation: AFS – Agricultural field scale; FL - Farm level; CL - Community level; LS - Landscape scale; RS - Regional scale; DR – Distant region GS - Global scale.

[b] Mechanisms of agricultural intensity change: LMI - Land management intensity; CI - Capital intensity; IUI - Input-use intensity; LI - Labour intensity; FC - Farm consolidation; FSD - Farm specialisation / diversification; RSC - Regional specialisation and concentration; VI - Vertical integration; KI - Knowledge intensification; IIM - Improved information management; CCPD – Crop/breed change and product differentiation; ID – Income diversification; C – Cooperation.

The second challenge is that accurately assessing the effects of agricultural intensity on ecosystem services entails the detailed consideration of several local-specific biogeophysical conditions, socio-ecological processes and complex feedback loops operating with different time-lags. Hence, assessing these processes for the whole of Europe in a comparable way, although possible through the use of large-scale spatially-explicit models (e.g., Maes et al., 2020; Mouchet et al., 2017; Stürck et al., 2018), requires a considerable degree of simplification in terms of both spatial resolution and formal representation of the processes in the models. Such large-scale models should only be used for the purpose of mapping major trends and identifying contrasting trajectories across regions (e.g., Felix et al., 2022; Stürck et al., 2018; Verhagen et al., 2018). For an accurate assessment at the local/landscape scale, dedicated models with more detailed data and process representation need to be developed.

With regard to this last point, one must assert that, for the generation of useful narratives to guide action in sustainability governance, it is the quality of the process of production and use of scientific information that matters most, and not necessarily the technical accuracy of the assessment per se (Giampietro et al., 2006; Renner and Giampietro, 2020). Sustainability assessments at the science-policy interface must often deal with "wicked problems", where facts are uncertain, values are in dispute, decisions are urgent, and stakes are high (Kuhmonen, 2018; Saltelli et al., 2020). Consequently, they are inherently fraught with both technical and social incommensurability, leading to considerable and unavoidable uncertainty, both in terms of normative framing and quantitative representation (Giampietro, 2003; Sala et al., 2013). On these grounds, sustainability assessments can greatly benefit from adopting a Post-Normal Science (PNS) approach (Sala et al., 2015; Saltelli et al., 2020). PNS encourages scientists to work closely together with an extended peer community constituted by all those with legitimate stakes or interests, so as to promote mutual learning and safeguard the quality of the process by acknowledging a plurality of perspectives and different types of uncertainty (Funtowicz and Ravetz, 1993; Mayumi and Giampietro, 2006).

In closing, we recommend the proposed approach to be integrally implemented as part of a participatory process involving different groups of stakeholders and experts, for the co-production of knowledge, negotiation of normative dimensions and specification of indicators. Such a process should be conducted in an iterative way, so as to ensure that: i) the chosen system representation is representative of all legitimate sets of perceptions, interests and concerns of different groups of actors; ii) the meaning of the indicators have a shared understanding among actors; and iii) the selected indicator metrics provide a good proxy for defining and assessing their different priorities and targets (Giampietro, 2003; Giampietro et al., 2006). Stakeholders should be involved from the very beginning during the problem formulation phase, because these pre-analytical choices will determine the quality and usefulness of the problem structuring used later on when developing and proposing solutions (Binder et al., 2010; Giampietro et al., 2006; Yegbemey et al., 2014). In addition, it is crucial to ensure that a diverse set of perspectives are included in the process, and that no single interest dominates or constrains the problem-solving process. Power asymmetries, in particular, need to be given special attention, since large organisations may attempt to mainstream implausible narratives on the framing of problems and solutions in order to promote internal agendas, for example, by endorsing “socio-technical imaginaries” that avoid “uncomfortable knowledge” (e.g., Giampietro and Funtowicz, 2020) or manufacturing doubts regarding scientifically well-supported knowledge claims (e.g., Goldberg and Vandenberg, 2021; Kitcher, 2010). The experts leading the process must therefore have an active role in checking the quality and plausibility of the narratives endorsed by different actors and/or generated by the assessment. For this purpose, a diverse set of reflexive analytical tools (e.g., controversy studies, sensitivity auditing, ethics of science for governance) is available and should be applied in order to ensure the saliency, legitimacy and credibility of the different narratives (Saltelli et al., 2020).

The application of the approach through literature review, as illustrated in this article, should therefore be understood only as a first step in supporting researchers during the preparatory phase of an assessment, allowing them to:

- obtain a first comprehensive overview of agricultural intensity and sustainability themes that are potentially relevant, as a basis for mapping out stakeholder groups with legitimate interests and concerns;
- identify available methods and data sources, as the basis for evaluating potential requirements and feasibility of the assessment (e.g., in terms of resources and expertise) and defining priorities;
- identify, a priori, potential blind spots and limitations of the assessment. These include intensity and/or sustainability themes that are potentially relevant but will not be sufficiently covered, due to a lack of resources and data. This, in turn, facilitates transparent communication to the general public, and/or identification of alternative methods (e.g., synthesis studies, participatory methods) that may complement the assessment.

Overall, we consider the approach presented here to be a step forward in defining transparent procedures towards the development of sustainability assessments that can anticipate the feasibility, viability and social desirability of alternative agricultural development pathways. The creation of such transparent information spaces will hopefully stimulate an informed public debate about the operationalisation of SI and increase the quality of deliberation over the sustainability of agriculture and its potential contribution to achieving SDGs.

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.08.014.

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