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Giving regenerative agriculture an agronomic perspective: a proposed framework from the food and beverage industry

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Food systems face significant challenges that include increasing demand for agricultural products and accelerating environmental degradation. Regenerative agriculture has emerged as concept to reduce environmental harm while maintaining or even improving productivity. However, adoption of regenerative agriculture remains limited. This partly due to the absence of a shared definition and a standardised process to monitor, assess and report regenerative agriculture outcomes. To address this gap, SAI Platform, a member-led organisation within the food and beverage sector, collaborated with stakeholders to develop a global framework for regenerative agriculture. Drawing from a review of existing frameworks and consultations with SAI Platform members, farmers, and academics, we developed a framework that defines regenerative agriculture as an outcome-based approach that enhances environmental impact. It includes eight regenerative agriculture outcomes across the environmental areas of soil health, biodiversity, water and climate and suggests indicators to quantify progress. The framework process emphasises the need to understand local contexts and farmer needs when implementing regenerative agriculture. It does so through a four-step process that includes (i) a context analysis to identify key material criteria of a production system, (ii) the prioritisation of outcomes based on the context analysis, (iii) the selection of practices to achieve improved performance against prioritised outcomes, and (iv) the development and implementation of continuous improvement plans to monitor and report progress. Farm groups or individual farms can use this framework to independently verify the implementation of the steps defined in the framework and claim different performance levels for progress towards regenerative agriculture. These claims create a foundation for regenerative agriculture programmes, incentive mechanisms, and corporate reporting. While the framework is a starting point, collaboration and refinement are necessary to address evolving challenges in implementation. SAI Platform commits to research and stakeholder engagement to continuously improve the framework and support fair transitions towards regenerative agriculture.

KEYWORDS

regenerative agriculture, sustainable agriculture, soil health, biodiversity, water, climate, value chain, outcome-based

1 Introduction

The global food system faces unprecedented challenges: global food demand is projected to increase by more than 50% between 2010 and 2050 (van Dijk et al., 2021). In addition to a growing global population, increasing disposable incomes and changing dietary patterns in many parts of the world will increase the demand for resource-intensive foods, such as animal-based products, by 70% in the same period (Searchinger et al., 2018). Climate change and the ongoing degradation of agriculture's natural resource base threaten current food production and are projected to have an increasingly negative impact on farming productivity (Godfrey, 2021).

Business as usual is not an option moving forward. Globally, agriculture currently contributes approximately 25% of greenhouse gas emissions (Hong et al., 2022; Poore and Nemecek, 2018), 75% of freshwater withdrawal (Aryal et al., 2024), and is responsible for 80% of ocean and freshwater eutrophication (Poore and Nemecek, 2018). In all these domains, current levels of resource degradation exceed planetary boundaries (Folke et al., 2021; Zabel et al., 2019; Richardson et al., 2023). Several levers exist to secure food supply without further exceeding planetary boundaries. They include the reduction of food waste (Conrad et al., 2018) and the shift to more plant-based protein in diets, especially in the Global North (Laine et al., 2021); however, it is commonly acknowledged that current productivity levels of food systems need to be maintained or increased to meet future demand and avoid the conversion of natural ecosystems to farmland. This is a primary driver of habitat and biodiversity loss (Dasgupta, 2021) whilst also releasing carbon stocks into the atmosphere (Benton et al., 2021).

In response to these challenges, regenerative agriculture has emerged as a paradigm to reduce and reverse the negative impact of farming on the environment whilst maintaining or even improving productivity (Rhodes, 2017). Regenerative agriculture is based on an evolving consensus that farming systems that positively contribute to regenerating soil health, water resources, and biodiversity are vital to the long-term health and resilience of the whole food and beverage sector (Kelley, 2021). Whereas the term 'regenerative' has been associated with 'agriculture' and 'farming' for some time (Giller et al., 2021a, 2021b), the concept of "Regenerative Agriculture" was first described in the 1980s (Francis et al., 1986; Rodale, 1986) and has gained traction amongst farmers, businesses, and civil society in the last decade (Newton et al., 2020). Many organisations in the public and private sectors have since devoted substantial resources to researching and implementing regenerative agriculture across diverse farming systems and value chains (Giller et al., 2021a, 2021b).

Regenerative agriculture is based on a broad range of interpretations and definitions (Newton et al., 2020; Lal, 2020). They range from enhancing efficiency in food production and reducing environmental impact to partially "reversing climate change" (National Academies of Sciences, Engineering, and Medicine, 2019). This lack of a clear definition stands in contrast with other concepts for sustainable farming. For example, organic farming is defined explicitly by the processes (principles and practices) it permits or prohibits, regardless of outcomes (Rigby and Caceres, 2001). On the other hand, the definitions of Climate-Smart Agriculture (CSA) and Sustainable Intensification are explicit about expected outcomes upon the application of these ways of farming (Campbell et al., 2014). CSA emphasises climate change resilience, mitigation, and productivity (Walsh et al., 2024), while sustainable intensification prioritises the efficient use of farming resources such as inputs, water, land, and labour (Pretty and Bharucha, 2014). These definitions are explicit about expected outcomes but mostly indifferent about the tools and levers used to achieve them. Many interpretations of regenerative agriculture today take a hybrid approach that underlines both practices and principles as well as expected outcomes (Schreefel et al., 2020).

Newton et al. (2020) highlight that the ambiguity surrounding the term "regenerative agriculture" presents several challenges. These include:

i) Difficulty in evaluating the claims regarding the benefits or outcomes of regenerative agriculture and the lack of effective communication between scientists and practitioners.
ii) Confusion among consumers and stakeholders about the validity and significance of production claims.
iii) Increased risk of the term being misused for greenwashing or exploited for marketing purposes.
iv) Challenges for policy and programme development to evaluate and promote regenerative agriculture.

Additional challenges include difficulty in developing globally applicable regulations and incentive mechanisms (Goswami et al., 2017; White and Andrew, 2019); and the risk of perpetuating the divide between existing ideologies of sustainable farming, particularly between advocates of intensified versus extensified agriculture (Giller et al., 2021a, 2021b).

As a result, despite the growing interest in regenerative agriculture, tangible on-the-ground action has remained relatively limited (Kassam et al., 2019). While certain regenerative practices have been adopted in specific contexts, the broader, large-scale implementation of regenerative agriculture has yet to materialise. This delay heightens the risk of further environmental degradation (Stevenson et al., 2019), whilst also making it increasingly difficult for many organisations in agricultural value chains to meet their sustainability commitments (Giller et al., 2021a, 2021b). In response, Newton et al. (2020) suggest that those using the term "regenerative agriculture" should clearly define it within the specific context and purpose for which they intend to apply it.

The food and beverage sector is intrinsically linked to agricultural value chains, sourcing raw materials directly or indirectly from farmers. Through their production and quality standards, companies in this sector significantly influence agricultural practices. At the same time, they face growing pressure from consumers and regulators to adopt more sustainable sourcing methods and reduce emissions throughout production and processing (van Bussel et al., 2022). Many food and beverage companies view regenerative agriculture as a solution to these challenges, leading them to engage with the concept and set public targets for its implementation within their supply chains. Typically, these commitments are tied to land area (e.g., hectares or acres under regenerative practices) or to volume (e.g., percentage of raw materials sourced from farms practising regenerative agriculture), with each company following their definitions and frameworks. As a result, the sector has developed fragmented and varied interpretations of what constitutes "regenerative agriculture."

The Sustainable Agriculture Initiative Platform (SAI Platform) is a global non-profit organisation leading the food and drink industry's transition to sustainable and regenerative agriculture. Established in 2002 by Danone, Nestlé, and Unilever, SAI Platform now includes over 190 members spanning the entire value chain, from farmers to retailers (SAI Platform, 2021). In 2021, SAI Platform and 33 of its member organisations recognised the urgency to agree on a shared definition for regenerative agriculture and an aligned approach to monitor, assess and report impact across the food and beverage industry. They subsequently tasked SAI Platform with developing a global, sector-wide framework for regenerative agriculture – Regenerating Together global framework for regenerative agriculture. This framework aims to standardise the assessment of progress toward regenerative agriculture outcomes. This method paper describes the methodology used to develop the framework. It outlines the framework process and discusses the challenges and opportunities of an outcome-based framework for the food and beverage industry.

By creating approach and publishing this framework, SAI Platform seeks to prevent duplicating efforts in both implementing and monitoring at the farm and farm group levels. It also acts as a framework for monitoring and reporting efforts of on-farm interventions. It provides the boundaries for the food and beverage industry to make independently verified claims and statements around their sustainable sourcing efforts. This aims to safeguard the concept of regenerative agriculture and reduce the risk of greenwashing (Schreefel et al., 2024).

SAI Platform's members have made ambitious commitments to and allocated resources for scaling regenerative agriculture practices in agricultural supply chains. They will use the hereby presented framework – and future iterations of it – to guide activities and decisions to do so. This article presents the methodology behind the framework. By publishing this framework and the associated methodology, we aim to actively engage with diverse stakeholders to foster a transparent, science-based dialogue that supports the ongoing refinement of both the framework and the approach to implementing regenerative agriculture.

2 Methodology

The hereby described work has the ambition to serve as a global framework for the food and beverage sector. It allows for the assessment of progress towards regenerative agriculture at farm or farm group level and supports reporting progress towards regenerative agriculture outcomes across supply chains.

Workshops were held with subject matter experts from SAI Platform member organisations to initiate the development of this framework and foster sector-wide collaboration. These organisations span from multi-national organisations to processors and farm cooperatives representing diverse cropping systems, as well as dairy and beef production globally.

During these sessions, the following guiding principles and objectives for the framework were agreed upon through majority approval:

- The framework should define regenerative agriculture for the food and beverage sector.
- The framework should be outcome-based by prioritising outcomes and not enforcing the adoption of specific practices.
- The framework outcomes and their related indicators should be based on science and credible reporting methodologies.
- The framework should include universally relevant outcomes. They should be applicable to all land-based farming systems, including beef, crop, and dairy production. Outcomes should represent all domains of environmental sustainability, going beyond the predominant approach to only focus on greenhouse gas emissions.
- The framework should be adaptable to specific locations and should allow the identification and prioritisation of context-specific environmental and production challenges.
- The framework should allow for an assessment of progress towards regenerative agriculture that can be reported on at farm or farm-group level. The intent is to support reporting and externally validating regenerative agriculture performance claims.
- The framework should be flexible and enable discussions between farm, farm groups, farm advisors and buyers on environmental and production priorities.

2.1 Review of existing programmes

To develop the proposed framework with the above guiding principles in mind, we conducted an extensive literature review to map existing regenerative agriculture frameworks, initiatives, standards and certifications. The goal was to inform the structure of our framework, and define the relevant impact areas, outcomes and indicators and harmonise with existing initiatives that implement regenerative agriculture. To do this, we first developed a landscape analysis to summarise our findings. A key aim of the landscape analysis was to build the hereby presented framework on existing approaches to define and implement regenerative agriculture.

Based on the Textile Exchange's Landscape Analysis of regenerative agriculture programmes (Kelley, 2021), we used a comprehensive Google search approach to identify 23 relevant programmes that publicly address regenerative agriculture. These programmes were used for subsequent analysis. Given that our framework has the intention of being a global framework for the food and beverage industry that can be externally verified, we clustered these programmes based on their authorship between existing industry-led programmes for regenerative agriculture ($N = 7$) and standards and certification schemes ($N = 16$). We then assessed the scope of each programme in relation to the farming systems they support and their focus in terms of the indicators they cover. We clustered these indicators into six categories: soil, biodiversity, water, climate, socio economics, and animal welfare (Table 1).

Based on the clustering, it became apparent that four categories were more prominent across the existing programmes. They are soil health ($N = 21$), water ($N = 22$), biodiversity ($N = 21$), and climate ($N = 14$). We defined these categories as core impact areas of our framework (Table 1). Impact areas are defined as broad environmental or social domains where regenerative agriculture seeks to create positive change. These areas represent key aspects of ecosystem health and sustainability that are directly affected by agricultural practices.

These impact areas shape our definition of regenerative agriculture, as seen in Box 1.

TABLE 1 The qualities of the four impact areas of SAI Platform's Regenerating Together global framework for regenerative agriculture.

Impact area	Qualities
Soil health	Enhance soil structure, fertility, and biological activity, promote maximising nutrient use efficiency (and nutrient cycling wherever possible), water retention, and carbon sequestration, leading to resilient and productive ecosystems.
Water	Ensure optimal water use, reduce runoff and pollution, and enhance water retention in soils, maintain a balanced water cycle and support long-term sustainability for agriculture and surrounding ecosystems.
Biodiversity	Promote the diversity of species and ecosystems above and below ground, support pollination, pest control, and genetic resilience, while preventing habitat loss and invasive species.
Climate	Minimise greenhouse gas emissions and enhance carbon sequestration, while enabling farms to adapt to climate change, supporting resilience in farming systems and communities.

2.1.1 Regenerative agriculture outcomes and indicators

The identified impact areas served as the boundaries for the development of outcomes and indicators in our regenerative agriculture framework. Drawing from Newton et al.'s (2020, pg. 5) synthesis of outcomes included in definitions or descriptions of regenerative agriculture across 229 journal articles, we selected outcomes referenced five or more times. These outcomes were systematically mapped to the defined impact areas (Table 2). Two outcomes—pertaining to food security and nutritional quality—were deemed out of scope for our framework. Additionally, several outcomes related to farmer livelihoods and socio-economic dimensions were not presently reviewed.

The assessment and reporting of indicators, particularly those addressing socio-economic factors in agricultural systems, involve significant complexities. Challenges include issues of data privacy, practical applicability, and the labour-intensive nature of semi-quantitative data collection (Wilson and Buller, 2001). Our landscape analysis corroborated this, revealing that many current initiatives lack systems for monitoring impacts within the socio-economic domain. Acknowledging the critical role of socio-economic factors in enabling the transition to regenerative agriculture (Klauser and Negra, 2020), we commit to incorporating farmer livelihoods in subsequent iterations of the framework. Meaningful and actionable socio-economic indicators will be defined, leveraging the approach utilised by the Consultative Group for International Agricultural Research (CGIAR) for "agronomic gain"—a framework encompassing productivity, environmental, and socio-economic impacts (Saito et al., 2021). In the interim, we emphasise the inclusion of socio-economic considerations in our broader definition of regenerative agriculture (Box 1).

Several rounds of consultation with subject matter experts from our membership and with SAI Platform's Regenerating Together Advisory Board, which includes farmers, ranchers and academic experts in regenerative agriculture (Annex 3) were held

BOX 1 The definition of regenerative agriculture according to SAI Platform's Regenerating Together global framework for regenerative agriculture.

Regenerative agriculture

"Regenerative agriculture is an outcome-based farming approach that protects and improves soil health, biodiversity, climate, and water resources while supporting farmer livelihoods."

using the guiding principles referred to above as review criteria. A refined list of eight outcomes across four impact areas was identified as key proxies for assessing progress towards regenerative agriculture for our framework.

For each identified outcome, corresponding indicators were established. We see indicators as means to measure and evaluate progress toward achieving specific outcomes. Acknowledging the limitations of single generic indicators for assessing complex outcomes (Gasso et al., 2015), some outcomes, such as "increased soil health," are represented by multiple indicators. We are committed to continuously updating the list of indicators based on emerging science and stakeholder feedback (see Figure 1).

2.2 Framework implementation process

Our review of existing programmes and frameworks revealed many existing frameworks were either narrowly focused—being specific to production systems, geographies, or practices—or broad in terms of blanked outcome and practice recommendations, independently of farming context, making them challenging to implement effectively at the farm level. Given the diverse needs of our global membership, we identified a clear gap: the need for a framework that is both globally applicable and adaptable to local conditions. This insight drove the development of our approach, which balances global relevance with local flexibility through the framework implementation steps outlined below.

In addition to the guiding principles, and review of existing programmes and frameworks, our framework's implementation process was inspired by the proposition of Giller et al. (2021a, 2021b) to incorporate five questions in the design and implementation of regenerative agriculture. They are:

1. What is the problem to which regenerative agriculture is meant to be the solution?
2. What is to be regenerated?
3. What agronomic mechanisms will enable to facilitate this regeneration?
4. Can this mechanism be integrated into an agronomic practice that is likely to be economically and socially viable in a specific context?
5. What political, social and/or economic forces will drive the use of the new agronomic practice?

This led us to develop a four-step process for our Regenerating Together global framework for regenerative agriculture implementation (Figure 2). The individual elements of the four steps are shown in Table 3.

TABLE 2 Regenerative agriculture outcomes covered in journal articles reviewed by Newton et al. (2020), used in combination with existing industry-led frameworks to define eight outcomes and respective indicators included in SAI Platform's Regenerating Together global framework for regenerative agriculture – Regenerating Together outcomes.

Dimension of regenerative agriculture (Newton et al., 2020)	Number of journal articles referring to the dimension	Impact areas covered by the Regenerating Together framework	Outcomes covered by the Regenerating Together framework	Indicators covered by the Regenerating Together framework
To improve soil health (e.g., structure, soil organic matter, fertility)	49	Soil Health Biodiversity Water Climate	Increase soil health	• Water infiltration • Soil organic carbon content • Aggregate stability • Area of soil cover • Water holding capacity
To increase carbon sequestration	21	Soil Health	*Indicator included in 'increase soil health'*	
To increase crop health and/or resilience	9	Soil Health Biodiversity Water Climate	Increase nutrient use efficiency	• N-, P-, K-use efficiency
			Optimise crop protection	• Integrated Pest Management • Environmental Impact Quotient
To improve water health (e.g., hydrology, storage, reduce pollution)	18	Water	Increase water use efficiency	• Volume of irrigated water
To improve ecosystem health (including ecosystem services)	21	Biodiversity	Enhance on-farm habitat provision	• Area of on-farm habitat
To increase biodiversity	26	Biodiversity	Increase cultivated crop and pasture diversity	• Number of species cultivated
To create a circular system and/or reduce waste	14	Climate	Improve manure management	• Ammonia emissions • Methane emissions
To reduce greenhouse gas emissions	5	Climate	Reduce greenhouse gas emissions	• CO_2 eq footprint • Deforestation Free Feed
To maintain or increase yields	*10*	*Farmer Livelihoods*		
To maintain or improve farm productivity	*18*	*Farmer Livelihoods*		
To improve social and/or economic wellbeing of communities	*21*	*Farmer Livelihoods*		
To increase farm profitability	*19*	*Farmer Livelihoods*		
To improve food access and/or food security	*10*	*Out of scope*		
To improve food nutritional quality and/ or human health	*13*	*Out of scope*		

2.2.1 Context analysis

This step helps farms gain a comprehensive understanding of their environmental context at both farm and landscape levels, identifying key inherent environmental risks associated with their specific farm or production system. It directly addresses the first guiding question in Giller et al. (2021a, 2021b) to identify the problem that regenerative agriculture aims to solve.

Agriculture is highly dependent on the context, shaped by agroecological and socio-economic factors such as climate, soil types, market access, infrastructure, and local knowledge (Giller et al., 2021a, 2021b). Furthermore, the environmental challenges and footprint of farming vary significantly depending on location and farming practices (FAO, 2000). For instance, in arid regions, water use may be a critical environmental constraint; whereas in other areas, the overuse of fertilisers and nutrient leaching could pose the main challenge. Given that existing definitions of regenerative agriculture propose a wide range of potential environmental benefits, we aimed to create an approach that identifies and addresses the most pressing environmental issues specific to a farming system.

To achieve this, we designed the first step of the framework to analyse the farm's or production system's context and identify the most significant environmental risks at both the farm and landscape levels. These risks were grouped into two categories: (1) production risks derived from environmental factors, such as weather patterns or water availability, and (2) environmental risks resulting from ongoing farming activities, such as biodiversity loss or excessive water extraction.

The aim of the context analysis is not just to identify the most critical risks within a given landscape but also to foster a shared understanding of material risks between farmers and companies that procure raw materials from them. This approach minimises the likelihood of imposing arbitrary outcomes and indicators on farmers and encourages a collaborative discussion about the most urgent

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Matrix of regenerative agriculture programmes

✓ Applicable to Agriculture System or Initative Type / Functionality
\+ Indicator is covered by research or indicator is assessed by practice-based standard
++ Specifically denotes that the indicator is assessed by outcome-based standard

Organisation	Region	Agricultural System					Initiative Type / Functionality												Regenerative Agriculture Indicators Covered by Programme: Soil		Biodiversity			Water		Climate			Socio-Economic					Animal Welfare	Source
		Crops	Dairy	Beef	Small-Scale	Large-Scale	Project Development	Outcome-based Standard	Practice-based Standard	Continuous Improvement	Self-Assessment	2nd Party Verified	3rd Party Verified	Legislation-backed	Farm-level Accounting Tool	Carbon Accounting	Carbon Credit Provider	Conservation, Research, Advocacy, Advisory	Soil Carbon	Soil Health	Soil Biodiversity	Plant Biodiversity	Animal Biodiversity	Water Quality	Water Availability	GHG Emissions	Energy Use	Other Carbon Storage	Farmer Livelihoods	Legal Compliances	Markets and Resources	Health and Safety	Working and Living Conditions	Animal Welfare	
Industry-Led Regenerative Agriculture Frameworks																																			
One Planet Business for Biodiversity (OP2B) Framework for Regenerative Agriculture	Global	✓	✓	✓				✓		✓	✓								++	+	++	++			++				++				++		[1]
Danone Regenerative Agriculture Scorecard	Global	✓	✓	✓				✓	✓	✓	✓								++	++	++	++	++	++	++	+								++	[2]
General Mills Regenerative Agriculture Self-Assessment	Global	✓	✓	✓	✓	✓			✓	✓	✓								++	++	++	++	++	++	++	+								++	[3]
McCain Regenerative Agriculture Framework	Global	✓						✓		✓									++	++	++	++		++	++				++						[4]
Nestlé Regenerative Agriculture Farm Assessment	Global	✓	✓					✓		✓	✓	✓							++	++	++	++	++	++	++	+									[5]
PepsiCo Positive (Pep+)	Global	✓	✓																+	+	+	+		+	+	+			+	+				+	[6]
Unilever Regenerative Agriculture Principles	Global	✓	✓		✓	✓		✓		✓	✓								++	++	++	++	++	++	++	++	++		++						[7]
Regenerative Agriculture Standards, Initiatives and Certifications																																			
Audubon Conservation Ranching Programme	USA			✓	✓	✓			✓				✓					✓			+	+	+	+	+									+	[8]
Certified Regenerative by A Greener World (AWG)	USA		✓	✓				✓		✓			✓						++	++	++	++	++	++	++	++								++	[9]
Coffee Sustainability Reference Code (Global Coffee Platform)	Global	✓			✓	✓		✓		✓		✓	✓						++	++	++	++		++	++	++	++		+	++	++	++	++		[10]
IntegraTrust iScore	SA	✓	✓	✓	✓			✓		✓		–										++			++	++									[11]
Land to Market (Savory Institute EOV)	Global	✓	✓	✓	✓	✓		✓		✓		✓							++	++	++	++	++		++										[12]
Organic Certification (NOP, NPOP, EU)	Global	✓	✓	✓	✓	✓			✓				✓	✓						+	+	+	+	+	+				+				+	+	[13]
Rainforest Alliance	Global (Tropics)	✓			✓	✓		✓	✓	✓	✓		✓						++	++		++		++	+	++	++		++	++		++	++		[14]
Regen1	USA (CA)	✓	✓	✓					✓	✓	✓								+	+	+	+		+					+			+	+	+	[15]
Rege[N]ation Certification (Intertribal Agriculture Council)	USA	✓	✓	✓					✓			✓								+	+	+	+	+	+				+						[16]
regenagri	Global	✓	✓	✓	✓	✓			✓	✓			✓		✓	✓	✓		+	+	+	+		+	+	+	+	+							[17]
Regenerative Organic Certification™ (ROC)	Global	✓	✓	✓					✓	✓			✓	✓					+	+	+	+	+	+	+			+	+	+	+	+	+	+	[18]
Regenified	Global	✓	✓	✓				✓	✓				✓						++	++	++	++	++		++		++							++	[19]
Soil Carbon Initiative	USA	✓	✓	✓			✓	✓	✓	✓			✓						++	++	++	+	+	+	++	++									[20]
Terra Genesis Regenerative Outcome Verification (ROV)	Global	✓			✓		✓	✓					✓						+	+	+	+			+				+						[21]
The Economics of Ecosystems and Biodiversity	Global	✓	✓	✓	✓															+	+	+	+	+	+	+			+		+	+	+		[22]
4 per 1000	Global	✓	✓	✓	✓	✓												✓	+	+		+	+	+	+	+			+	+					[23]

FIGURE 1
Landscape analysis of regenerative agriculture programmes. based on Kelley, 2021. Programmes are segmented into industry-led Frameworks or Standards ($N = 7$) or initiatives and certification schemes ($N = 16$). Each programme was evaluated against (1) the agricultural systems they address: crop and livestock, as well as scale of farming operations; (2) the regions they cover, (3) the type of programme they are and the function they serve, and (4) which regenerative agriculture indicators they address, either directly by outcome-based standard (++) or indirectly through practice-based standard (+) across the categories: soil, biodiversity, water, climate, socio-economic, animal welfare. References are provided in Annex 1.

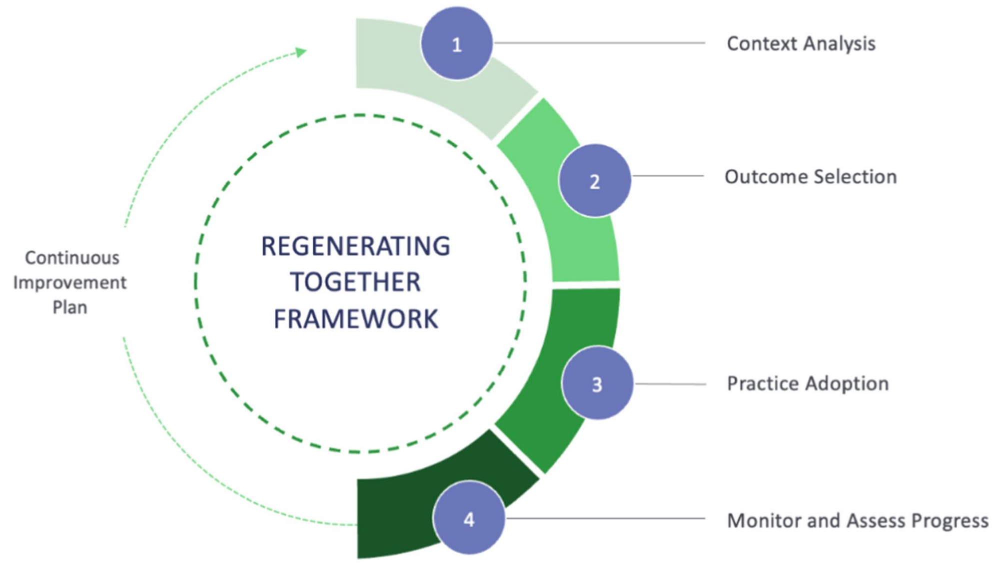

FIGURE 2
The four-step process to implement SAI Platform's Regenerating Together global framework for regenerative agriculture.

challenges across the value chain. This provides a platform to co-create the roadmap of solutions to be adopted at farm level and enhance the adoption of regenerative agriculture practices by farmers (Silva et al., 2021).

Through consultations with members and stakeholders, we identified 12 material criteria across the four impact areas of our framework (Table 4). These criteria are scored on a scale of 1 to 3 based on predefined evaluation metrics, integrated into a questionnaire (Annex 2). It is important to underline that the purpose of this context analysis is to create a relative – and not an absolute – scoring of material criteria. The scoring process is intentionally subjective, serving as a foundation for constructive engagement between farms, their advisors and the food and beverage companies.

TABLE 3 An overview of SAI Platform's Regenerating Together global framework for regenerative agriculture with material criteria, impact areas, outcomes, indicators, and practices to improve performance on outcomes.

1. MATERIAL CRITERIA

- Soil Erosion
- Soil Fertility Loss
- Soil Salinity
- Soil Compaction
- Groundwater Depletion
- Surface Water Depletion
- Crop Diversity Loss
- Habitat Loss
- Pesticide Leaching
- Nutrient Leaching
- Air Pollution
- Non-Renewable Energy Use

2. OUTCOMES AND INDICATORS

- Increase soil health and fertility: Water infiltration; Soil organic carbon content; Aggregate stability; Area of soil cover; Water Holding Capacity
- Increase nutrient use efficiency: N use efficiency; P use efficiency; K use efficiency
- Optimise crop protection: Integrated Pest Management; Environmental Impact Quotient
- Increase water use efficiency: Volume of irrigated water
- Enhance on-farm habitat provision: Area of on-farm habitat
- Increase cultivated crop and pasture diversity: Number of species cultivated
- Improve manure management: Ammonia emissions; Methane emissions
- Reduce greenhouse gas emissions: CO_2 eq footprint; Deforestation Free Feed

3. PRACTICES

- Minimise soil disturbance
- Controlled traffic farming
- Cover crops
- Mulching / crop residue cover
- Diversified crop rotation
- Protection of on-farm habitat
- Agroforestry and silvopasture
- Hedgerows and green buffers
- Riparian buffers
- Integrated grazing management
- Manure management
- Integrated nutrient management
- Integrated pest management
- Irrigation management
- Herd/flock management
- Feed from sustain. sources

TABLE 4 Material criteria across the four impact areas [...] covered by SAI Platform's Regenerating Together global framework for regnerative agriculture.

Impact area				Material criteria
Soil health	Water	Biodiversity	Climate	
x			x	Soil erosion
x				Soil fertility loss
x				Soil salinity
x	x	x		Soil compaction
	x			Groundwater depletion
	x			Surface water depletion
		x		Crop diversity loss
		x	x	Habitat loss
x	x	x	x	Pesticide leaching
x	x	x	x	Nutrient leaching
			x	Air pollution
			x	Non-renewable energy use

2.2.2 Outcome selection

Building on the findings from the context analysis, this step focuses on selecting and prioritising environmental outcomes that are most relevant to the specific farming context. Regenerative agriculture can target a wide range of outcomes (Newton et al., 2020), but their relevance may vary depending on the specific context (Giller et al., 2021a, 2021b). This step aligns with the second question in Giller et al. (2021a, 2021b) and reinforces the framework's emphasis on defining relevant outcomes rather than imposing specific processes to achieve them.

We have defined outcomes as environmental improvements that result from the implementation of regenerative agricultural practices. As previously mentioned, this current version of the framework focuses on environmental outcomes, with social outcomes to be developed. Outcomes are the desired results within each impact area, e.g., healthy and productive soils.

Indicators are used to track and assess progress towards achieving outcomes. They provide data points that can be regularly monitored to quantify the effectiveness of regenerative practices. An overview of the definitions of impact areas, outcomes, and indicators is provided in Box 2.

The outcome prioritisation is closely linked to the context analysis. It is facilitated by a simple binary matrix (Table 5), allowing farms to align their efforts with the most critical environmental challenges identified.

2.2.3 Practice adoption

This section addresses the third and fourth questions in Giller et al. (2021a, 2021b) by helping farmers select and implement practices that improve performance on prioritised outcomes based on local feasibility. The framework deliberately avoids prescribing specific practices, instead offering guidance on practices that could best achieve the desired results in each unique context.

BOX 2 Definitions of impact areas, outcomes and indicators of regenerative agriculture according to SAI Platform's Regenerating Together global framework for regenerative agriculture.

Impact areas

Impact areas are broad environmental or social domains where regenerative agriculture seeks to create positive change. These areas represent key aspects of ecosystem health and sustainability that are directly affected by agricultural practices, including soil health, water, biodiversity and climate.

Outcomes

Outcomes are environmental or social improvements that result from the implementation of regenerative agricultural practices. Outcomes are the desired results within each impact area, e.g., healthy and productive soils.

Indicators

Indicators are used to track and assess progress towards achieving outcomes. They provide data points that can be regularly monitored to quantify the effectiveness of regenerative practices.

As an outcome-based framework, our focus is on the improvement of farms or farm groups in relation to prioritised regenerative agriculture outcomes, tailored to the specific context of each farming operation (including production system, geography, and agroecology). However, measurable improvements in regenerative agriculture outcomes can take time to manifest and are often influenced by external factors beyond a farmer's control, such as weather conditions. This poses a challenge when monitoring progress over time, especially when it comes to rewarding farmer groups for their efforts.

In some cases, farms may reach a point of saturation for certain outcomes, such as soil organic carbon (Berthelin et al., 2022), meaning further significant improvements may not be possible. Additionally, farms may be implementing good practices but lack the outcome data to demonstrate their efforts. Concerns have been raised that setting standards too high to qualify as part of the regenerative agriculture journey could discourage farmers from participating, as they may feel the goal is unattainable. Focusing solely on outcomes, therefore, may overlook the value and importance of practice adoption. There is growing evidence that certain practices directly contribute to the improvement of regenerative agriculture outcomes. We aim for our framework to promote an enabling environment for farms to receive the necessary support to select and adopt practices relevant and beneficial to their context, supporting them in making progress on their prioritised outcomes. Through various testing of our framework with farms across the world and conversing with the farmers on our Regenerating Together Advisory Board, it became apparent that communicating in terms of practices can be more impactful in driving on-the-ground change. Through a hybrid approach, we aim to leverage the selection of context-specific outcomes to identify the most suitable practices to be adopted and monitored. This approach aims to foster dialogue between farms and the food and beverage industry through locally relevant practice adoption, while, simultaneously monitoring outcomes, enabling companies to communicate their sustainability efforts at a corporate level. With this framework being outcome-based and acknowledging the importance of practices, rather than imposing specific practices, the framework empowers farms and their trusted advisors to select the practices that will lead to improved performance on prioritised outcomes. These practices are then integrated into continuous improvement plans, where farms report both the practices implemented and the extent of their implementation.

An overview of the regenerative agriculture practices included in our framework can be found in Table 6. The list does not include all the possible on-farm actions that farmers can implement but highlights some major practices that can contribute to regenerating agricultural systems, which must be adapted to the local context. This list of practices is intended to complement and build on publicly available resources that are available in certain geographies and jurisdictions that provide farms with technical and financial support for practice selection and adoption. Key examples include the United States Department of Agriculture's Natural Resources Conservation Service (NRCS, 2024), which offers extensive guidance through its Conservation Practice Standards database, or the Strategic Plans of the EU's member states falling under its Common Agricultural Policy (CAP, 2023). We are committed to growing the list of practices based on growing scientific and on-farm evidence and in alignment with overarching agricultural policy frameworks.

To support this process, the framework suggests practices that are likely to enhance performance against the prioritised outcomes, drawing from existing research and data. The initial dataset has been developed for field crops in temperate farming systems, based on a structured review of 114 publications identified through a rapid review of scientific literature (Threels et al., 2025). This work was inspired by Giller et al. (2023) who operationalised the concept of regenerative agriculture for coffee and cocoa production systems. Table 7 presents the results of this analysis, linking various regenerative agriculture practices to specific outcomes, with an emphasis on both the strength of the connection and the supporting evidence.

We are currently collaborating with partners to expand this work across other farming system archetypes, including perennial crops, housed livestock, grazed livestock, and mixed farming systems, among others.

It is important to note that the practices listed in Table 7 are not exhaustive. Farms and farm advisors are encouraged to select practices relevant to their systems, provided they result in improved performance against the prioritised outcomes.

2.2.4 Monitor and assess progress

Ongoing evaluation of progress towards outcomes is crucial for accurately measuring the long-term impact of regenerative agriculture, ensuring that the intended environmental benefits are realised and sustained over time (Newton et al., 2020). This includes setting baselines and monitoring progress over time.

With the intent to acknowledge and reward farms that have engaged in regenerative agriculture and are improving their performance on regenerative agriculture outcomes, we have developed distinct performance levels to serve as the basis for incentive mechanisms and market access. Verified claims form the cornerstone of most incentive programmes for promoting sustainable agriculture (Salzman et al., 2018).

The performance levels have been based on the review of existing industry frameworks for regenerative agriculture and refined based on consecutive rounds of consultation with SAI Platform members and SAI Platform's Regenerating Together Advisory Board. Today, our global framework for regenerative agriculture defines four performance levels to capture distinct farmer engagement and progress towards outcomes (Table 8). They have the ambition to

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TABLE 5 Correlation indication matrix for the links between material criteria and outcomes to guide prioritisation of outcomes to report progress against in a farming system.

Material criteria	Regenerative agriculture outcome							
	Increase soil health and fertility	Increase nutrient use efficiency	Optimise crop protection	Increase water use efficiency	Enhance on-farm habitat provision	Increase cultivated crop and pasture diversity	Improve manure management	Reduce greenhouse gas emissions
Soil erosion	++				+			
Soil fertility loss	++	+					++	
Soil salinity	++	+						
Soil compaction	++							
Groundwater depletion	+			++				
Surface water depletion	+			++				
Crop diversity loss			+		+	++		
Habitat loss					++			
Pesticide leaching			++			+		
Nutrient leaching	+	++					++	+
Air pollution							++	++
Non-renewable energy use								++

The matrix was built in a way that each outcome is strongly connected to at least one material criterion (++). Weaker correlations (+) will be highlighted by the framework to be considered in addition to the outcomes with a strong connection to a material criterion.
++, Strong link; +, Weaker link; ☐, No link.

TABLE 6 Regenerative agriculture practices and their descriptions included in SAI Platform's Regenerating Together global framework for regenerative agriculture.

Regenerative agriculture practice	Description
Minimise soil disturbance	Any crop establishment approach that reduces the intensity of soil movement.
Controlled traffic farming	Confine soil compaction to the least possible area by imposing permanent traffic lanes for field operations.
Cover and companion crops	Management practice or collection of practices that retains an element of living soil surface cover either between cash crops or during a cash crop.
Mulching/soil residue cover	Management practice or collection of practices that retains an element of soil surface cover either between cash crops or during a cash crop.
Diversified crop rotation	The diversity of the series of crops (cash and non-cash crops) that are grown in rotation per land parcel.
Protection of on-farm habitat	Any practice or collection of practices aimed to characterise and protect biodiversity in the farmed landscape.
Agroforestry and silvopasture	Integration of trees with agricultural crops and/or livestock either simultaneously or sequentially on the same unit of land.
Hedgerows and green buffers	Any landscape boundary feature and any in-field/field adjacent non-cash crop buffer area.
Riparian buffers	Any landscape river boundary feature that contains perennial/semi-perennial plants, with the aim of protecting river water.
Integrated grazing management	Any management practice or collection of practices that proactively plans livestock integration as part of a wider farming system.
Manure management	Any management practice or collection of practices that proactively plans manure storage, handling and application to optimise positive outcomes and minimise negatives.
Integrated nutrient management	Any management practice or collection of practices that proactively plans nutrient cycles for cash crops.
Integrated pest management	Any management practice or collection of practices that proactively plans for the prevention, detection and control of pests, weeds and diseases.
Irrigation management	Any management practice or collection of practices that proactively plans for water need, water sourcing.
Feed from sustainable sources	Farming system used to grow source material for livestock feed.
Herd/flock management	Any management practice or collection of practices that proactively plans for elements of herd/flock health and welfare.

accommodate different realities across farming systems worldwide. For instance, access to data, resources, and incentives to shift towards regenerative agriculture might differ depending on location and value chain. We propose for the engaging, advancing, and leading levels to be eligible for accounting towards regenerative agriculture impact commitments, and to stimulate peer pressure to go beyond the engaging level in more developed geographies and value chains.

3 Discussion

Operationalising the concept of regenerative agriculture at scale is a formidable challenge. It often requires substantial changes in farming operations as farmers must adapt new practices, acquire new knowledge and equipment, and engage in new value chains. Additionally, many regenerative agricultural value chains impose extra layers of reporting to ensure compliance with production standards and corporate impact claims.

The hereby presented framework aims to facilitate the widespread adoption of regenerative agriculture practices globally by addressing key barriers that have hindered scaling efforts thus far, namely:

- The lack of a unified definition of regenerative agriculture limits the ability to consistently assess and report impact (Newton et al., 2020). This is exacerbated by the existence of various frameworks for regenerative agriculture with different outcomes and processes, creating confusion on approaches to follow.
- A need to translate global concepts into localised action plans, enabling farm-level transitions and allowing farmers to focus on prioritising actions most relevant to their unique contexts (Giller et al., 2021a, 2021b).
- A need to balance between academically driven frameworks with emphasis on science that often lack attention to the implementation aspects as well as the frameworks developed by the private sector, focusing on being practical and resource-efficient (de Olde et al., 2018; Saltelli and Giampietro, 2017).

Amidst the proliferation of diverse initiatives for regenerative agriculture, we identified a clear need for a framework that is practical to implement to be widely accepted across the food and beverage industry. Such a framework aims to establish a standardised approach to implementation, enabling farmers to participate in regenerative agriculture without constraining them to specific supply chains or certification schemes. It also aims to acknowledge and reward farms for their efforts by qualifying for different performance levels. Further, the hereby presented framework offers the possibility for an independent verification process to allow companies to make claims related to their sustainable and regenerative sourcing efforts, thus aiming to safeguard the concept of regenerative agriculture and reward farms for their engagement. As an organisation representing over 190 companies within the food and beverage sector, SAI Platform is distinctively positioned to foster industry alignment around a shared definition and framework for regenerative agriculture.

To minimise duplication in assessment and reporting efforts, our framework is grounded in outcome indicators derived from existing regenerative agriculture frameworks while integrating recent scientific advancements. This approach is reflected in two ways. First, our focus on the four impact areas—soil health, biodiversity, water, and

TABLE 7 Correlation indication matrix for the links between practice categories and SAI Platform's Regenerating Together regenerative outcomes for arable farming systems, adapted from Threels et al. (2025).

Regenerative agriculture practices	Regenerative agriculture outcomes and indicators								
	Increase soil health and fertility			Increase water use efficiency			Increase Cultivated Crop and Pasture Diversity	Enhance On-Farm Habitat Provision	Reduce Greenhouse Gas Emissions
	Optimise Soil Organic Carbon Content	Minimise Soil Erosion from Water and Wind	Optimise Water Infiltration	Optimise Water Holding Capacity	Optimise Water Use	Minimise Water Pollution			
Minimise soil disturbance	SI	SI	IC	IC		IC	SI		AI
Soil cover	IC	MI	IC	IC	SI	IC			
Integrated grazing practices	MI	IC	IC	IC					
Precision irrigation	IC				IC	IC			IC
Functional plant diversity	SI	MI	IC				MI		MI
Farm areas with shrubs or trees	IC	MI				SI	SI	IC	IC
Precision nutrient management	MI		IC	MI	IC	SI	MI		AI
Integrated pest management						IC	SI		AI
Crop rotation adaptation	MI	IC	MI	IC	IC	MI	SI		IC

SI, Strong Indication; MI, Moderate Indication; IC, Inconclusive; AI, Ambiguous Indication; □, No Indication.

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TABLE 8 Regenerating Together Performance Levels, including their requirements, against SAI Platform's Regenerating Together global framework for regenerative agriculture.

Regenerating Together 4-Step process	On-boarding	Engaging	Advancing	Leading
1. Context analysis	Yes	Yes	Yes	Yes
2.1 Outcome selected	Min 2 outcomes across 2 impact areas	Min 2 outcomes across 2 impact areas	Min 2 outcomes across 2 impact areas	Min 4 outcomes across 4 impact areas
2.2 Outcome baseline and continuous improvement plan	/	Yes	Yes	Yes
3. Practice adoption	/	Min 2 practices	Min 2 practices	Min 4 practices
4. Outcome progress	/	/	Yes	Yes

climate—aligns with the priorities identified in most publicly available programmes and initiatives reviewed. Second, we incorporate mechanisms to contextualise regenerative agriculture interventions based on specific farming systems rather than prescribing blanket practice recommendations (Giller et al., 2021a, 2021b). Additionally, our framework aims to enable transparent, harmonizable and context-specific selection, assessment and reporting of regenerative agriculture outcomes. It allows flexibility in selecting indicators for implementing regenerative agriculture, as advocated by Schreefel et al. (2024).

We believe that the hereby presented framework offers a unified approach to regenerative agriculture that will create a level playing field for farmers and suppliers to engage in regenerative agriculture. As some existing frameworks for regenerative agriculture have already been used to start regenerative agriculture projects or included in supplier contracts by the food and beverage industry, we are also developing a mechanism for these frameworks to be benchmarked against what is presented here. This to avoid farmers being locked in specific frameworks and value chains and make sure regeneratively produced raw materials can be sold and sourced through diverse channels.

Our framework follows an outcome-based definition of regenerative agriculture (Newton et al., 2020) to avoid imposing specific practices on farmers independently of context, which can lead to limited adoption and impact. This has for instance been shown in the case of conservation agriculture in Africa (Giller et al., 2015; Palm et al., 2014). However, an outcome-based approach offers several challenges itself:

Firstly, outcomes must be well-defined and meaningful (Newton et al., 2020). Through continuous consultations with members, academics, and farmers, we believe that we have established a list of outcomes and respective indicators that can serve as meaningful and quantifiable proxies for the impact of farming on the environment. However, this list presents a first iteration that is heavily theoretical. We will therefore continue to refine and improve it based on feedback from users and stakeholders.

Secondly, priorities for environmental outcomes can be different along the value chain. Whereas the food and beverage sector is under strong pressure to reduce greenhouse gas emissions in their supply chains (Shrimali, 2021), farmers often respond to changes in practices that lead to more tangible benefits for them, such as productivity, resilience of production, and production costs (Klauser and Negra, 2020). Our framework's context analysis is designed to foster collaboration between farmers and their customers in setting priorities. Although we are aware that the hereby presented framework cannot address al potential power imbalances in negotiations between farmers and processors, we designed the framework to emphasise farmer engagement and co-creation of continuous improvement plans as key to capture the adaptability and relevance to on-farm contexts and farmer-inclusion in decision-making processes. We are committed to building case studies that exemplify good practices, focusing on co-creation and farmer engagement rather than imposition and box-ticking.

Thirdly, the direct measurement and reporting of many outcomes can be technically challenging, expensive, and tedious (Latruffe et al., 2016). To avoid overburdening farmers with monitoring requirements, we emphasise a pragmatic approach to quantification. Many farmers already report on outcomes due to regulatory or incentive schemes; therefore, we allow flexibility in the metrics and quantification methodologies they use, provided they meaningfully reflect progress. To ensure that the framework inspires "doing" rather than "monitoring," we see it as a paradigm to keep the quantification and reporting burden low. Furthermore, certain outcomes, such as soil organic carbon, can take years to show improvement (Moinet et al., 2023; Powlson et al., 2014). In such cases, we recommend incentivising the adoption of practices with strong evidence of positive long-term impact. This approach has been successfully applied to coffee and cocoa farming (Giller et al., 2023) and replicated for field crops (Threels et al., 2025). We are working to extend this to other farming systems.

Lastly, we must emphasize that the hereby proposed framework entirely focuses on agricultural production only. However, to create regenerative and equitable agricultural systems and value chains, other aspects to be addressed as well. These include food packaging, transport, waste, as well as broader shifts in nutrition, which are beyond the scope of this paper, but are featured in recent literature, such as the EAT Lancet report on Healthy Diets from Sustainable Food Systems (Willet et al., 2019).

4 Conclusion and outlook

We view regenerative agriculture as a process of continuous improvement toward the improvement of crucial environmental resources that comprises four steps.

1. Context specific identification of the inherent ecological risks and crucial resources within a farming system.

2. Determination of outcomes which should be prioritised and monitored to effectively mitigate these key risks and improve the condition of crucial resources.
3. Selection and adoption of locally relevant and appropriate practices that improve performance on prioritised environmental outcomes.
4. Continuously monitor and evaluate whether the implemented practices lead to improvements in regenerative agriculture outcomes, which is crucial for validating and reporting progress.

With the hereby presented framework, we aim to take the first step in defining regenerative agriculture for the food and beverage sector. By doing so, we seek to actively facilitate discussions across diverse stakeholder groups on what regenerative agriculture entails and the outcomes we can expect from farms and the supply chains that adopt regenerative agriculture practices (Newton et al., 2020). This will lead to the continuous improvement of our framework and its implementation based on learning and stakeholder input. Our framework intends to provide a common language, allowing decision-makers to use the same principles to tailor the transitions to their contexts.

SAI Platform and its membership are committed to supporting the adoption of regenerative agriculture practices in their supply chains. To do so, many member companies and partners have already committed to implementing the hereby presented framework with their suppliers across a wide range of agricultural products and commodities. These activities span across diverse farming systems—from smallholder farms in South Asia and Africa to large-scale commodity farming in Europe, North America, and Latin America. SAI Platform is dedicated to supporting these efforts through developing resources to support the implementation of the framework, such as protocols for verifying claims based on regenerative agriculture performance levels and guidance for establishing baselines and monitoring progress on the framework's outcomes. These resources are currently being tested with selected members and partners and will be released early in 2025. SAI Platform will also support members in implementing the framework and using supporting resources through projects and partnerships globally. These projects will start in 2025 and involve diverse partners from implementation, academia, philanthropy, and finance. Feedback from these activities will be systematically collected to continuously improve the framework and the solutions that support its implementation to make sure our solutions are robust and implementable at scale. To foster collaboration and dialogue between the stakeholders across the sector, we intend to share and disseminate the learnings. Additionally, through these projects on the ground, we aim to understand how the transition to regenerative agriculture impacts farmer livelihoods. In future iterations, we aim to include socio-economic indicators to capture this dimension more effectively.

Overall, it must be underlined that changes in practices and behavior work best if they are based on inspiration, rather than imposition (Gill, 2002). We therefore see it as our role to inspire our members, as well as the broader sector through case studies and sharing of learnings that will be acquired during piloting and implementation of the framework.

Recognising that the food and beverage industry is just one link in the broader agricultural value chain, we propose this framework as a starting point for consultation and engagement with stakeholders across all levels of agricultural production systems and value chains. By releasing the framework and transparently sharing the methodology behind it, we aim to continue to foster a dialogue with diverse stakeholders—including farmers, academia, civil society, the public sector, and industry partners. Our goal is to co-create a shared vision for regenerative agriculture. This approach emphasises proposing rather than imposing a vision of what regenerative agriculture can achieve and the outcomes we can expect.

A shift to more sustainable – or regenerative – agriculture is urgently needed. With the hereby proposed framework, we want to contribute to making this shift happen and to engage with farmers, academia, civil societies, the public sector, and industry in doing so.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DK: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. JC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. AC: Conceptualization, Methodology, Writing – review & editing. YL: Resources, Validation, Writing – review & editing. ID: Formal analysis, Funding acquisition, Resources, Writing – review & editing. MargH: Writing – review & editing. SL: Writing – review & editing. RT: Writing – review & editing. JL: Writing – review & editing. MartH: Writing – review & editing. PC: Writing – review & editing. LU: Writing – review & editing. RC: Formal analysis, Methodology, Writing – review & editing. DF: Funding acquisition, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1576611/full#supplementary-material

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