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How to monitor the 'success' of agricultural sustainability: A perspective

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ABSTRACT

Global food security is threatened by widespread degradation of agricultural land and associated loss of ecosystem services. In response, farming approaches such as regenerative agriculture are heralded by industries and governments as mainstream solutions to keep the global food system within planetary boundaries. The low level of consensus on science-based approaches to the monitoring and verification of the efficacy of such solutions, however, has left many initiatives vulnerable to allegations of greenwashing. In this paper, we present a comprehensive perspective on the role of indicators for monitoring agricultural systems. We subsequently propose a flexible yet coherent framework for the transparent, time and context-sensitive selection of indicators for monitoring the extent to which sustainability initiatives contribute to their goals.

1. Introduction

The global food system causes severe pressures on the environment and our planetary boundaries (Rockström et al., 2009): it releases about one third of annual anthropogenic greenhouse gas (GHG) emissions, causes about one-third of terrestrial acidification and is responsible for the majority of global eutrophication of surface waters (Crippa et al., 2021; Poore and Nemecek, 2018). In turn, these environmental impacts pose a direct threat to global food security, primarily through the process of land degradation. Erosion, salinization, compaction, acidification, and chemical pollution have collectively led to the degradation of approximately one third of our global land area (United Nations, 2022). In response, emerging approaches to land management, hitherto often considered as niche initiatives, are now heralded by industries and governments as mainstream solutions to keep the global food system within planetary boundaries (e.g. Danone, 2021; EIT Food, 2021). Regenerative agriculture is one of such approaches receiving a lot of attention from corporations, decision makers, and researchers in the food system (Tittonell et al., 2022): between 2015 and 2020, news items dedicated to regenerative agriculture increased by 2982% (from 200 to 6163 items), mirroring an increase in items on the scientific database Web of Science of 2500% (from 2 to 52 items) (Giller et al., 2021). Regenerative agriculture is one of the approaches to bolstering ecosystem services with the aim of enhancing all dimensions (people, planet, and profit) of a sustainable food production (Giller et al., 2021; Schreefel et al., 2020). However, the low level of consensus on science-based approaches to monitoring and verification is restricting the efficacy and transparency of implementation (de Olde et al., 2017a), and has left many initiatives vulnerable to allegations of greenwashing (Creswell, 2022; Diab, 2022). For example, the global foundation for organic agriculture IFOAM Organics Europe, (2023) recently warned against the greenwashing of regenerative agriculture, calling out seven multi-national actors in the food systems (e.g. PepsiCo, Cargill, Danone and Unilever). Therefore, there is now an urgent requirement to match the zeal with which agricultural sustainability initiatives are pursued and promoted by farmers, industries, and policies, with a framework for monitoring and assessing their effectiveness (European Commission, 2023; Wade et al., 2022).

In this knowledge vacuum, a number of monitoring and verification approaches have been developed to assist industries, policymakers, and

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the primary production sector in setting science-based targets for agricultural sustainability, often focusing on practices rather than outcomes (e.g. Danone, 2021; ROA, 2021). One of the key considerations in developing and applying monitoring schemes is assessing the purpose of the monitoring scheme: for who is it for and with which goals in mind? To define this, it is essential to involve the intended end-users and their decision-making processes in the monitoring design and setup. Different stakeholders have different needs and objectives. For instance, farmers may strive to improve practices to meet specific environmental goals; certifiers may assess compliance with voluntary standards; value-chain actors may aim to maximize consumer loyalty at minimal cost; and regulators may seek adherence to publicly set standards. To be truly effective, the design of monitoring systems must be tailored to these diverse decision-making contexts, taking into account the different goals, contexts and operational logistics to ensure effectivity (Nikinmaa et al., 2023). In most cases, however, we observe the application of uniform or generic indicators across contrasting contexts, referred to as one-size-fits-all or fixed minimum sets of indicators (Gasso et al., 2015), without due consideration of the diversity of agronomic, biophysical and socio-cultural contexts between, and even within, individual value chains within the food sector. This has resulted in the emergence of a myriad of individual approaches to monitoring that are competing for validation and scaling.

If we zoom out to learn from current approaches to monitoring of agricultural sustainability in general, we find a multitude of frameworks and tools that use indicators (e.g. Coteur et al., 2019; de Groot et al., 2010; FAO, 2014; O'Donoghue et al., 2022; van Oudenhoven et al., 2012) to monitor *inter alia* the current status of farming systems, to identify trends, to forewarn the crossing of critical thresholds, to monitor the success of interventions in achieving specific goals, and to incentivize farmers (Chopin et al., 2021; Siddig et al., 2016; Soulé et al., 2021; Vanham et al., 2019). However, the selection process and use of indicators has often been contested (de Olde et al., 2017a; Gasparatos et al., 2008; von Wirén-Lehr, 2001). For example, the selection of indicators is often inconsistent (different initiatives select different indicators to monitor the same goals (de Olde et al., 2017a) or single-focused (only one indicator is selected to capture the performance of a broad topic (e.g. soil carbon to monitor soil health (Liptzin et al., 2022)). Furthermore, indicators that can be used to monitor the adoption rate of interventions (i.e. practice-based indicators) are frequently confused with indicators that capture the efficacy of interventions in the longer term (e.g. result-based indicators) (Bockstaller et al., 2015; Braband et al., 2003). Given the pivotal role of indicators in capturing change, it is perhaps surprising how many of the frameworks that advocate for the use of specific indicators lack a comprehensive theoretical foundation regarding the dynamics of transformative change and the principles of causality within intricate adaptive systems (Geels, 2011; Kim, 2023; Palomo et al., 2021). Academically driven frameworks often lack attention to the implementation aspect, while frameworks developed in the private sector or governments are often oversimplified or driven by cost considerations (de Olde et al., 2018; Saltelli and Giampietro, 2017).

In this paper, we bring together the knowledge from multiple domains in the field of soil monitoring, sustainability science, food systems thinking, and transition studies to give a holistic view on using indicators for monitoring agriculture sustainability. Rather than contributing to the already abundant pool of frameworks designed for monitoring agricultural sustainability, our framework adopts a different approach by taking a more fundamental perspective. Its primary objective is to offer guidance for conceptualizing indicators and causality in the context of agriculture as a whole by appraising each indicator for the context, location, and temporal timespan for which it is most relevant. Put simply: we can no longer apply generic minimum sets of indicators to monitor changes in agricultural systems. Instead, we must consider; 1) the goal of the monitoring system (what is the focus – or question to be answered), 2) the purpose (who is the monitoring information for, and at what scale of assessment), and 3) the context (the point of monitoring, the location of which the monitoring is focused, the type of agricultural system being monitored). We propose to harmonize the *process* of indicator selection, rather than its outcomes, resulting in a flexible yet coherent monitoring framework that provides a transparent, harmonizable, and context-sensitive selection of indicators and associated measurements. The framework is applicable across a range of scales from monitoring at the local land management scale, or for use in sustainability initiatives to verify the efficacy of changes to agricultural management practices or as tool to assesses policy implementation at regional to continental scales. We illustrate this framework with three case-studies that represent a variety of purposes and scales of assessment for similar goals. These illustrations are: 1) an almond farm in Spain, where decisions are made at field and farm level, 2) a value chain for oat production in Finland, where the focus of monitoring change extends across multiple farms within a country and 3) at a policy level, where our framework is populated using the French National Strategic Plan for the implementation of the EU Common Agricultural Policy.

2. Harmonizing terminology

Before we set off on this journey, we must address the terminology used in this paper, since terminology is not uniform among actors (Soulé et al., 2021). The term indicator is used among actors (i.e. farmers, researchers, industries, and governments) and knowledge domains (e.g. natural monitoring and food systems thinking) in various ways and used interchangeably with terms such as "metric" and "measurement". We use the term *indicator* according to E.M. de Olde et al. (2016) and Soulé et al. (2021) to point out a standard of monitoring that provides a narrative description in addition to quantitative characterization of something (see also Curran et al., 2016; Konys, 2018). Meanwhile, the term *measurement* refers to the activity of measuring compared to an existing scale and is often a degree or an amount of something, that quantify each indicator using a certain method and has a unit (e.g. CO_2 eq. per kg milk) (Liss et al., 2013; Moriarty et al., 2018). An indicator can in this case include multiple measurements.

Numerous indicators and associated measurements have been proposed for the monitoring, reporting, and valorisation of agricultural sustainability in general (de Olde et al., 2017b; Soulé et al., 2021; Vanham et al., 2019). There are many ways in which these indicators can be categorized (e.g. by cause-effect or direct-indirect relationships (Bockstaller et al., 2015; FAO, 2014)) and many different terms referring to the same type of indicator (Fig. 1). Based on a scoping review we distinguish four types of indicators: target, practice, result, and outcome-based indicators, each with associated measurements. To harmonize language, Fig. 1 illustrates the convergence in terms that are used for the types of indicators considered in this paper. For example, practice-based indicators are referred to by the OECD (2001) as "*driving force indicators*", while result-based indicators are referred to by Aramyan et al. (2007) as "*performance indicators*", and outcome-based indicators are referred to by the European Union (2018) as "*impact indicators*".

Here, we exemplify each of these indicator types with one example each (see bullet points below) for the single goal of reducing greenhouse gas (GHG) emissions with a focus on carbon, applied to three scales: at farm-level, within a value chain, and in policymaking. In reality, actors may have multiple goals and work in various contexts; this would require an iterative application of the framework for each goal and context.

- *Target-based indicators* show the presence of a plan to implement one or more interventions, for example:
  - o at farm-level: the presence of a carbon management plan;
  - o within a value chain: the presence of a corporate net-zero standard target;

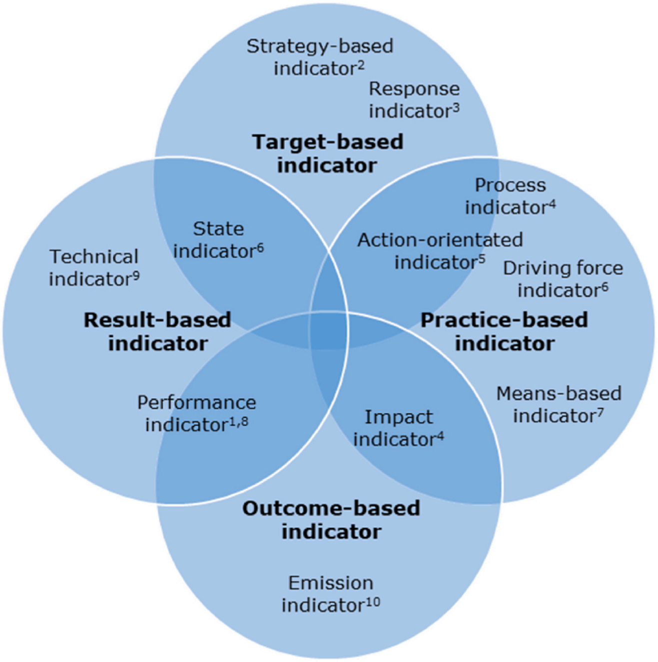

Fig. 1. Overview of the target, practice, result, and outcome-based indicators as well as adapted synonymous terms used in literature. The superscripts correspond with the following references: [1](FAO, 2014), [2](Mansor et al., 2008), [3](Becker, 2010), [4](European Union, 2018), [5](Braband et al., 2003), [6](OECD, 2001), [7](van der Werf and Petit, 2002), [8](Aramyan et al., 2007), [9](Luján Soto et al., 2020), [10](Bockstaller et al., 2015).

  - within policy: the publication of a nationally determined contribution to meet commitments to the Paris climate agreement.
- *Practice-based indicators* show the degree of implementation of interventions (i.e. practices, activities, new technologies), for example:
  - at farm-level: implementation of a practice e.g. sowing of cover crops;
  - within a value chain: number of farms using cover crops;
  - within policy: number of farmers that avail of agro-environmental and climate measures under the Common Agricultural Policy.
- *Result-based indicators* show the consequences or quality of the interventions, and therefore whether the intervention(s) applied had the desired effect in the midterm, by quantifying for example:
  - at farm-level: area of ground cover throughout the year;
  - within a value chain: average area ground cover in the supplying region;
  - within policy: change in area of national ground cover (reduction of bare soil).
- *Outcome-based indicators* show if the intervention has delivered on its original goals, in the end term, for example:
  - at the farm-level: a change in soil organic carbon content;
  - within the value chain: a change in the carbon footprint of products;
  - within policy: a change in national net GHG emissions.

3. The role of indicators to assess agricultural sustainability

3.1. Target-based indicators

Target-based indicators are considered useful, largely because of their ease of monitoring: they do not require high financial or time investments. Underlying the use of these indicators is the, often implicit, assumption that the creation of a plan (e.g. to reduce on-farm GHG emissions) will over time lead to the achievement of the goal of the intervention (i.e. to reduce national agricultural GHG emissions). However, the use of target-based indicators has been critiqued, because the plan to implement an intervention is often poorly correlated with the achievement of the goal set, and can only be used as a proxy at best (Braband et al., 2003; FAO, 2014). For example, the Irish Food Board recently reported its success in tackling climate change by its *Origin Green* farm sustainability program that had delivered 290,000 on-farm carbon footprint calculations since its inception in 2012, as well as 21,000 associated farmer feedback reports in 2021 alone (Bord Bia, 2021); both can be classified as target-based indicators that track the inception and scaling-out of farm advisory plans. At the same time, the Irish Environmental Protection Agency reported that total GHG emissions from Irish agriculture increased by more than 12% over the same time period (EPA, 2022), illustrating the poor correlation between the target-based indicators and outcome-based indicators, as reported separately by the two state agencies. Although target-based indicators can help to create awareness for actors regarding the importance of specific issues (e.g. climate change) (FAO, 2014), they can be sensitive to allegations of greenwashing; we therefore suggest that they are only appropriate where they define a transition process, in which practice, result, and outcome based indicators are also considered.

3.2. Practice, result, and outcome-based indicators

Practice-based indicators show the degree to which a plan leads to changed practices (Fig. 2). While changes in agricultural practices may still be only loosely correlated to eventual outcomes (Elmiger et al., 2023), practice-based indicators are commonly used in certification schemes (e.g. organic certification), since they allow for the immediate financial incentivization at a time where investment requirements are highest (i.e. at the start of a transition in farm management practices) (Tanaka et al., 2022). A potential hazard linked to the exclusive dependence on practice-based indicators in monitoring schemes is the inadequate guarantee of phasing out detrimental practices (Hebinck et al., 2022). For instance, the organic certification process often relies on practice-based indicators (Newton et al., 2020), which is frequently criticised for translating into 'checklists of do's and don'ts' (Alexandre de Lima et al., 2021). Despite organic farmers meeting all the certification criteria, these farmers are still allowed to plough plastics into their soil (Dentzman and Goldberger, 2020; Sa'adu and Farsang, 2023).

Result and outcome-based indicators deliver more direct insights into the progression towards goals and as such offer better accountability and improved incentivization (Braband et al., 2003; Janus and Holzapfel, 2017). The divergence between result, and outcome-based indicators lies within the temporal aspect and associated position in the causal chain which is strongly related to the purpose of assessment. Result-based indicators show the consequence of changed interventions in the midterm based on activity data. A combination of these result-based indicators will be more closely correlated to the desired outcome-based indicators that are strongly aligned to the original goal and that quantify the changes that have occurred. Outcome based indicators are typically monitored in the longer-term, and as such may be affected by external drivers over time (e.g. policies or climate). While widely applied in the health and education sectors, their use in agriculture is currently in a pioneering phase, while the suitability of such instruments for the sector is debated (Janus and Holzapfel, 2017). A common pitfall is the application of result and outcome-based indicators in isolation from practices; this hampers the interpretation and understanding of monitored results and outcomes when the context is not identified (Jones et al., 2021; Wade et al., 2022). For example, when only soil carbon is monitored to track progress towards climate goals, it remains unknown whether this progress can be ascribed to the original practice, changed intervention, or to other factors (e.g. rising energy and fertilizer prices). Therefore, the interpretation of these indicators requires contextualization in terms of practices, pedo-climatic conditions and land use. Here it must be noted that the use of indicators for monitoring is not a linear process (Niemeijer and de Groot, 2008): this

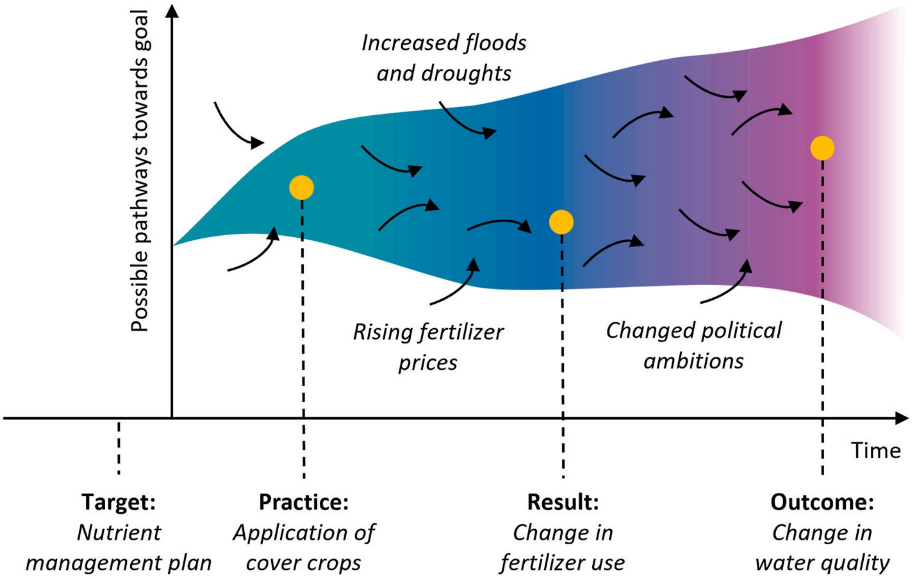

Fig. 2. Conceptual illustration of the relationship, as well as correlation, between practice, results, and outcome-based indicators over time. The yellow dots indicate one of a myriad of possible pathways in response to active and passive drivers (arced black arrows) influencing an intervention aimed at improving water quality. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

contextualization of result and outcome-based indicators with multiple practices does not always lead to the elucidation of clear causal relations. Models are an oft-used approach to infer and understand causal relationships between practices, pedo-climatic conditions, land use, results, and outcomes (see also Bockstaller et al., 2015), although Valencia et al. (2022) showed that many models struggle to capture causality in disruptively innovative systems. In Box 1, we illustrate the use of different types of indicators using water quality as an example.

4. A flexible yet coherent framework - perspectives for the future

4.1. From a minimum uniform set of indicators to a flexible framework

Given the diversity of indicators available, it is no surprise that, despite numerous attempts (FAO, 2014; Hanegraaf et al., 2019; Hristov and Chirico, 2019), science has thus far failed to agree on one unified minimum set of indicators for the assessment of agricultural sustainability (Joung et al., 2013; Sikdar, 2003). While the creation of uniform or generic minimum sets of indicators may appeal to the objectives of science, industry, and governments for coherent data comparison across various applications or value chains, this uniformity comes at the expense of reduced actor operability and reduced pertinence (Gasso et al., 2015). This may result in data collection for monitoring becoming the goal in itself, rather than a means to track progress towards a goal or set of goals for a given context and purpose. For example, current efforts to standardize indicators and measurements have largely ignored regional and soil-type related biases in quantitative sustainability analyses (Wade et al., 2022). Furthermore, the relevance of each indicator depends on the context, purpose, and scale of assessment, which may range from fundamental research on the impacts of agriculture practices, to supporting land managers in decision-making at a field scale, to monitoring long-term outcomes for policymakers at continental scales (Creamer et al., 2022).

Box 1
Illustration of using practice, result, and outcome-based indicators

To illustrate our point, we consider an intervention aimed at improving water quality in agricultural areas (Fig. 2). The intervention may be the establishment of a nutrient management plan, in line with the cross-compliance requirement for Good Agri-Environmental Condition (use of Farm Sustainability Tool for Nutrients) of the EU Common Agricultural Policy (European Commission, 2022a). In this case, the successful establishment of a nutrient management plan can be used as a target-based indicator, while the implementation of practices (e.g. leguminous or cover crops) at farm level gives a first indication of the degree to which these aspirations are being implemented. The *quality and effectiveness* of nutrient management planning is likely to become apparent in the medium term, for example through a reduction in mineral fertilizer application or sales: both are considered result-based indicators. However, these indicators do not only track the success of the nutrient management planning but are simultaneously sensitive to other active or passive drivers, e.g. a concomitant rise in fertilizer prices. The outcome-based indicator of the intervention, i.e. change in water quality, can either be monitored in the short, mid, or long-term after implementation of the intervention, since they are dependent on the context and speed of processes between fields and waterbodies. It may take many years for the effects of an intervention to be registered in a monitoring programme for water quality, as it takes time for nutrients to migrate and 'be flushed' through the pedosphere and watersheds (Fenton et al., 2011; Schulte et al., 2010). At the same time, other events, such as extreme erosive events, may result in a more immediate decline in water quality (Ketema and Dwarakish, 2021). This calls for a range of intermediate outcome-based indicators to be monitored over time. While this outcome-based indicator is most closely correlated to the original goal, it will not only reflect the outcome of the original intervention, but also of the many other driving forces (e.g. policies, markets, prices) as they have evolved over the intervening period. This example illustrates how, in isolation, neither practice-based indicators, nor result, or outcome-based indicators, can satisfactorily monitor the success of an intervention over time; this can be overcome by applying a combination of the three types of indicators.

The framework we propose (Fig. 3) breaks with the trend of generic minimal datasets and recommends the context-specific selection of indicators, which is simultaneously underpinned by a comprehensive and unified scientific framework. More specifically, our framework presents a 'menu of options' that allows for transparent and context-specific selection of indicators for monitoring at different moments in time across spatial scales (i.e. field to food system-level or governmental level). The framework guides actors (e.g. farmers, researchers, industries, policymakers) in the selection of relevant indicators and measurements based on three steps: 1) defining the 'setting', 2) selecting adequate 'indicators', and 3) selecting appropriate 'measurements' (Fig. 3). While this framework can in principle be used for monitoring the success of all forms of sustainability programs, in this paper we will apply it to agricultural practices focused on soil carbon enhancement and long-term storage. In the following sections we will describe both the framework itself, as well as the process of populating the framework for individual contexts.

4.2. *The setting of monitoring*

The setting defines the spatial scales and system boundaries of the monitoring scheme by assessing (see also Bockstaller et al., 2015).

- The *goals* of monitoring: The actor (i.e. user of the framework), together with local knowledge experts, specifies which goals and desired states they aim to achieve with their interventions (e.g. reduction in GHG emissions).
- The *purpose* of monitoring: Here actors can distinguish and choose, depending on their role in the agri-food system for example, to inform practical farm management decisions, inform consumers, or to show the territorial impacts for policymakers.
- The *context* of monitoring: Here, the actors define the agricultural system, scale, socio-cultural, economic, and pedo-climatic conditions of the agro-ecosystem of interest, for example, a Spanish almond farm on sandy soil, oats producing farming systems in the southern region of Finland, or a French policy initiative on soil health.

The framework explicitly enables for multiple goals, purposes, and contexts to be considered simultaneously. For instance, a farmer may need to address various goals, such as promoting soil health, which entails identifying diverse objectives reflecting the multifunctionality of soils (Schulte et al., 2014). Similarly, a value chain may seek to delineate multiple purposes, such as informing both customers and shareholders about the sustainability of a particular product concurrently. At a governmental level, there might be a need to monitor the efficacy of a specific practice across various farming systems, such as arable systems spanning multiple pedo-climatic conditions. It is worth noting that a change in context may or may not necessitate different indicators. For example, different indicators may be needed for different production systems (e.g. crop production vs. milk production), while a different soil type within a production system may only require the reference values to be adapted (see section 4.7 Benchmarking).

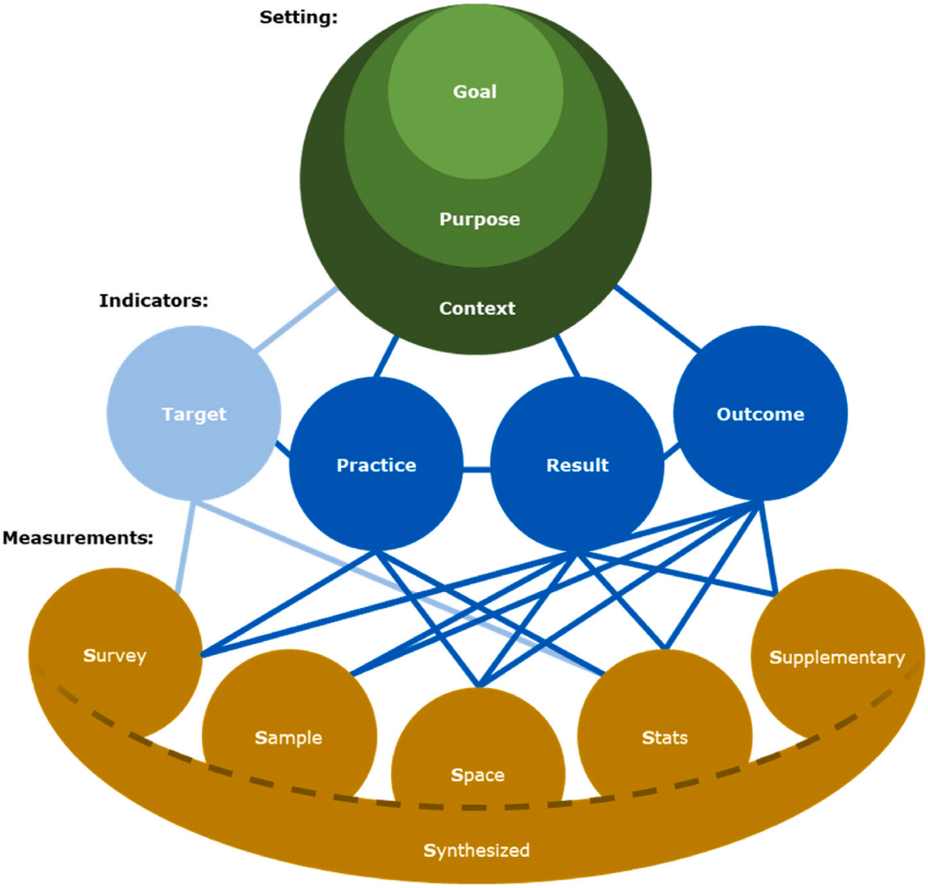

Fig. 3. A flexible yet coherent framework to select indicators and measurements for different settings. Target-based indicators have a divergent colour compared to the other indicators to show the small or specific role they can play in using indicators to monitor the transition towards agriculture sustainability. The varied lines between indicators and measurements indicate that some measurements can be applied to multiple indicators, while others are limited to specific indicators. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.3. Indicators for monitoring

The next step of the framework is to select the appropriate practice, result, and outcome indicators, which are defined based on the setting of the monitoring program (as shown in Fig. 3). While we consider the inclusion of target indicators optional and at the discretion of the user, we strongly advocate for the explicit incorporation of practice, result, and outcome indicators. A baseline assessment of practice, result, and outcome indicators should be conducted to further characterise the setting, with these indicators being reassessed over successive years. The timing of these indicators is contingent upon the type of measurement; for instance, practice indicators are evaluated at the start of the process or intervention and subsequently reviewed on an annual basis. Result indicators are assessed with a similar frequency, elucidating whether the intervention manifests any indications of success or failure. Result-based indicators typically delineate the trajectory of transition within two to five years following an intervention. Furthermore, outcome indicators should be gauged at the baseline, yet their pace of change over time may be gradual, thus warranting multi-annual monitoring cycles, over which changes may be detectible. Outcome-based indicators demonstrate the degree of success in achieving the original objectives, and their monitoring depends on their position in the causal chain; typically outcomes are monitored over a longer time-period of at least ten years. Throughout the monitoring timeframe, co-variates such as weather conditions and the timing and type of management interventions may also be assessed and reported, to aid the qualification and interpretation of indicators.

4.4. Measurements for monitoring

The final step in establishing the monitoring scheme is selecting measurements (approaches to data collection) that enable the evaluation of indicators. For each indicator, a wide range of potential measurements may be reported in the scientific literature. For example, Soulé et al. (2021) already identified 262 assessment methods for environmental sustainability, while Zwetsloot et al. (2022) distinguished 289 available measurements of soil biology relating merely to soil multifunctionality.

Here, we can distinguish several types of measurements.

- *Measurements by survey* refers to data collection in which farmers are interviewed for obtaining socio-economic and biophysical data, for example labour hours or perceived working conditions.
- *Measurements from stats* are typically derived from existing databases (e.g. European Farm Accountancy Data Network (FADN) (European Commission, 2022b), and national governments) on agricultural practices, results, and outcomes, for example on pest management or land use at national scale.
- *Measurements from space* are typically derived through remote sensing, for example using satellites monitoring land use change (e.g. area of various crop types) and landscape features (e.g. terracing and erosion).
- *Measurements by sample* refer to any form of on-site collection of empirical data, for example by monitoring species richness and abundance.

Additional measurements may include *supplementary and synthesized* measurements. Supplementary refers to types of measurements that includes co-variate information relating to, for example climatic conditions or wider topographical characteristics. Synthesized measurements include modelling approaches, which often uses multiple (though not necessarily all) types of measurements (e.g. sample, space, stats) as input. For example, a nitrogen balance is often computed using data from surveys (asking the farmer about management; farm inputs and outputs), stats (standard data about atmospheric nitrogen fixation), and samples (measuring the nitrogen content of feed and manure).

4.5. Recommendations for operationalisation

The selection of adequate indicators requires both expertise about the setting (i.e. purpose and context) of the user, as well as knowledge on the diversity and applicability of indicators and measurements in time. Therefore, the setting, indicators, and measurements are co-selected by the actors seeking to establish a monitoring campaign, with local experts, extension services, or knowledge brokers. However, experts may disagree on the criteria for defining monitoring indicators, as the underlying science can be contested (de Olde et al., 2017b). The selection of indicators and measurements is not immune to personal biases, either conscious or unconscious, of the actors involved, or to the power-relations between them (Alrøe et al., 2017; Turnhout et al., 2014). Participatory and reflexive methods offer significant advantages in navigating these challenges (Kovacic, 2018), including the facilitation of knowledge sharing, mutual learning among stakeholders, the cultivation of trust between various parties, such as farmers and agricultural advisors, and a heightened interest in the implementation of regenerative practices (Luján Soto et al., 2020; Reed et al., 2008; van Noordwijk, 2019). While supplementary S1 offers a more comprehensive overview of the operationalisation of the framework, we particularly suggest that.

- Actors collaborating with local independent knowledge experts formulate the goals, purpose, and context of the monitoring effort;
- Actors with local experts, extension services, or knowledge brokers select which practice-based indicators are relevant, within the specific setting, to achieve the desired goals;
- Local experts, extension services, or knowledge brokers select which result-based indicators are relevant in the medium term and outcome-based indicators in the end term;
- Prioritization approaches like heatmapping can aid in the selection of the most pertinent goals, purposes, and indicators (e.g. Grill, 2021; Sharpe et al., 2021), as extensive lists of such issues may complicate the pragmatic implementation of the framework (Fraser et al., 2006);
- Scientists may then propose a long-list of potential measurements (i.e. survey, stats, space, sample, synthesized) associated to target, practice, result, and outcome-based indicators;
- Using, for example, a logical sieve (Zwetsloot et al., 2022) with local independent knowledge experts could assist in iteratively filter long lists of measurements to a shortlist based on technical criteria for application (e.g. ease of field sampling and overall costs) (see also de Olde et al., 2016; Soulé et al., 2021).

4.6. Case study examples of the applicability of the framework

To illustrate the implementation of this flexible framework approach, we present three case studies representing different spatial scales of assessment. These encompass: 1) almond production at farm level in Spain (Fig. 4), 2) oat production at the value chain level in Finland (Fig. 5), and 3) the policy level where we populated our framework with the French National Strategic Plan (Fig. 6). For cases 1 and 2, we conducted workshops with users (i.e. farm and value chain managers) and local knowledge actors to define goals, purpose, and context, and to determine appropriate practice indicators. While multiple goals were considered in both workshops, carbon for building resilience to climate change emerged as a shared goal across contexts and purposes. For case study 3, we aligned goals with the Common Agricultural Policy (CAP). Additional details about the case studies, knowledge actors, and settings can be found in Supplementary Materials S1, S2, and S3.

In the first case study, land managers within a Spanish almond production system (context) aimed to initiate a monitoring campaign to identify essential indicators to inform their transition to regenerative agriculture. Their focus was on increasing soil carbon in changing climatic conditions (goal), with the aim of evaluating the efficacy of their farm management practices (purpose). Critical considerations during

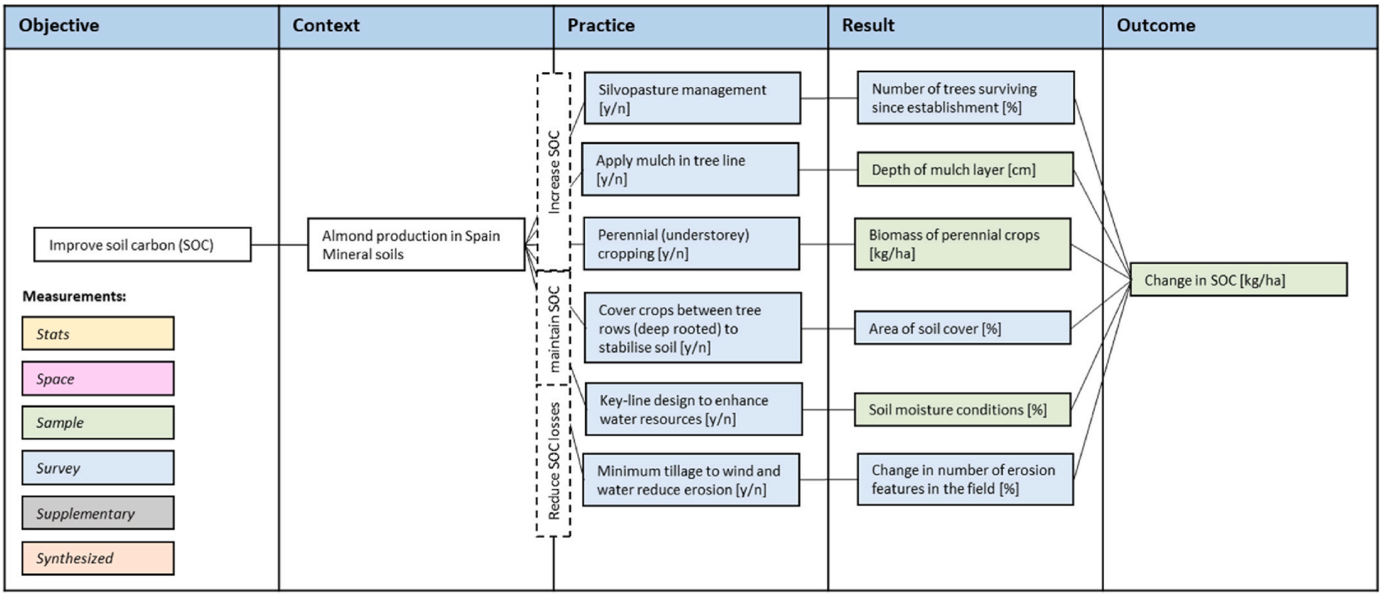

Fig. 4. Overview of the practice, result, and outcome indicators identified along with measurements for resilience to climate change in terms of carbon for the almond production farm in Spain. Dotted boxes indicate the potential impact of practices on eventual outcomes.

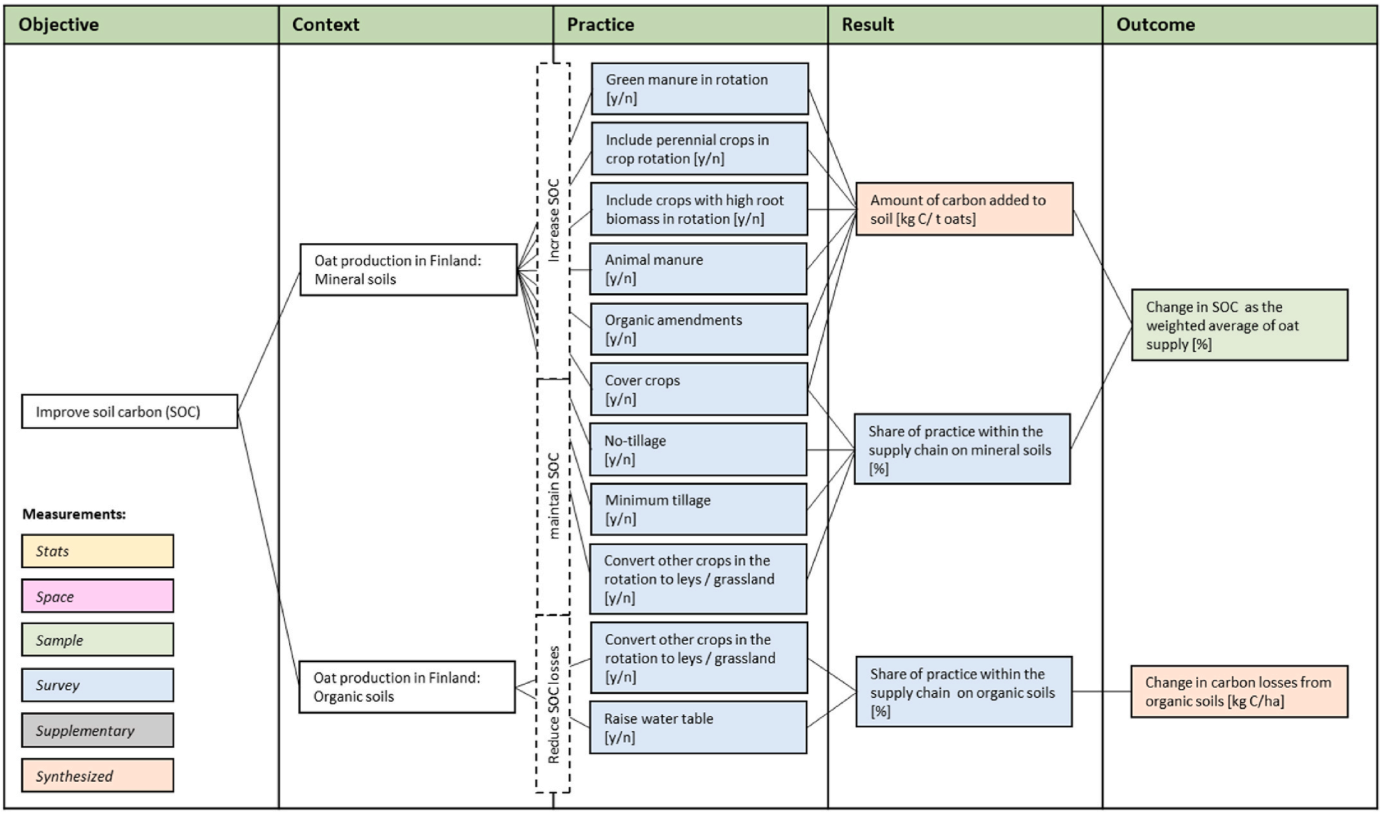

Fig. 5. Overview of the practice, result, and outcome indicators identified along with measurements for improving soil carbon at the value chain level focusing on oat production in Finland. Dotted boxes indicate the potential impact of practices on eventual outcomes.

indicator selection included various measurement types, prioritizing ease of data processing and interpretation, as well as the cost-effectiveness of sample analysis.

In contrast, the second case study involved a processing company seeking to monitor its success in reducing GHG emissions from soil carbon losses (goal) by implementing regenerative practices (purpose) on the Finnish oat farms in its supply chain (context). In this context it is necessary to manage diverse data sources informing the decision-making processes, necessitating careful consideration of sampling logistics and quality control in selecting indicator and measurement types, with less emphasis on cost and the level of specialisation associated with data analysis.

In the third case study, the existing monitoring framework for the French CAP National Strategic Plan was applied to our framework to

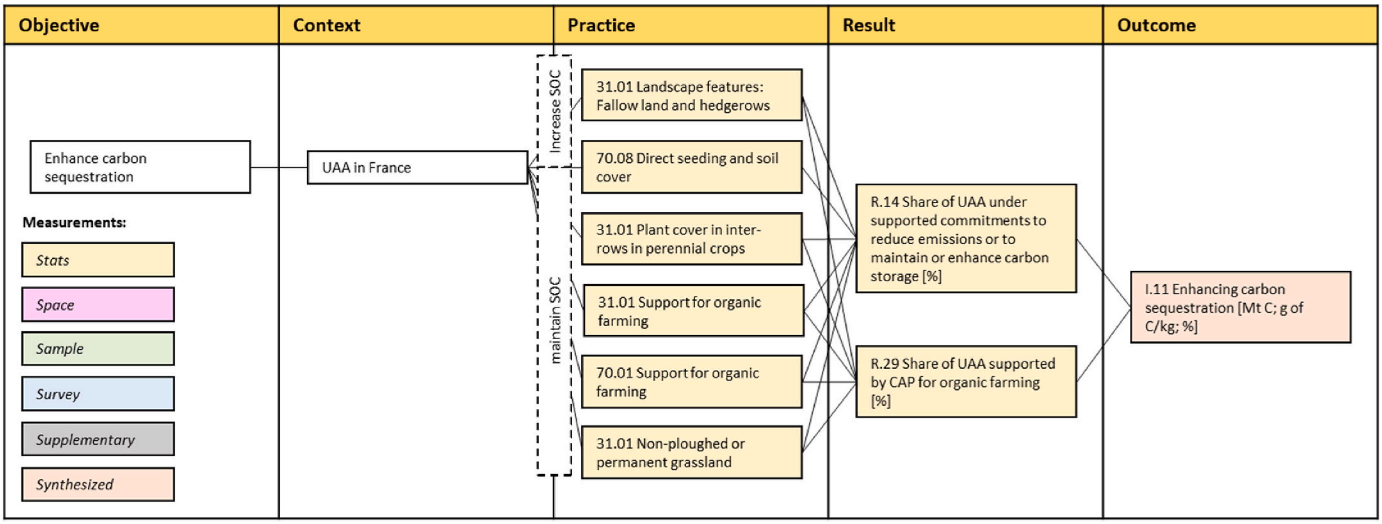

Fig. 6. Overview of the practice, result, and outcome indicators identified along with measurements for enhancing carbon sequestration for France's Common Agriculture Policy. Dotted boxes indicate the potential impact of practices on eventual outcomes. Practice indicator numbers are referencing France's intervention codes with 31.1 being eco-schemes, 70.01 and 70.08 being agri-environment measures.

illustrate how our framework aligns with national policy monitoring (Ministère de L'Agriculture et de la Souveraineté Alimentaire, 2023). In particular, we focused on the indicators aimed at contributing to climate change mitigation and adaptation, specifically focusing on carbon sequestration (goal). This plan applies to all utilized agricultural areas (UAA) in France (context) and evaluates the effectiveness of interventions (purpose). These indicators apply to two types of CAP interventions: the eco-schemes and agri-environmental climate measures specifically promoting carbon sequestration.

Despite notable differences in settings, including climatic conditions (e.g., Mediterranean, temperate oceanic and subarctic) and monitoring perspectives (i.e., farmer, value chain, and policy perspectives), all case studies shared a common focus on enhancing carbon at the farm level, leading to some common practice-based indicators, such as the use of cover crops and minimum or no tillage. At the same time, other practices were specific to each setting. For example, in Spain, practices included key-line design and the establishment of perennial systems with silvopasture and intercropping management; practices that are relevant to addressing the specific Spanish pedo-climatic context of erosion and desertification. Practices prioritized in Finland focused on annual crops with a short cropping cycle, and included the establishment of rotational grass lays and livestock interaction. Additionally, the Finnish case study included farms on organic (peat) soils, that require a very different set of practices relating to water table management to prevent carbon oxidation(de Jong et al., 2021). In the policy example, practice indicators aligned with CAP subsidies such as eco-schemes and agri-environmental climate measures.

Result-based indicators derived from the case studies provide an early indication of the efficacy of the interventions in contributing to the original goals, and may indicate any trade-offs with other goals or practices. Result indicators are cost-effective and can often be employed with low specialisation or infrastructure at the local scale. For example, in case study 1, tree survival rates or mulch layer depth can be determined in situ by farmers themselves. At the value chain level, monitoring may involve assessing the percentage of farmland devoted to cover crops or no-tillage practices. At the Member State scale, percentages of UAA supported by CAP for organic farming can indicate trends in practice implementation. Data for these indicators often come from existing national data structures collected for reporting to the CAP (stats).

Outcome-based indicators employed in the case studies are linked closely to their specific shared objective of enhancing soil organic carbon (SOC). Outcome indicators my typically be measured over multiannual cycles, e.g. with five-year increments, as most outcome indicators are only expected to respond slowly to changing practices. While the outcome indicators themselves may be similar across our three case studies, their associated measurement types varied. At the farm level, sampling soils to detect changes in SOC aligned with practical constraints, providing a cost-effective proxy for decision-making. In the second case study, changes in SOC were expressed as the weighted average of the oat supply of the company. This nuanced approach reflected a consensus among knowledge actors, who underscored the importance of expressing changes in SOC relative to productivity to address trade-offs between climate mitigation and economic sustainability; had absolute SOC changes been adopted as an outcome indicator instead, then this would have unduly incentivised the practice of "no oat or crop production". In our third case study at the policy level, monitoring of outcome indicators involved a large-scale sampling campaign coupled with biogeochemical modelling (synthesized) to capture national carbon sequestration rates.

These examples of application across diverse case studies underscores that indicator selection depends on specific settings, including goals, purposes, and contextual factors. Even where contrasting settings yield similar indicators, variations in measurement types may be required due to diverse capabilities and resources available to each initiative.

4.7. Benchmarking

Once monitoring data is being collected, how can we establish whether the numerical data represent a 'good' or 'poor' progress? Traditionally, monitoring data is benchmarked against reference values, which, for example, can indicate if a goal's desired state is achieved. In some cases, absolute standards have been agreed upon, and monitoring must reflect compliance with these standards. In other cases, progress over time needs to be evaluated using more targeted and context-specific monitoring. Additionally, in scenarios such as those further down the value chain, direct comparison and ranking of options may be necessary, requiring consistency in measurement and sampling methods. At times, single reference values (threshold values) have been used across a diversity of pedo-climatic conditions; one example is the proposal to use a single benchmark for Soil Organic Matter (SOM) across the EU. Here, failure to recognize that a single reference value may be considered either high or low, depending on the local climatic conditions, led to erroneous inferences on ‘soil quality’ in individual EU Member States (Spink et al., 2010). Furthermore, reference values often lack standardisation and different indicators may use different types of reference values, namely normative or relative, to monitor success (Acosta-Alba and Van der Werf, 2011). Normative reference values are typically based on science or policies, and they facilitate the quantification of goals by representing target values (desirable conditions) or environmental thresholds (limits of environmental pressures), such as the planetary boundaries (Rockström et al., 2009). Relative reference values can be derived by comparing the monitoring data to similar data collected within the same ‘setting’ (e.g. comparing the performance of a farm with what is average in that region, or how the top 5% is performing). In some cases, information is not available for wider benchmarking, this is especially the case for data on soil biodiversity (van Leeuwen et al., 2019), which restricts possibilities for standardisation (Gasso et al., 2015) and may result in poor comparisons and conclusions (Hortal et al., 2015; Siddig, 2019).

5. Future perspectives

Actors in the food system are often challenged by the complexity associated with the selection of the most appropriate indicators and measurements because of the myriad of options, as such the purpose and context are often forgotten when selecting indicators and focus is given only to cost and expediency, or over-simplification of more complex systems. This results in a poor selection of indicators, such as reducing the assessment of soil health to a single indicator such as soil carbon (Gasparatos et al., 2008). This is particularly a risk in private certification standards that operate at a global level where generic requirements are put on farmers despite the significant variation in their contexts (Dietz et al., 2022).

We have now arrived at a moment in time where the commonplace expediency in the choices of indicators of success for agriculture can be replaced with a scientific framework that brings together and builds on decades of research worldwide. We have shown that different types of indicators have their own use, position in the causal chain, and timing. Therefore, combining different types of indicators and measurements is key for future monitoring in agricultural systems. By harmonizing the process rather than the outcome of indicator selection, our framework can be flexibly applied to contrasting contexts and can be used by different stakeholders worldwide (e.g. farmers, industries, governments), for a range of purposes.

Although our framework helps overcome issues like ’checking-the-box’ approaches, or unnecessary reliance on expensive measurements, we must caution against the risk of potential greenwashing. While designed for transparency, frameworks like the one described in this perspective can still be used inappropriately. For example, there is the risk that goals, indicators and measurements could be tailored in such a way that they are predesigned to demonstrate the success of an initiative. It is for this reason that we emphasise the role of actors and transparent documentation in collective selection processes that explicitly involve independent local knowledge actors (Gardner et al., 2019).

Further research is necessary to evaluate the framework and its actual application on a wide range of case-studies across sectors and scales. While we have illustrated its applicability within the scope of environmental sustainability, examples pertaining to the social and economic dimensions of sustainable food production is required to demonstrate its versatility across multiple domains. Here, we recognize that the interconnectedness of environmental stability and human well-being (Rockström et al., 2021) must be captured to support additional and achievable transition pathways, as illustrated by the inclusion of fairness and justice considerations in the recent discourse on planetary boundaries with considerations of Rockström et al. (2023).

As individual indicators, by definition, relate to a sub-section of our global food system, they are non-neutral and biased towards specific goals (Gasper et al., 2019). This implicit bias towards certain sections of the food system, and associated actors, influences their uptake (Bernard et al., 2014), necessitating debates about their equitability, salience, fairness, credibility, and legitimacy (Cash et al., 2003). An example of contested science can be observed in industries and policies, where carbon footprints per unit of product as a marker for environmental sustainability has emerged as the preferred indicator to describe the climate impact (Laurent et al., 2012). While this indicator has been shown to effectively capture gains in efficiency, it does not capture absolute emissions (and therefore climate impact) of an entire sector or supply chain, which may be increasing simultaneously (O’Brien et al., 2014), nor the interactions with social and economic aspects such as working conditions, animal welfare or farm income. Most concerningly, the exact choice of indicator and associated measurement, may in some cases incentivize radically opposing systems of agricultural production: for example, livestock systems based on outdoor grazing may reduce the carbon footprint of dairy produce, while increasing national GHG emissions from agriculture while livestock systems based on feeding housed animals imported feed may reduce national emissions at the expense of a higher carbon footprint along the supply chain (*ibid.*). This places an onus on all actors involved in indicator selection to be transparent and exhaustive in their search for indicators that can track and inform the success of sustainability initiatives.

We find ourselves at a unique crossroads in time where agricultural sustainability has the attention of farmers, citizens, industry, and policymakers alike. At the same time, we have amassed sufficient scientific evidence and practical experience within the sector to ensure that the transition process towards mainstreaming regenerative agriculture across farming systems and contrasting contexts, is underpinned by fit-for-purpose knowledge, thus securing a sustainable future for the land that humanity relies on for tomorrow’s food and wellbeing.

CRediT authorship contribution statement

L. Schreefel: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **R.E. Creamer:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **H.H.E. van Zanten:** Writing – review & editing, Methodology. **E.M. de Olde:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **K. Koppelmäki:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **M. Debernardini:** Writing – review & editing, Investigation, Formal analysis. **I.J.M. de Boer:** Writing – review & editing, Conceptualization. **R.P.O. Schulte:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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 A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2024.100810.

Data availability

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

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