Community Science

SHORT RESEARCH ARTICLE
10.1029/2024CSJ000092

Special Collection:
Transdisciplinary Collaboration for Sustainable Agriculture

Key Points:

- Engagement with national stakeholders reveals important gaps in information provided by global agricultural sustainability indicators
- Tailoring agricultural sustainability indicators toward stakeholder needs while preserving global comparability remains challenging
- Co-evaluation of sustainability indicators in a scientific setting provides a basis for co-learning and open exchange among stakeholders

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

C. Folberth,
folberth@iiasa.ac.at

Citation:

Folberth, C., Sinabell, F., Schinko, T., Hanger-Kopp, S., Lappöhn, S., Mitter, H., et al. (2025). Integrating global comparability and national specificity in agricultural sustainability indicators through stakeholder-science co-evaluation in Austria. *Community Science*, *4*, e2024CSJ000092. https://doi.org/10.1029/2024CSJ000092

Received 22 MAY 2024
Accepted 26 JAN 2025

Integrating Global Comparability and National Specificity in Agricultural Sustainability Indicators Through Stakeholder-Science Co-Evaluation in Austria

C. Folberth[1], F. Sinabell[2], T. Schinko[3], S. Hanger-Kopp[3], S. Lappöhn[4,5], H. Mitter[6], T. Sandén[7], and E. Süssenbacher[8]

[1]Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, [2]Austrian Institute for Economic Research (WIFO), Vienna, Austria, [3]Population and Just Societies Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, [4]Institute for Advanced Studies (IHS), Vienna, Austria, [5]Federal Institute of Agricultural Economics, Rural and Mountain Research (BAB), Vienna, Austria, [6]Department of Environmental Systems Sciences, University of Graz, Graz, Austria, [7]Department for Soil Health and Plant Nutrition, Austrian Agency for Health and Food Safety (AGES), Vienna, Austria, [8]Department for Agri-environmental Programmes and Organic Farming (ÖPUL), Federal Ministry of Agriculture, Forestry, Regions and Water Management (BML), Vienna, Austria

Abstract Agriculture is central to sustainable development both from provisioning and pressure perspectives. It is hence imperative to measure its diverse outcomes, for which various global indicator systems have been developed. Yet, these come with trade-offs, for example, between comparability among countries versus specificity to national context. This poses the question how relevant generic indicators are for national stakeholders and how specific information requirements can be integrated within a globally comparable assessment. Herein, we present the co-evaluation of an existing system of global agricultural sustainability indicators with national stakeholders from agricultural practice, research and education, public administration, private sector, and NGOs in Austria, representing an expert community. Focusing on the relevance of the indicators and the requirements for complementary metrics, we found that particularly social themes and related indicators were highly specific to the national context, followed by economic and environmental aspects. Co-interpretation of selected indicator trajectories showed that drivers and interactions were highly complex and may change over time, emphasizing also the importance of complementary contextual information. Yet, availability of data to measure indicators proposed by stakeholders remains a key limitation to the adaptation of the indicator system. We outline two options for improving the relevance of the global indicator system: (a) substituting less relevant indicators or (b) introducing a second tier covering regionally important aspects. To explore which of the two options is most appropriate across geographies and whether unified approaches to such a regionalization are indeed feasible, we propose to include the co-creation of regionalized indicator frameworks in future iterations across agriculturally diverse countries.

1. Introduction

Agriculture is fundamental to human life providing a range of ecosystem services such as food and income (Power, 2010). Environmentally friendly agricultural management can make a considerable contribution to the preservation of ecosystem goods and services (Glötzl et al., 2011). Intensive agricultural production in turn often causes their degradation, including a range of disservices such as nutrient pollution and contributes to some of the major threats to Earth System functioning (Rasmussen et al., 2018; Steffen et al., 2015).

The need to steer agriculture toward improvements in its multifaceted outcomes has led to the development of a wide range of sustainability indicators ranging from single aspects such as crop nutrient management over consideration of the three classic sustainability dimensions environmental, economic, and social, to comprehensive sets including societal drivers (Chopin et al., 2021). Such indicators have been defined and measured from global scales to the farm level (Chopin et al., 2021). Globally consistent indicators have been developed for example, for Sustainable Development Goal 2.4.1 "Proportion of agricultural area under productive and sustainable agriculture" by the United Nation's Food and Agricultural Organization (FAO) (Gennari & Navarro, 2019; Tubiello et al., 2021). At continental scales, a system of agricultural sustainability indicators has been developed for the EU, which dedicates the major portion of its common budget to agricultural support stipulating

10.1029/2024CSJ000092

the reporting of associated outcomes (Magrini & Giambona, 2022; Scown & Nicholas, 2020). National-scale indicators in turn can aid in depicting specific challenges faced by countries and are commonly developed by national research institutions (Lynch et al., 2019).

The multitude of indicator systems, their inconsistencies, and limited global comparability has motivated the development of a globally applicable and measurable agricultural indicator system by Zhang et al. (2021), termed the Sustainable Agriculture Matrix (SAM) that builds the foundation of the present study. The SAM indicator system's rationale is to quantitatively measure agricultural sustainability across the three classic dimensions over time to evaluate progress and provide guidance for improvement with a focus on performance of the production side. That is, indicators relate to outcomes of farming. To measure progress and allow for international comparison, key requirements for indicators to be included are spatial coverage of available data for more than 120 countries, temporal coverage of at least two measurement points, and monotonicity of indicator states. This resulted in a set of 18 indicators with six in each sustainability dimension (Figure 1; Table 1), which allows for their balanced aggregation within and across dimensions.

Developed by an interdisciplinary group of academic experts, it remained elusive in how far such a globally applicable and comparable indicator system is useful for stakeholders and decision-makers in individual countries. Agricultural sustainability indicators are often highly context-specific, vary in space and time, and low- and middle-income countries may face issues diverging from those in high-income countries (Zhen & Routray, 2003). Thus, a trade-off remains between top-down and bottom-up development of agricultural sustainability indicator systems, where the former may allow for comparability, and the latter for the kind of specificity important to national and sub-national decision making (Binder et al., 2010). Indeed, measuring agricultural sustainability can be considered a wicked problem in that there is no uncontested problem framing nor a clear solution, and multiple interests and values confound the problem even more (Hamm, 2009). Transdisciplinary research designs offer one way to address wicked problems and find the least objectionable solutions (Hakkarainen et al., 2022).

Using a global indicator system as a framework can help compare indicators across different places and scales. This makes it easier to benchmark and assess progress. An iterative and reflexive process with national and subnational stakeholders developing this system further ensures that it is relevant and useful at the respective governance levels. This reasoning has motivated an international transdisciplinary research project "SAM consortium" to co-evaluate the indicator system among researchers and non-academic stakeholders within several independent country case studies (Zhang et al., 2022).

Transdisciplinary research can take many forms and a variety of concepts relate among others to the mode of engagement, phases of cooperation and collaboration, and roles of partners with the typically common objective to co-produce knowledge and outcomes that have legitimacy in a given context (Chambers et al., 2021; Hakkarainen et al., 2022). Within the SAM consortium, co-production of knowledge takes place in two ways. Within the international consortium partners from research, private, and non-governmental sectors jointly designed the research agenda from proposal to implementation. Within each country the national consortium partners engaged with national stakeholders to co-evaluate the indictor system and co-produce knowledge about agricultural sustainability indicators per se and in the respective country setting specifically (Zhang et al., 2022). In the SAM consortium, the stakeholder communities, that is, those groups of people with vetted interests in sustainable agriculture, operate at national and international and in part subnational levels. This is in contrast with many other transdisciplinary research projects, which frequently involve local challenges of sustainable development and resource management (Chambers et al., 2021, 2022; Norström et al., 2020).

Herein, we present the process and outcomes of the Austrian case study conducted within an expert stakeholder community with vetted interest in national scale agricultural sustainability indicators. The particular research questions we address are

1. What is the relevance of global agricultural sustainability indicators for Austrian stakeholders?
2. What are stakeholders' requirements for country-specific tailored or complementary information?
3. How can indicator dynamics and their linkages be interpreted and what context information or expertise is required for this?

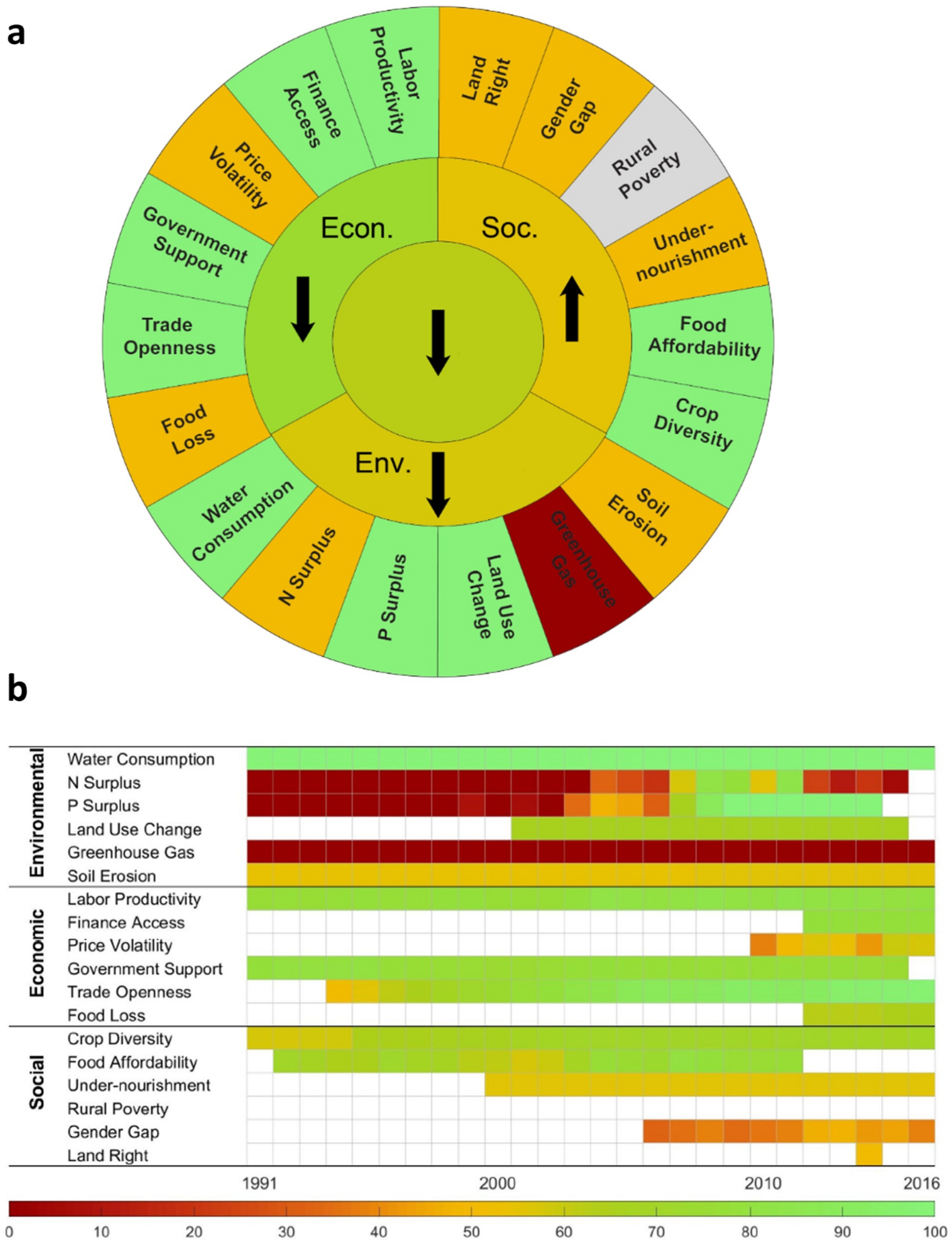

Figure 1. The 18 SAM indicators and their states for Austria (a) averaged for 2010–2014 and (b) annually from 1991 to 2016 within the economic (Econ.), environmental (Env.) and social (Soc.) dimensions reproduced under a CC BY 4.0 license from Zhang et al. (2021). Colors show the indicator state with green = good, yellow = critical, and red = poor. Gray indicates missing data, arrows average temporal trends in the period 2010–2014. N is nitrogen, P is phosphorus. See Table 1 for details. As for most high-income countries, there is no data on rural poverty provided in the underlying database. Indicator values in panel b are transformed and scaled so that the threshold for "sustainable" is at the value 66, that is, between orange and green, and the threshold for "critical" is at 33, that is, between orange and red.

10.1029/2024CSJ000092

Table 1
Indicators Included in the Sustainable Agriculture Matrix (Zhang et al., 2021), the Major Theme They Address, Green and Red Annual Sustainability Thresholds, and Units

Major theme	Indicator	Green	Red	Units
Environmental Dimension				
Water availability	Sustainability of irrigation water consumption (**SUSI**)	1	2[e]	$\frac{km^3 \text{total annual irrigation water}}{km^3 \text{sustainable annual water use}}$
Pollution	Nitrogen surplus (**Nsur**)	52	69[e]	kg N ha^{-1}
	Phosphorus surplus (**Psur**)	3.5	6.9[e]	kg P ha^{-1}
Land use and loss of biodiversity	Land cover change due to agricultural activities (Lost forested area) (**LCC**)	0	0.0053[e]	$\frac{\text{ha deforested area}}{\text{ha cropland area}}$
Climate change	Total GHG emission from agriculture activities per harvested area including pastureland (**GHG**)	0.86	1.08[e]	ton CO_2eq ha^{-1}
Soil fertility and soil health	Soil Erosion (**SER**)	1	5[e]	ton ha^{-1}
Economic Dimension				
Agricultural labor productivity	Agricultural GDP per agricultural worker (**AGDP**)	7,946	460[s]	$\frac{\text{2011 US\\$ PPP}}{\text{number of agricultural workers}}$
Agricultural support	Government agricultural expenditure per agricultural worker (**AEXP**)	2405	25[s]	$\frac{\text{2011 US\\$ PPP}}{\text{number of agricultural workers}}$
Market access	Total agricultural export values as a percentage of agricultural GDP (**TROP**)	71	17[s]	%
Credit availability	Access to finance for farmers (**A2F**)	100	25[s]	Score
Farmer's risks	Crop price volatility (**PVOL**)	0.10	0.23s	–
Food loss	Food loss percentage (**FLS**)	2.2	6.6s	%
Social Dimension				
Farmers' wellbeing	Rural poverty ratio (**RPV**)	2	13[s]	%
Equality	Global gender gap report score (**GGG**)	0.8	0.7[e]	Score
Rights	Land rights (**LRS**)	3	2[s]	Score
Health and nutrition	Prevalence of undernourishment (**UDN**)	0	7.5[e,s]	%
Resilience	Crop production diversity (**RSH**)	48	22[s]	Count (h-index)
	Food affordability (**RSE**)	1	0.3[e,s]	%

Note. Letters in column "Red" indicate expert-based (e) or statistical (s) thresholds for both red and green values. Statistical thresholds are based on the 25th and 75th percentiles of the global distribution, expert-based mostly on scientific literature or defined in Zhang et al. Sustainable water use refers to preserving a regionally defined environmental flow.

2. Methods

2.1. Agricultural Characteristics of the Study Country Austria and SAM Results

After the end of the Austro-Hungarian empire in 1918 it took decades to boost agricultural productivity to reduce the import dependence of staple foods in Austria, mainly achieved through public support for intensification (Bruckmüller et al., 2002). At present, 47% of the agricultural production value are derived from crops, 43% from livestock, and around 10% come from services and non-agricultural secondary activities such as direct marketing and tourism (Statistics Austria, 2023). The vast majority (96%) of the approx. 110k agricultural holdings is classified as family farms, that is, predominantly based on family labor. Austria's agriculture is based on comparatively small-scaled farms (average farm size was 23.5 ha), yet with a trend toward fewer and bigger farms such as a decrease in the number of holdings by 50% between 1995 and 2021 (Statistics Austria, 2022). Simultaneously, the area under organic farming continues to increase, with Austria having the largest share of organic farming area (26%) within the EU (EC, 2022). Despite a declining contribution to GDP (0.9% without forestry) and employment, agriculture still comprises about one third of the land cover, with equal parts of arable land and permanent grassland (Statistics Austria, 2022). Beyond provisioning goods and services it is crucial for cultural identity and the appearance of the cultural landscape that are in turn relevant to other sectors such as

10.1029/2024CSJ000092

tourism (Forbord et al., 2012). Alpine climate and highly heterogeneous topography render the country, incl. parts of its agricultural areas, environmentally distinct from other European countries. Yet, structural similarities manifest in the extensive use of agronomic inputs and the strong influence of EU policies (Sinabell, 2022).

While there is no systematic, continuous public assessment of the sustainability of Austrian agriculture thus far, the Ministry for Agriculture publishes annually the so-called Green Report (sub-title The situation of Austrian Agriculture and Forestry) that provides comprehensive figures on agricultural outcomes and contextual information (https://gruenerbericht.at). The Federal Environmental Agency publishes an Environmental Inspection Report every three years (Umweltbundesamt, 2022). Sustainability assessments harnessing indicators similar to those defined in SAM grouped into the domains Environmental Quality and Resource Protection, Income and Economic Stability, Business Organization, and Quality of Life and Social Topics have been published irregularly by one of the authors (Sinabell, 2014, 2018). Based on member countries' reporting requirements for the Common Agricultural Policy (CAP), the EU is collecting and publishing comprehensive data relating to the agricultural sector that are available in databases of the EU's Common Monitoring and Evaluation Framework (EC & DG AGRI, 2015). These have most recently, after conclusion of this study, in part been compiled in an online dashboard (EC DG AGRI, 2024).

The SAM score card for Austria in the period 2010–2014 (Figure 1a) shows foremost positive outcomes and an on average green state with a positive trend in the economic dimension, large variation in outcomes and a negative trend in the environmental dimension, and an overall moderate but improving state in the social dimension. Consequently, the total average is also at the fringe between green and yellow states, albeit with a deteriorating trend. The poorest state is identified for greenhouse gas (GHG) emissions, which are far beyond the red threshold. Annual values over the period 1991–2016 (Figure 1b) show that in the longer run the indicator states for nutrient surpluses improved substantially with a recent rebound for N surplus. In the economic and social dimensions, trade openness and crop diversity showed continuously positive trends with subsequent stabilization, while indicators such as price volatility, food affordability, and gender gap exhibit strong temporal variations. Notably, economic and social indicators are more limited than environmental indicators in their temporal coverage.

2.2. Research Design and Approach

A schematic of the research design is provided in Figure 2. The project itself is based on the initial SAM framework and assessment (Zhang et al., 2021; Figure 2a) that motivated the formation of an international transdisciplinary consortium involving partners from academia, research institutions, private sector, and non-governmental organizations in six countries. These partners jointly designed an international research agenda (Zhang et al., 2022; Figure 2b) the national project presented herein was embedded in besides projects in seven more countries. These partner projects were carried out independently regarding their methodologies and approaches but were aligned in terms of key research questions. Outcomes from individual country studies were then synthesized at the consortium level (Figure 2f), which is beyond the scope of the research presented herein.

The overarching objective of the project was to elicit stakeholders' perceptions of the SAM indicator system, including their requirements for complementary or alternative indicators and the background information and expertise required to interpret indicator trajectories (blue framed center part in figure). The process should clarify the usefulness of the SAM indicator system and its usability as a "boundary object" (Star & Griesemer, 1989) at the national level.

The co-evaluation process (Figure 2c) took place in two one-day workshops and intermittent one-on-one consultations over a period of 13 months in the years 2021–2022. It followed principles of co-production based on Norström et al. (2020), aiming for a plurality of perspectives in a context-based setting, with a clearly defined goal, and it was carried out in a highly interactive manner. Interactions were designed to aid systems thinking throughout the process. As part of the co-evaluation process, the group also engaged in co-interpretation of indicator dynamics, which we refer to separately in the remainder to distinguish between the focus on evaluation of indicator relevance and suitability per se and their interpretation more specifically.

The first in-person workshop (Figure 2cI) took place in October 2021 and focused on the relevance of the indicators presently included in SAM to elicit suggestions for complementary and alternative indicators, changes in indicator conceptualizations, and thresholds for indicator states. A background document summarizing the indicator system in German language was sent to the participants 2 weeks prior. The workshop started out with a

10.1029/2024CSJ000092

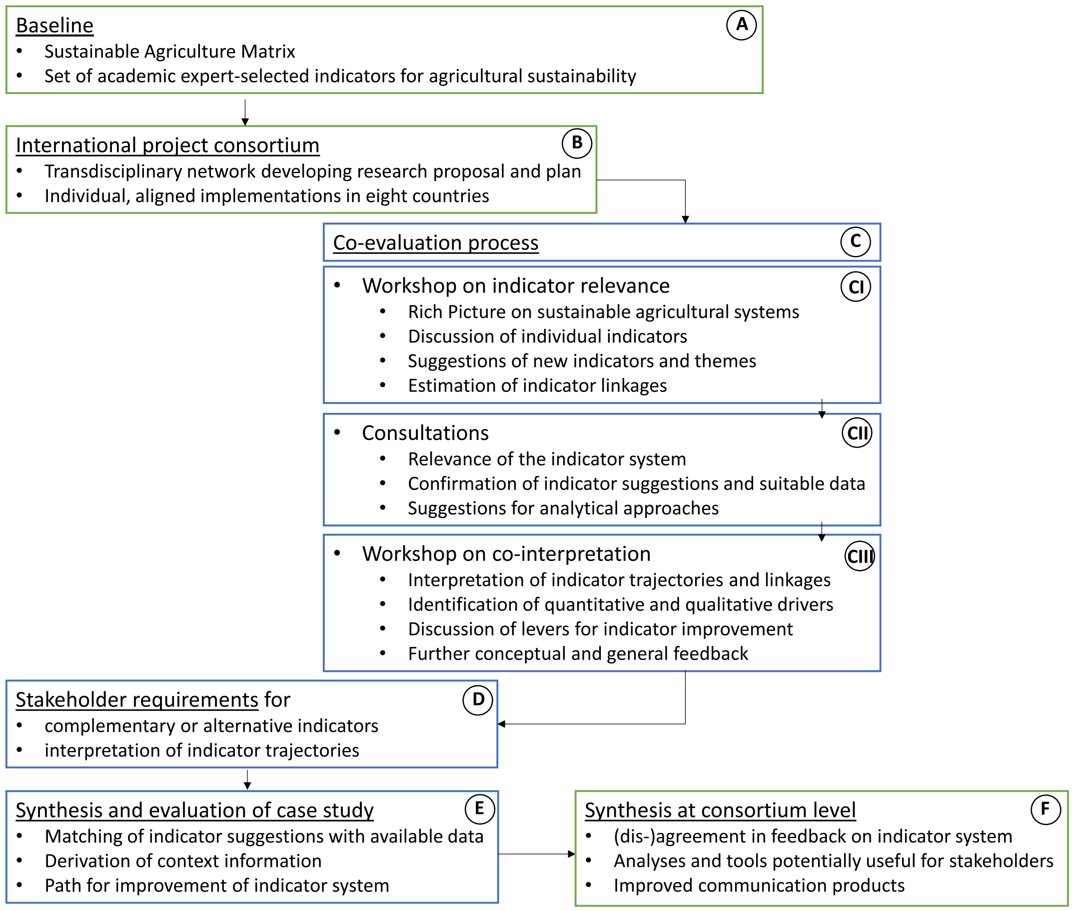

Figure 2. Research design of the Austrian country case study and co-evaluation process. Green boxes refer to elements outside the scope of the Austrian case study but providing the international framework it is embedded in. Blue boxes refer to elements of the Austrian case study presented herein. Further details are provided in Section 2.2.

Rich Picture exercise in three breakout groups sketching elements of agricultural systems relating to sustainability (Figure 3). Rich Pictures (Bell et al., 2016; Grant et al., 2019) are an exercise originating from Soft Systems Methodology (Checkland, 1989). They are a flexible and systems-based means to open a discussion allowing participants to share diverse perspectives on a complex topic visually and minimize researcher bias as they require little facilitation. Based on the Rich Pictures, participants also identified metrics to assess various aspects of sustainable agriculture. Only in the next iteration, the SAM indicators were the center of the discussion including suggestions for their improvement, as well as alternative or complementary indicators. Subsequently, participants were prepared to estimate the indicator states for Austria and to discuss their thresholds in a plenary. The fourth session had again three breakouts to discuss potential synergies and trade-offs among indicator pairs filling in a correlation matrix. Across all three breakout groups this sparked extensive discussions around context-specificity and conditionality. This session did accordingly not provide any tangible outcomes but motivated a closer focus on the interpretation of indicator dynamics, their drivers, and interactions in the second workshop (see below). The day ended with a reflection in the plenary, and a questionnaire to elicit more explicitly indicator suggestions.

Follow-up consultations (Figure 2cII) took place throughout 2022 at the stakeholders' workplaces with one to two participants from each organization and one member of the research team about half a year after the first workshop. The focus was on potential complementary or alternative indicators and available data researched since the first workshop. In addition, suggestions for additional analyses based on the indicators were collected.

Outcomes from the first two interactions fed into the second in-person workshop (Figure 2cIII), which was held in October 2022. Its objective was to jointly explore and co-interpret selected indicators and their drivers in depth as part of the overarching co-evaluation process. Key indicators from the environmental and economic dimensions

10.1029/2024CSJ000092

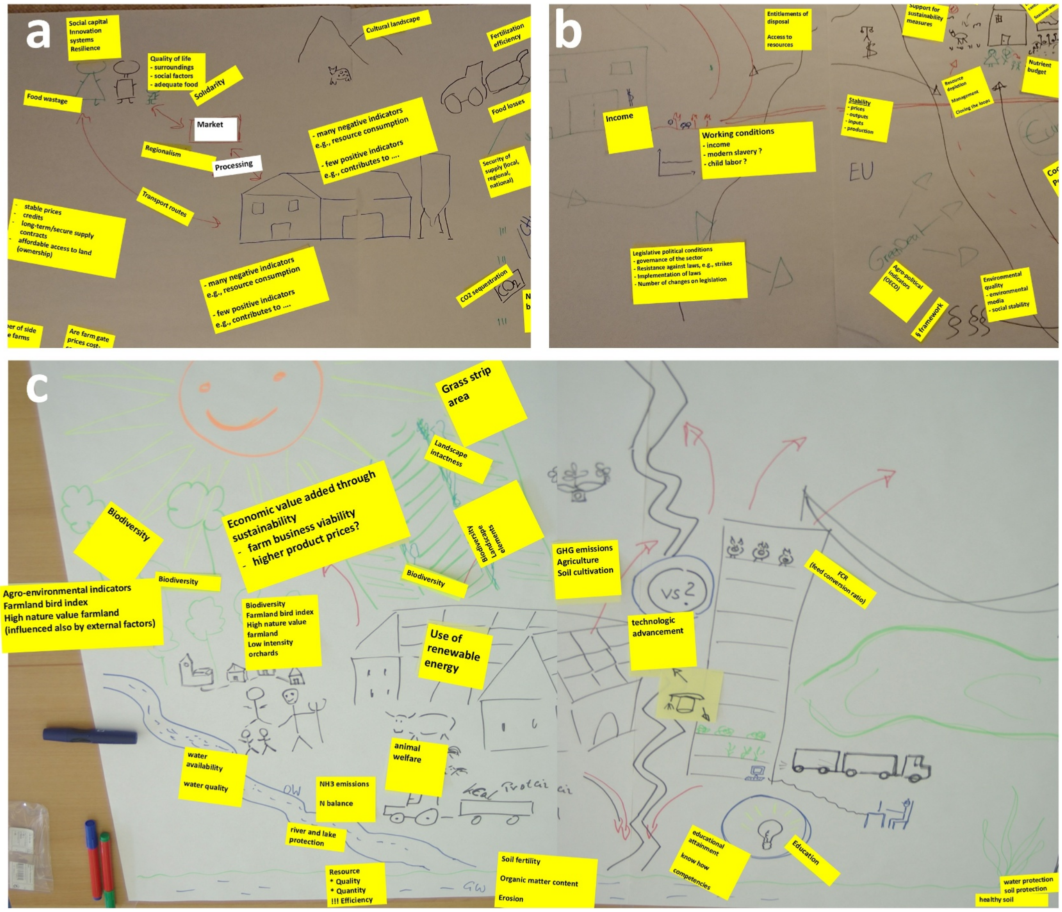

Figure 3. Rich picture from three breakout groups in the first workshop. German language post-its and writing on the sheets have been superimposed with English translations. The two top panels are excerpts for better readability. The full pictures are shown in Figures S15–S17 in Supporting Information S1.

served as points of departure for two breakout groups. Breakouts started with interpretations of the dynamics of the respective indicator over time with a focus on their specific drivers for positive and negative change. Eventually, interventions to improve the respective indicator states were discussed and relevant actors identified. While the latter are part of the visualizations herein, they were not further evaluated due to the focus of this paper on the indicator system co-evaluation and -interpretation. Discussions were visualized interactively by the participants as qualitative systems maps (Hanger-Kopp et al., 2024) indicating causal relationships where possible and comprehensive annotations (Figures 4 and 5) to document and structure the discussion. The mapping exercise highlighted the complexity of the topic and particular uncertainties, for example, with respect to available data, diverging interpretations, and generalizability. Discussions also provided further feedback on indicator definitions, sustainability thresholds, and their potential improvements. This workshop as well ended with a round of reflections.

The combination of individual and group exchange and the uptake of the provided inputs in the different phases of the processes ensured legitimacy. The indicator requirements voiced by stakeholders were iteratively matched with available data (Section 2.4) to evaluate the potential for further indicator system developments. Mutual exchange between scientists and stakeholders ensured a two-way information flow. Eventually, the outcomes of the co-evaluation served for sketching out options to improve the country-specific relevance of the indicator system. The process followed an overall qualitative approach regarding suggestions for further improvement of the indicator system. That is, suggestions were not weighted based on the number of mentions or agreement among participants, but all feedback was treated equally important. The only quantitative evaluation of feedback was done regarding the relevance of present SAM indicators based on a questionnaire. Suggestions for indicators

10.1029/2024CSJ000092

Figure 4. Systems map produced by the stakeholders in the breakout session for the interpretation of dynamics in the agricultural GHG emissions indicator in the 2nd workshop with English translations superimposed. See Figure S2 in Supporting Information S1 for unedited German language version and Figure S3 in Supporting Information S1 for full scale English language version. Regions marked with dashed blue lines and labeled with capital letters A–D indicated parts that are referred to in the text and focus on specific topics. The bottom left insert marked with (x) is an enlargement of a portion in the upper center-right marked with an (x) as well.

or broader themes were classified as "alternative" or "novel" depending on whether the topic was already covered in SAM.

2.3. Represented Community, Stakeholder Organizations, and Research Team

Per its initial design and quantification, the SAM indicator system assesses agricultural sustainability at the national scale and in an international context. This renders it most relevant for an informal community of professionals in research, practice, education, and administration that engage in national topics of agriculture in an international context. Accordingly, key criteria for the selection and invitation of Austrian stakeholder organizations were a vetted interest in agriculture at the national scale and in European or wider international processes. The project team (authors CF, FS, TS, S H-K) mapped potentially relevant stakeholders in a first step based on its

10.1029/2024CSJ000092

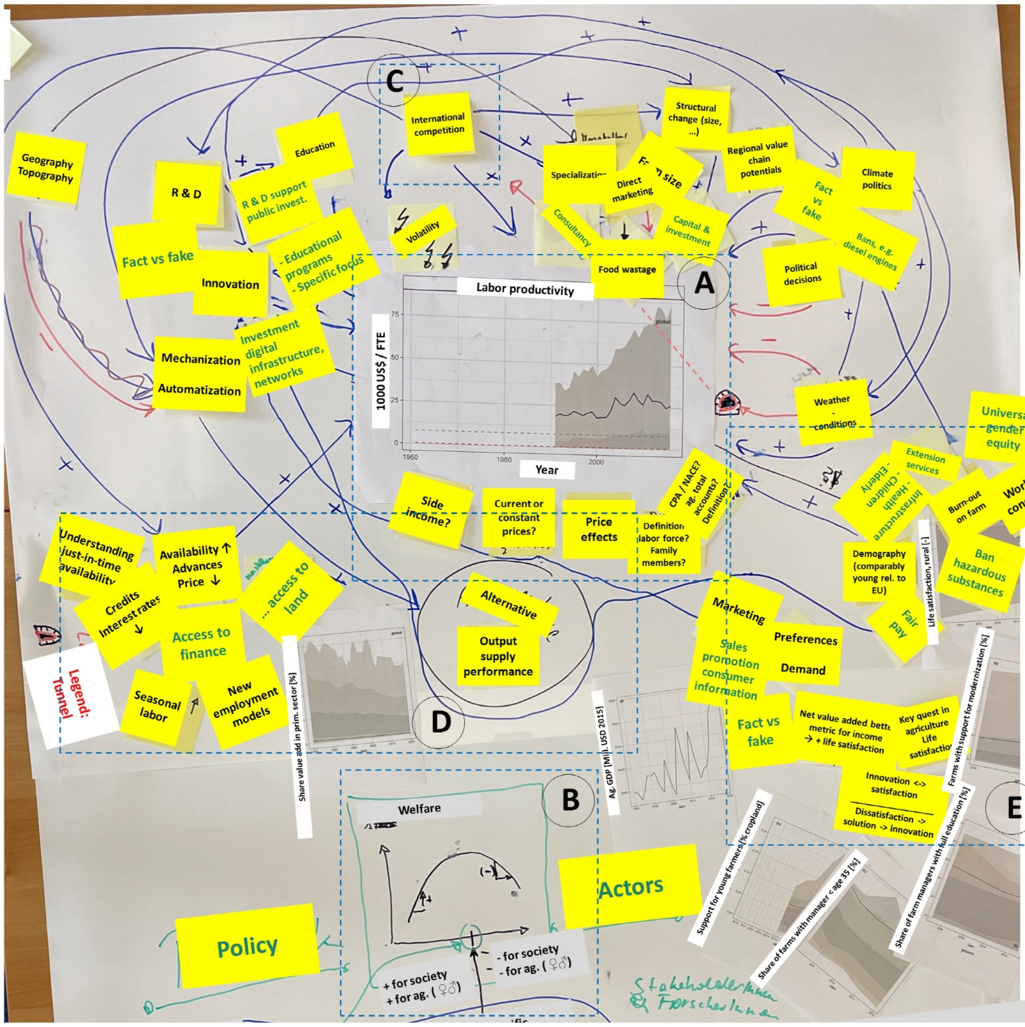

Figure 5. Systems map produced by the stakeholders in the breakout session for the interpretation of dynamics in the agricultural labor productivity indicator in the 2nd workshop with English translations superimposed. See Figure S4 in Supporting Information S1 for unedited German language version and Figure S5 in Supporting Information S1 for full scale English language version. Regions marked with dashed blue lines and labeled with capital letters A–E indicated parts that are referred to in the text and focus on specific topics.

experience and expertise in Austrian agriculture (Sinabell, 2018, 2022), public reports (Opancar, 2014), and earlier participatory research projects, for example, (Karner et al., 2022).

Out of 20 organizations invited, 14 participated (Table S1 in Supporting Information S1). Out of these, about half were from applied and academic research and education with diverse disciplinary backgrounds (incl. livestock nutrition, plant breeding, economics), the other half from public administration (incl. ministries, federal agencies), agricultural practice (incl. chambers, individual farmers), private sector (incl. marketing agency), and NGOs (incl. farming promotion). All of them were engaging in topics of agricultural sustainability with a focus on the national scale but also links to finer scales or international processes. These have a strong influence on developments in the Austrian agricultural sector, most notably through EU policies, trade agreements, and participation in high-level international processes such as the United Nations Framework Convention on Climate Change. Participating organizations' scopes include for example, the evaluation and implementation of EU policies and vice versa representation of Austrian interests in international policymaking, the development of marketing instruments for Austrian agricultural products within the country and abroad, the training of extension agents and teachers for farmer education, or the representation of civil society interests. Three participants ran their own farms in part-time or were active on their family-owned farms. Participants of the first workshop were asked to indicate further organizations for which the study may be relevant (i.e., snowball approach), which did not provide any suggestions in addition to those already considered. The interdisciplinary research team was composed of four researchers with backgrounds in environmental science, economics, policy, and governance from two institutions of applied research.

To foster representation of the community also in the publication of project outcomes, all project participants were invited to contribute to the present manuscript as co-authors, which four persons agreed on. The author team is therefore composed of the project team (first four authors) and additional community members (second four authors). During the prior engagement processes, outcomes of each iteration were shared with participants to ensure validity and completeness of outcomes.

2.4. Quantitative Data Sources and Processing

A primary data source was SAM itself, which is based on UN databases and scientific literature (Zhang et al., 2021). Within SAM, raw values are first calculated for each indicator, for example, the nitrogen (N) surplus per hectare cropland [kg N ha^{-1}] and subsequently transformed to a scale from 0 to 100 whereas 0 is the poorest and 100 the optimal state. For the co-evaluation of SAM outcomes, composed indicators were disaggregated to their original values where helpful for interpretations. The agricultural productivity indicator AGDP [USD 2015 cap^{-1}] for example, is calculated from the numerator national agricultural GDP [USD 2015] and the denominator fulltime labor equivalents [cap] (see Table 1, column Unit), both of which affect the indicator's outcome independently.

Indicators and themes proposed during the co-evaluation process were matched with publicly available data from international databases such as Eurostat (EC, 2022), FAOSTAT (FAO, 2022), ILOSTAT (ILO, 2022), or the OECD Statistics database (OECD, 2023) combined with published literature, for example, (Sinabell, 2018). Similarly, quantitative context information was researched from these data sources, including changes in farm size, crop use, and demand for agricultural products among others. Qualitative context information was researched from reports on agricultural and environmental policies at the Austrian, European and global levels. New and alternative indicators were categorized into performance indicators or context indicators based on whether proposed indicators and presently available data allow for judging an indicator in terms of good or poor state (performance) or whether the information that can be provided is rather of interpretive value (context). This categorization may be subject to normative bias and may change with further iterations of the co-evaluation.

3. Results

The case study design yielded comprehensive insights into perspectives on sustainable agriculture, the relevance of the SAM indicator system, complementary suggestions for themes or specific indicators, and key information required for the interpretation of indicator trajectories. These are summarized in Table 2 and elaborated in the following subsections. Phrasing that contains elements of discourse within this section hence reflects discussions within the co-evaluation and –interpretation processes and accordingly outcomes of the study. The actual discussion of the project outcomes is provided in Section 5. All information provided in this section accordingly pertains to feedback obtained during the project, except for an evaluation of data availability to measure suggested indicators provided Text S1 in Supporting Information S1 and briefly referenced in Section 3.2.

3.1. Perspectives on Sustainable Agriculture

Highly diverse rich pictures produced in the first workshop prior to the actual co-evaluation processes revealed a wide range of themes and elements voiced as important by participants (Figure 3). These range from partly overlapping themes on stability in inputs and outputs (e.g., panels a and b) or technologic innovation (panels a and c) over the common theme of environmental outcomes (all panels) to very particular topics such as value chain fairness (panel a), governance (panel b), and farmers' education (panel c). Also the addressed scales range from a rather local focus (panel c) to Austrian agriculture embedded in the EU and rest of world (panel b; see also Figure S17 in Supporting Information S1). These records of key elements for assessing agricultural sustainability provided a first basis to compile new and alternative indicators.

Table 2
Summary of Topics and Key Outcomes of the Co-Evaluation Process

Topic	Key outcomes
Indicator relevance (Section 3.1 (general) and 3.2 (SAM-specific))	• Components of agricultural and agri-food systems relevant to measure are highly diverse ranging from a social focus to specific environmental outcomes • This also includes various scales and agricultural systems • General relevance of SAM indicators depends on the scale in question, decreasing in the order global > EU > Austria • Thematic relevance of SAM indicators decreases along the dimensions environmental > economic > social for Austria
Conceptualization of indicators and indicator suggestions (Section 3.2)	• Normalization of indicators challenges the interpretability due to (a) changes in both numerator and denominator and (b) the choice of the latter, for example, GHG emissions per area • The majority of indicators has a perceived negative loading, that is, focus on avoided adverse outcomes rather than benefits • The directionality of indicator rating is in part normative, for example, for government expenditure or trade openness • Comprehensive sets of indicator suggestions were collected throughout the co-evaluation process across all three dimensions (Tables S3–S5 in Supporting Information S1) • The measurability of indicator suggestions is limited by spatial and temporal coverages with best conditions for economic indicators and poorer for environmental and social ones (Text S1 in Supporting Information S1)
Conceptualization of framework (Section 3.2)	• Some monotonic SAM indicators would be more informative with a bell-shaped distribution, for example, nutrient surpluses versus nutrient budgets incl. deficits and surpluses • The varying thresholds for green and red indicator states may cause bias as expert-based thresholds are typically very narrow while percentile-based thresholds are very wide • This can affect their comparability and the averaging within and across dimensions • SAM indicators using national averages of outcomes obfuscate the variation within countries spatially and among farming systems
Relevant context information (Sections 3.3 and 3.4)	• Context-dependence of indicator outcomes and even more so interactions among indicators • Drivers of indicator outcomes change over time and range from global (e.g., food demand, trade) over macro-regional (e.g., EU policies) to national (e.g., structural change, farming systems) • (semi-)quantitative context data is hence vital for sound interpretations (e.g., farm sizes and numbers, quality of governance, and food demand)

Note. Detailed elaborations are provided throughout Section 3 in the indicated subsections.

3.2. Co-Evaluation of Relevance and Conceptualization of the SAM Indicator System

Stakeholders' perception of the relevance of SAM indicators decreased with narrowing geographic extent from the global to the national scale (Figure S1 in Supporting Information S1). While most indicators were considered relevant at global scales, this was less so the case at the European scale, and least for Austria. Thematically, environmental indicators were rather considered relevant across scales, while economic and social indicators were considered least relevant for national scale assessments. A specific remark was that indicators in the social dimension such as undernourishment, rural poverty, food affordability, and land rights appear to be foremost tailored toward the so-called Global South. These do typically not present challenges in Austria and most EU member states where more prominent social themes are intergenerational continuity, decent working conditions, education, or animal well-being.

Conceptually, a general notion about the indicators was their often-negative framing relating to agricultural pressures and the avoidance of adverse outcomes rather than beneficial contributions of farming. A further limitation applying to several indicators is the focus on only parts of their potential distribution, while the whole range of values may be relevant (see Table S2 in Supporting Information S1 for compilation of key feedback). This is for example, the case for N and P surpluses, whereas balances of these nutrients would also account for unsustainable nutrient deficits. Similarly, there are indicators that have conceptual counterparts. This applies for example, to Trade Openness, whereas self-sufficiency is a more prominent topic of concern in Austria, or Access

10.1029/2024CSJ000092

to Finance (i.e., credits) versus the degree of indebtedness in the farming sector. Stakeholders noted which element of these pairs to select appears to be a question of norms and perspectives.

The selection of indicators for a specific theme turned out to be sensitive to the country context as well. The biodiversity indicator Land Cover Change (LCC) was considered marginally relevant for Austria and most of Europe in the context of biodiversity. Over the past decades, the region has been experiencing a decline in agricultural land alongside net afforestation (and conversion of agricultural to built-up land). Consequently, the indicator LCC is solely considered relevant for assessing the net GHG balance (Figure S1; Table S2 in Supporting Information S1). For biodiversity in turn, in-situ indicators such as the farmland bird index or landscape fragmentation were suggested to address present concerns in the European context (Table S2 in Supporting Information S1). For example, an established impact indicator of the CAP to assess biodiversity across European countries is the high nature value farmland, defined as the percentage of "Utilized Agricultural Area farmed to generate High Nature Value."

The normalization of indicators was a key concern of stakeholders, especially in the case of GHG emissions, which are related to the agricultural area. Stakeholders criticized that this denominator entails that countries with extensively managed farmland receive a larger allowance for GHG emissions although farmland expansion may have detrimental impacts in the LCC context. A suggested alternative would be to use agricultural output as the denominator following a CO_2 footprint approach. Further in-depth discussions and co-interpretation of the indicator (see Section 3.4.1) underpinned the importance of normalization bases and the need to carefully evaluate options.

Matching the comprehensive indicator suggestions with available data, which was performed by the research team with inputs from stakeholders, resulted in a mixed picture of data availability. Owing to length and focus of the present article this is elaborated Text S1 in Supporting Information S1. In brief, suggestions for alternative or new environmental indicators can mostly be covered by EU data and are typically not timely available but reach farthest back in time, while economic indicators would be most timely available and with global coverage. Social indicators can again rather be obtained for EU countries and on average for the shortest time periods.

Indicator thresholds for green and red states caused concern in several aspects. First, the mostly science-based thresholds in the environmental dimension are not necessarily in line with national targets. For example, the N Surplus threshold for a green state is 52 kg N ha^{-1} (Table 1), which is substantially higher than targets set by EU policies. Furthermore, it was noted that the gaps between red and green thresholds (i.e., the yellow range) are narrower if based on expert knowledge than if based on percentiles (cf. thresholds and percentiles in Figure S6 in Supporting Information S1), which may bias the aggregation of indicator values and limit their comparability. This informed the design of display items for the second workshop (see results in Section 3.4). Here, graphs included raw values for indicators, the red and green thresholds of the SAM indicator system, as well as the ranges and percentiles of indicator raw values.

3.3. Requirement for Broader Context Information

Context emerged as a key determinant for the interpretation of indicator values and trajectories, identification of synergies and tradeoffs, and the conclusions drawn for the improvement of indicator states (see also Section 3.4).

One contextual key driver of agricultural sustainability was change in global demand for agricultural products. This was considered highly relevant for adverse developments in the environmental dimension such as GHG emissions driven by increasing global demand for livestock products. The same applies to the ever-increasing trade in agricultural products. Essentially, stakeholders voiced that it is challenging to assess a country's (contribution to) agricultural sustainability when solely focusing on the production side as this ultimately serves to meet demands—often globally. This includes both, imports to Austria such as livestock feed and exports such as dairy products.

Stakeholders acknowledged that national-scale assessments are a first step in a global comparison. Yet, more detailed information on site conditions and farming structures were considered necessary to derive recommendations. That is, regions with similar agri-environmental conditions may be more informative to compare than contrasting whole countries with their sub-national diversity in these conditions. On top of this, farm system typologies comprising farm specialization (e.g., dairy farming vs. arable farming) and farm structures (e.g., low-

10.1029/2024CSJ000092

input smallholder vs. large commercial farming) can be expected to entail larger differences in sustainability outcomes between them than between countries.

Finally, governance was identified as an overarching driver and modulator of agricultural change. While SAM assumes governance to be exogenous, it emerged in the co-evaluation process as a key driver. This includes regulations across administrative levels, for example, from the European to the national level, that serve to limit externalities (Figure 4) or provide benefits to farmers (Figure 5).

3.4. Co-Interpretations of Indicator Dynamics and Drivers

The second workshop focused on in-depth interpretations of two exemplary key indicators: (a) greenhouse gas emissions from the environmental dimension, which have constantly been in the red range and identified as highly relevant and topical in an Austrian context by stakeholders and (b) agricultural labor productivity from the economic dimension, which relates to the viability of farming and had emerged as a central topic for the future development of farming in the stakeholder discussions. The two following subsections summarize the results of these co-interpretations. Capital letters in brackets therein refer to marked regions in the breakout figures.

3.4.1. Agricultural Greenhouse Gas Emissions

The co-interpretation break-out on agricultural GHG emissions [t CO2eq ha^{-1}] (Figure 4a) first evolved around the temporal trajectory, which peaked in Austria in 1985, falling to just above the initial value until 2007 with eventually a slight rebound and being permanently far in the red range (Figure S6 in Supporting Information S1). Statistically, however, Austria was within the 75th to 95th percentiles until 1997 and subsequently below the 75th percentile. Animal husbandry contributed 80%–90% of total agricultural GHG emissions followed by mineral nitrogen fertilizer (Figure S8b in Supporting Information S1). Following IPCC methodology, the indicator is currently based exclusively on emissions directly attributed to the agricultural sector (livestock activity, soil-borne GHGs, and rice cultivation). However, the breakout group considered it important to also account for pre- and post-production emissions (e.g., fertilizer production) that may equal or exceed indirect emissions in high-input farming in Austria (B).

The normalization of emissions by agricultural area was criticized throughout the co-evaluation process as it may hamper both the interpretation and the development of recommendations (B). In particular, the rebound of area-based emissions after 2007 was largely due to a decrease in agricultural area (Figures S8a and S8b in Supporting Information S1). This was highlighted as a key limitation of composite indicators. It was hence voiced important to consider both the numerator and the denominator separately in indicator interpretations. Stakeholders proposed normalization by production volumes as this relates environmental externalities to output. If such a footprinting approach was pursued, in the workshop done exemplary for the most important livestock products in Austria, beef and milk, the ranking of Austria in a global comparison would flip to below the 25th percentile, that is, a green range in statistical terms (see also Figure S7 in Supporting Information S1). While this is a positive outcome for this specific indicator, concerns were raised that a low CO_2 footprint is in turn typically achieved in intensive livestock systems, which entail other externalities (not shown).

Drivers of change in GHG emissions identified by the group were wide-ranging and not always reflected in the data underlying the indicator. These included technology (e.g., livestock breeding), demand for livestock products, various political instruments, and processes on EU (e.g., milk quotas) and global levels (e.g., UN Earth Summit (Rio)), and world market effects (e.g., entry of New Zealand in milk trade).

As SAM serves inter alia for analyses of synergies and trade-offs among indicators and there is a correlation between GHG emissions and N surplus in most countries (Figure S20 in Supporting Information S1), the latter was prompted to evaluate potential causal relationships. Essentially, the group found that the negligible contribution of fertilizer-based to total GHG emissions (Figure S8b in Supporting Information S1) disqualifies it as a dominant causal driver of GHG emission trajectories. The group's interpretations revealed in turn a complex picture involving substantial increase in feed crop production for intensive animal husbandry over the past decades, simultaneous specialization of farms in either livestock or arable farming, and the consequent interruption of manure N cycling between these two systems, which increases demand for mineral fertilizer. Fertilizer surpluses in turn are rather affected by grain market prices as farmers tend to apply fertilizer in excess if high prices for high-quality wheat are expected (D, C).

10.1029/2024CSJ000092

The co-interpretation stressed the multitude of drivers from various societal domains that jointly determine GHG emissions and may change over time. The long-term correlation of GHG emissions with N surplus was therefore considered a result of indirect interactions with overarching mechanisms such as environmental regulations affecting both simultaneously.

3.4.2. Agricultural Labor Productivity and the Viability of Farming

Based on the materials provided, the socioeconomic break-out on the viability of farming first identified that Austria's agricultural labor productivity was consistently well in the green range of the SAM framework, that is, above the 75th percentile (Figure 5a). As in the case of GHG emissions, both sides of the term were found to be required to interpret basic indicator dynamics. This revealed that in the period 1995–2010 the agricultural GDP remained fairly constant with an on average 10% increase but strong fluctuations (Figure S12a in Supporting Information S1) while the number of full-time equivalents (FTE) decreased by about 25% (Figure S12b in Supporting Information S1) and hence primarily drove the indicator's trend. Moreover, it was stated by the participants that a clear definition of the boundaries of the agricultural system and of labor force is required for the correct interpretation of the data, as changes in the data were sometimes only due to changes in the methodology for data collection. In addition, it was critically questioned whether the relationships between indicators could change over time and whether there could be tipping points (B). In this context, it was discussed whether an increase in labor productivity above a certain level could lead to the social isolation of farmers and increase rural unemployment as indicated by the above-mentioned decrease in FTE, and hence present several trade-offs.

Perceived drivers of the indicator's trends and dynamics were clustered (see unmarked post-it clusters around center region A) into market structures (incl., international competition, and specialization), research, innovation and education, availability of resources (e.g., labor, also depending on prices), social factors (e.g., demography, working conditions), agri-environmental conditions, as well as sales and returns (e.g., marketing, demand, food waste). As a central driver international competition (C) was mentioned, which impacted the volatility of output prices and added value. Another one was the discrepancy between incomes in agriculture and incomes in other sectors. This resulted in an ongoing process of labor-saving structural change in Austria. Both drivers promote specialization and structural change toward fewer and typically larger holdings (Figure S13 in Supporting Information S1) with fewer FTEs (Figure S12b in Supporting Information S1). Similarly, the availability and prices of inputs were determined by international markets, including the just-in-time delivery, interest rates on loans, or seasonal labor. According to the participants, the availability of labor was affected by economic alternatives, adequate public services, access to extension services, and the social security system (D). Jointly, these drivers contributed to the motivation to work in agriculture and continue family farming (E), which is the predominant farm model in Austria and reflected in the demographics of the agricultural work force: the country has a very high proportion of farm managers under the age of 35 compared to other European countries (Figure S14a in Supporting Information S1) and an above-average proportion of farm managers with high education (Figure S14b in Supporting Information S1).

Consequently, the indicator labor productivity was found to provide basic information on the country's performance in an international context but the relevance to stakeholders was voiced as being very limited without the aforementioned breakdowns. Moreover, the proposed alternative theme "viability of farming" requires comprehensive further information that explains underlying demographic change on the one hand and dynamics in economic outcomes on the other.

4. Community Impact and Mutual Benefits

It was a key ambition in the design of the project to not solely harness the participants' expertise for the scientific advancement of the project but to also provide community and individual benefits. In particular, the research team aimed to offer a platform for exchange among stakeholders, to present stakeholders an overview of available data and their characteristics, and to introduce a tool for monitoring agricultural sustainability.

Feedback obtained at the end of the second workshop indicates that stakeholders appreciated the joint system-based evaluation and interpretation exercises (Table 3). Specific examples include having had the opportunity to jointly work out the "*complexity of indicators*" and discuss "*what drives what*" in the context of agricultural sustainability. This is supported by a more comprehensive statement that "*Sometimes one wishes for very specific conclusions/results/synergies/trade-offs/etc. It becomes more and more clear that these hardly exist. It was nice*

Table 3
Stakeholders' Key Takeaways and Feedback on Second Workshop From a Flash Feedback Round

ID	Comments	ID	English
1	• It's all very complicated—everything is associated with everything • Sustainability is a buzzword—very worn out! • The art to simplify the chaos challenges the project leads • Many small steps required to be able to visualize the consequences • Very well organized—very pleasant atmosphere • Further participants welcome	6	• At first glance unambiguous indicator is multifarious and differentiated • Thresholds whether good/poor are challenging to identify • Causal chains are not always unambiguous/not identifiable • What drives what? • Until what point is it good?
2	The state of research on greenhouse gas emissions is limited, simultaneously there is a lot of expert knowledge on relationships. For example, it was not clear whether also fossil fuel emissions are accounted for in greenhouse gas emissions. Levers such as regional alimentation and limiting food waste are known but not their implementation.	7	• Labor productivity ≠ sustainability not exhaustively discussed in the group • Very interesting exchange among participants the interactive exchange and the "casual" interaction have contributed to the labor productivity of the group
3	• Overall positively surprised! (good group size, no overburdened agenda) • Sometimes one wishes for very specific conclusions/results/synergies/trade-offs/etc. It becomes more and more clear that these hardly exist. It was nice that the day still felt "successful." • Within short time, we—very diverse participants—even managed to speak the same language	8	• Complexity of indicators • Importance of different perspectives contributing from different regions of the world • The role of research • Critical scrutinizing of data • Establishing interconnections between the individual topics
4	• Relevant and content-rich examination of two sustainability indicators from completely different perspectives based on the diversity of represented organizations • View beyond one's own nose was enabled and the diverse aspects, in which the two selected indicators play a role, were illustrated	9	• Thanks
5	• Different perspectives/perceptions • Insight that indicators can be interpreted very differently - > therefore information about indicator framing important • … That many factors influence the indicators, incl. synergies/trade-offs - > more = not always better • A lot to do in the direction of research/high expectations on agriculture • Expectations for SAM • more clarity on "what is actually sustainable"? • SSP-specific instructions for actors along the food value chain, incl. policy	10 11	• Conclusion: Everything is complicated/complex o Because influencing factors on each indicator/in each area are enormous • Well-founded preparation of the whole team • Methodology—as feasible motivating and integrating everyone • Content is a real challenge—breaking down a global challenge to national indicators and playing it again "back up" • Happy to join again

Note. The original German language feedback and corresponding translation shown here are provided in Table S7 in Supporting Information S1. The columns labelled ID refer to individual anonymized stakeholders.

that the day still felt "successful."" The last part of this statement indicates that while it was challenging—and could hardly be expected—to fully map out all drivers and complete trajectories of the exemplary indicators, the exercises, and discussions in a transdisciplinary setting per se provided new insights, particularly when it comes to highlighting the systemic complexities of a sustainable future for agriculture. An aspect also valued by several participants was the "*very interesting exchange among participants*" with "*different perspectives/perceptions*" facilitated by the fact that "*[w]ithin short time, we—very diverse participants—even managed to speak the same language*." This suggests that despite the often-faced polarization of interests in the agricultural system, the exchange in an informal setting with clear objectives was appreciated. It also highlights the opportunity for co-creation of knowledge, co-learning, and to explore subjects in depth.

5. Discussion

5.1. Options for Improving the SAM Indicator System and Its Relevance

The co-evaluation process yielded comprehensive insights into stakeholders' information requirements, and their coverage by the existing indicator system. Essentially, it revealed that a range of SAM indicators is well suited—especially in the environmental dimension—, while several topics of high national relevance are missing thus far, especially in the social dimension.

A persistent limitation for rendering the indicator system more relevant for national stakeholders while maintaining its conceptual design is the availability of suitable data (see Text S1 in Supporting Information S1). This

10.1029/2024CSJ000092

suggests that the co-creation of an improved indicator framework will need to inherently consider data availability to arrive at measurable solutions. In this context it needs to be noted that there are complementary efforts ongoing to improve the measurability of presently challenging themes with consideration of national specificity. For example, an OECD Joint Working Party on Agriculture and the Environment (JWPAE) has been established in 2022 to prepare guidelines to develop an indicator on agrobiodiversity on a global scale, at least for OECD countries, that accounts for heterogeneity of natural areas and agricultural systems. Once such an indicator is operational, it may fulfill criteria for both global comparability and national specificity.

Conceptually, stakeholders valued the set of indicators as it provides global comparability of agricultural sustainability performance across the three sustainability dimensions. Other indicator systems serving as sources of information for Austrian stakeholders in turn either focus on the national scale or the scale of the EU (see Section 2.1). Hence, an indicator system tailored towards only regionally quantifiable and relevant indicators would be missing this important point. Based on this valuation, we propose two options for improving the SAM indicator system, which are to (A) replace specific indicators considered less relevant with those suggested by stakeholders and presently measurable or (B) extend the indicator system with a second tier of regionally relevant indicators (Figure 6, center panels). This can either be based on the geographic and economic region such as the EU or on other country characteristics such as income groups, which has earlier been shown to reveal patterns in SAM indicator outcomes (Zhang et al., 2021).

While option (A) can preserve global comparability to perform an assessment of relevance for specific stakeholders, it is presently limited to the remaining generic SAM indicators and those new indicators measurable at global scales (c). However, replacing only few indicators narrows down the thematic requirement for available data as compared to option (B) and better reflects that the agreement on indicator relevance varies among the sustainability dimensions (e.g., Figure S1 in Supporting Information S1). Option (B) is less prone to limitations in global data coverage and preserves the global comparability at the first tier. However, it has its own limitations in that it retains SAM indicators that have been judged as rather irrelevant herein and requires the availability of sufficient data to quantify an equally large set of additional regionally relevant indicators in each dimension. Which of the two options is most useful and feasible was beyond the study's scope and will have to be evaluated in future iterations, ideally across geographies, to ensure that modifications robustly reflect diverse stakeholders' requirements.

Notably, there is a range of further indicator systems addressing agricultural and food system sustainability globally, often originating out of international organizations or academia. These have in part been earlier compared to SAM, which indicated partial overlaps but also clear distinctions in indicators and scope (Zhang et al., 2021). A most recent development is the Food System Dashboard (FSD; https://www.foodsystemsdashboard.org) that compiles a comprehensive set of >280 global indicators and selected country-specific ones. These can fill some of the gaps identified herein such as rural poverty earlier not quantified for Austria and indicator suggestions such as crop productivity and self-sufficiency (Tables S3–S6 in Supporting Information S1). In turn, it does not include SAM indicators such as soil erosion or land tenure. Consequently, it appears that diverse indicator systems can provide important insights how to further extend each within its specific objectives and scopes. Studies such as the one herein provide general insights on topics relevant to measure that can inform enhancements across the board.

5.2. The Importance of Context

The high relevance of context information to support interpretations of the indicator system was an important outcome of the co-evaluation process. Spatially explicit context information and indicator data (e.g., nutrient budgets) would allow to distinguish outcomes between farming systems (incl. farm types, sizes, and input intensities). Complementary information and evaluations could elucidate the roles of demand and consumption sides as well as governance. In line with this, Huber et al. (2024) recently reviewed globally existing farm typologies, showing that linking farm typologies to the policy making process improves their validity, transferability, and relevance.

To distinguish outcomes by farming system at international scale, an internationally accepted classification of diverse farming systems, for example, smallholder versus industrial farming as well as data of high spatial resolution or differentiated by farming systems will be required. Within SAM, only selected environmental indicators, that is, Nsur, Psur, SUSI, SER, and LCC are based on spatial data. Also farming systems have hardly

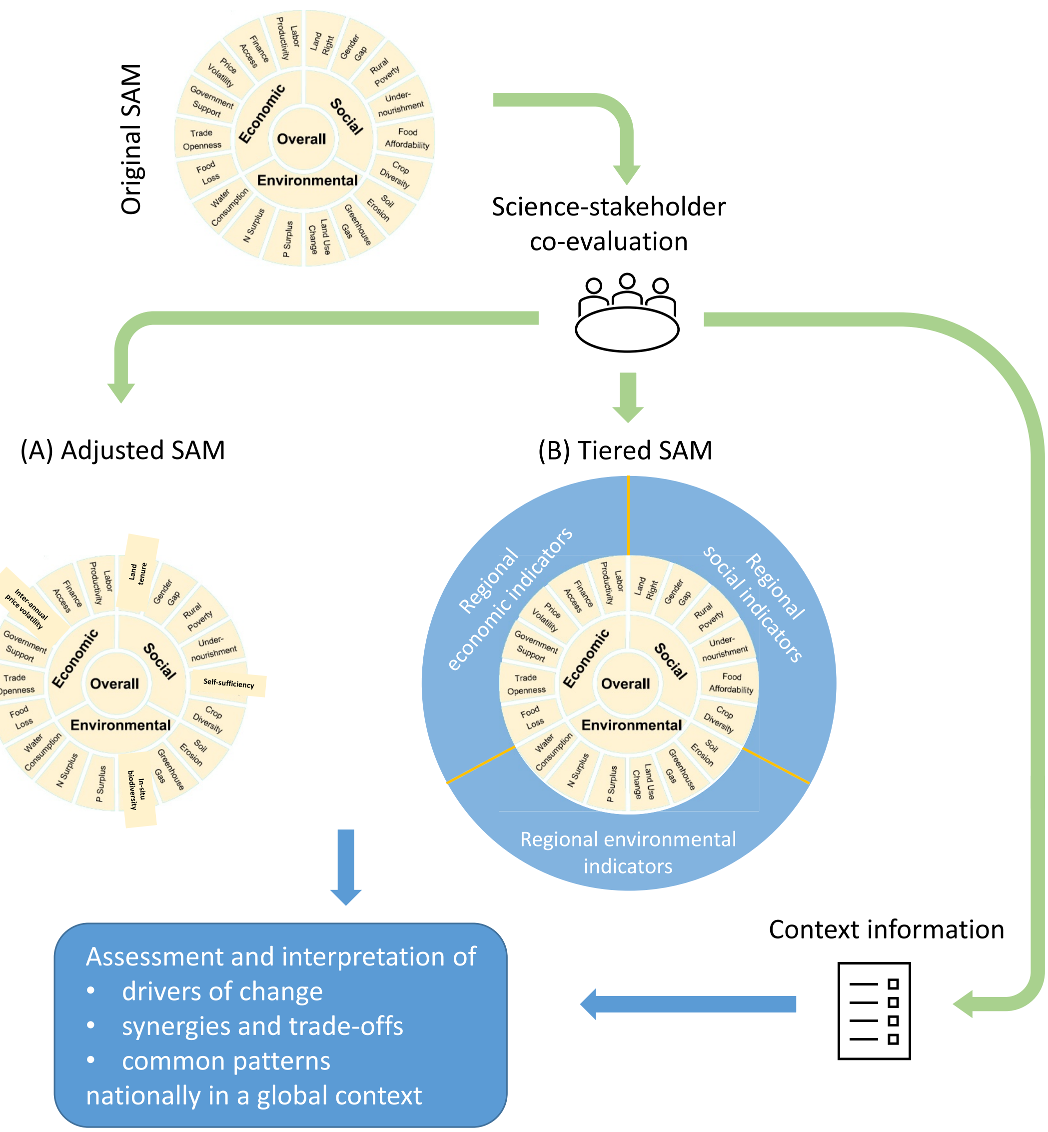

Figure 6. Options to improve the SAM indicator system through adjustment or extension, and provision of contextual data, based on feedback from national stakeholders provided in the co-evaluation process.

been mapped globally in detail, with few initial efforts available to distinguish farming systems at the landscape scale (Jung et al., 2024; Malek & Verburg, 2020). As pre-processed data, the European Commission's statistics database Eurostat (EC, 2022) provides selected items such as farmers' income by size of holding or by farm specialization based on the agricultural census conducted in multi-year time steps. FAOSTAT provides global national accounts of farming systems such as the distribution of farm holding sizes (FAO, 2022) that may serve as covariates in initial analyses of indicator outcomes. Yet, this will not solve the limitation of averaging out higher and lower performing farming systems at the sub-national scale as voiced important by stakeholders and shown to matter substantially (Einarsson et al., 2018; Quemada et al., 2020).

Within the co-evaluation process stakeholders also voiced need to include demand-side information and data that can aid in interpretations of indicator states, for example, the role of population growth and per capita meat demand as determinants of GHG emissions (Figure 4). Linking the present indicator values to consumption directly would require the normalization by production volumes and tracing their trade to final consumption. This would eventually allow for quantifying the externalization of sustainability outcomes that has been confirmed herein to be highly relevant in high-income, import-dependent countries. Such combined exploration of production- and consumption-related indicators is still subject to development. Especially social indicators are challenging to attribute to specific products (Mancini et al., 2023; Wiedmann & Lenzen, 2018) compared to environmental footprints (Halpern et al., 2022).

Beyond the classic sustainability dimensions, governance is the dimension most frequently included in indicator frameworks for sustainable agriculture (Chopin et al., 2021). Its importance has equally been reflected in the co-evaluation process herein. As the SAM indicator system focuses on outcomes of farming, that is, performance-related indicators (Zhang et al., 2021), governance appears to be best located with other contextual information. However, thus far data to measure governance consistently at global scales are limited to either generic or very specific items (Text S1 in Supporting Information S1). Furthermore, studies evaluating agricultural environmental outcomes in a governance context show that spatial and temporal variations in governance systems, the various levels of governance, and interlinkages among sectors substantially affect outcomes (Musacchio et al., 2020; Weitz et al., 2017). This underpins that most relevant characteristics as well as levels and scales of governance in a global context of agricultural sustainability may yet need to be identified while the available generic information could provide a starting point for evaluations of general patterns. For example, trade-offs in crop yields and cropland N surplus have recently been analyzed in the context of institutional quality (Wuepper et al., 2020).

5.3. Emergent Themes

Key emergent themes recurring during the co-evaluation process were the telecoupling of indicator outcomes through international production and consumption chains including leakage effects, questions of fairness foremost from the producer perspective, and the viability of farming, all of which are in part interconnected. The individual indicators are also linked to each other, so that possible trade-offs between them were discussed.

Telecoupling here refers to remote impacts of consumption of agricultural products (e.g., Figure S17 in Supporting Information S1). In Austria, this is prominently the case for soybean as a feedstock, which is predominantly imported from Brazil, has been contributing to deforestation in the country of origin, and may provide Austrian farming with a more sustainable outcome (Gavrilova et al., 2010; Mancini et al., 2023). Vice versa, Austria is an important livestock producer that also supplies other countries but carries the associated GHG emissions. Accordingly, solutions for improving indicator states are embedded in a global context and require appropriate actions. For example, stakeholders voiced concern that imposing taxes for GHG emissions or N surplus on producers at the Austrian or EU level would likely result in leakage effects, that is, increase imports from regions without such policy instruments (Figure 4). Therefore, policies would be required at international scales or would have to be extended to imports to ensure effectiveness and fairness as in the example of the EU's Carbon Border Adjustment Mechanism (Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 Establishing a Carbon Border Adjustment Mechanism (Text with EEA Relevance), 2023).

Fairness spanned a variety of topics. These ranged from proposing the income in agriculture relative to the whole economy as an alternative or complementary indicator for labor productivity (Figure S19 in Supporting Information S1) that also relates to the viability of farming as a motivational aspect (see below), over fairness in international trade (Figure S17 in Supporting Information S1) to fairness in the quantification of indicator states. With respect to the latter, one intergenerational justice concern was that deforestation for cropland already occurred in Europe several centuries ago, which provides a historic bonus in the LCC indicator. However, while selected aspects of fairness may be measurable such as income distributions, reaching a stable consensus on this highly normative topic can be expected to pose an enormous challenge (Hendrickson & James, 2016) and may require its own dimension with dedicated indicators (Gudbrandsdottir et al., 2021) to be fully accounted for. Still, this appears an important area for future research as fairness aspects may eventually aid proactively targeting potential conflicts across different stakeholder groups.

Finally, the viability of farming spans diverse topics as well, primarily in the economic and social dimensions as expressed in various indicator suggestions and elements of the agri-food system voiced as important for assessing agricultural sustainability (see also Section 3.4.2). These include economic indicators such as equity ratio, degree of indebtedness, or the above-mentioned relative income in agriculture all the way to competitiveness, innovation, education, and public services. The proposed age structure in the farming sector may serve as a performance indicator synthesizing both social and economic outcomes as generational renewal. Further aspects considered important in the context of viability are stability and resilience, including stability of production under increasingly adverse and variable climate conditions, price and income stability, and resilience of supply chains including labor force availability (Figure 5).

5.4. Reflections on the Project's Approach and Potential Ways Forward

Our study is prone to several caveats and limitations that are in their majority common and challenging to evade in this area and setting of research. First, due to the group size, the workshop participants cannot be considered representative for the whole of stakeholders in Austrian agriculture, albeit they cover all categories included in the Agricultural Knowledge Information Service (Opancar, 2014). While we aimed at a diverse participant profile, and had for example, an equal gender balance, stakeholder identification and participation was certainly affected by resource constraints. Yet, based on the diverse backgrounds of participants and researchers, and earlier experience in transdisciplinary research in the sector and region by the research team, we trust that the group largely brackets the range of perspectives and expertise. This has also been supported by the fact that stakeholders invited to the first workshop did not identify additional stakeholders when asked in a snow-balling exercise for additional invitees to the second workshop. In turn, our stakeholder identification approach building on publicly accessible information, prior expertise, networks and snow-balling techniques may have created bias toward research and boundary organizations, missing less visible actors (Lemke et al., 2024). Last but not least, we have observed stakeholder fatigue and lack of capacity to participate, which reduced the diversity of participants with respect to sectors. To address the limited group size, we avoided weighting of obtained feedback and picked up any inputs and feedback provided on equal terms.

Furthermore, the various ways to design a workshop might affect their outcomes. For example, the fact that team members without facilitation training were involved in the exercises may have caused bias but was necessary to facilitate and bound the discussion given time limitations. Time constraints also allowed us to use qualitative system maps only to document and structure the discussion, but not to derive fully-fledged causal loop diagrams. Still visual aids such as the mapping create an additional level of reflection important to co-production efforts. To make sure that no feedback and voices are lost, each workshop included a round of reflection, and debriefs were sent out for further inputs after each workshop and the intermittent personal consultations served for confirming feedback obtained in the first workshop.

Based on the feedback obtained and experience made in the process, we conclude that adequately facilitated, indicator co-evaluation and -interpretation may also serve awareness raising and social learning and may eventually contribute to identifying compromise solutions. Yet, this needs further systematic exploration, also for the purpose of applying such formats internationally and across scales of governance. This may eventually also contribute to better addressing cross-scale and -regional issues linked to telecoupling of agricultural outcomes, which has emerged as an important aspect in knowledge co-production for agricultural sustainability both herein and in the literature (Zaehringer et al., 2019).

In the context of transdisciplinary research as an enabler of transformative change toward sustainability (Hakkarainen et al., 2022), the approach and outcomes of this case study can first of all serve as a basis for deeper engagement across spatial and governance scales in follow-up projects to ensure acceptance and legitimacy of sustainability indicators eventually applied in practice. A consequent next step would be the actual co-creation of context-specific indicators and an integrative indicator system. This may in turn serve as a credible, salient and legitimate foundation to enact and manage transformative change toward sustainability as a common ultimate objective of transdisciplinary collaboration (Chambers et al., 2021, 2022; Hakkarainen et al., 2022).

6. Conclusions

The co-evaluation process revealed that the SAM indicator system is considered useful for the international comparison of Austrian agriculture in a global context but would have to be substantially adapted to become an applicable policy and decision-making tool for Austrian stakeholders. According to the stakeholders' views, especially the economic and social dimensions but also environmental indicators such as biodiversity require more specificity.

There are several options to address such an incompatibility with a global approach. The most straightforward way to facilitate both global comparability and national or regional relevance appears to be the introduction of a second tier of sustainability indicators that represent the latter on top of those already included. This will, however, need to be legitimized and reiterated in a co-evaluation process to ensure its usefulness and applicability. Ideally, it is reproduced for contrasting agricultural and economic geographies. For emergent normative topics such as fairness within and across countries as well as generations, the development of commonly agreeable indicators may be very challenging. However, stakeholder forums have proven an adequate starting point for discussing dimensions of fairness—a topic gaining in importance in academia—not least because such co-creation methodologies themselves strengthen procedural and recognitional fairness.

Both, the co-interpretation of key indicators and the discussions of synergies and trade-offs among indicators highlighted the importance of context information and the dynamics of drivers over time, indicating that analyses of trade-offs and synergies among indicators require high scrutiny. In this regard, the SAM indicator system would benefit from contextual information that can support common global interpretations based on quantitative analyses to elucidate drivers of agricultural sustainability and global patterns in time and space.

The co-evaluation process was well-received by all parties with comprehensive feedback obtained to further advance the development of indicators and a common appreciation of exchange, knowledge gain, and co-learning. This suggests that also the wider international community occupied with sustainable agriculture may profit from engaging in similar processes. Future iterations across geographies and governance levels would also be valuable to elucidate whether the approach and setup can be replicated at different scales or be further improved to harness the outcomes of mutual benefit in a wider range of settings.

Conflict of Interest

Christian Folberth is serving as a guest editor of the Special Collection this manuscript has been submitted to. Otherwise, the authors have no conflict of interest to declare.

Data Availability Statement

Key outcomes of workshops and consultations, including high resolution figures, are provided in an open online repository at Folberth et al. (2024). Online databases and literature sources for each of the abbreviated data sources in Tables S3–S6 in Supporting Information S1 are provided in Table S8 in Supporting Information S1. SAM indicator data have been obtained from Zhang et al. (2021).

Acknowledgments

This research was funded in whole by the Austrian Science Fund (FWF) (10.55776/I5353). For the purpose of open access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission. The authors express their gratitude to the stakeholders who contributed to this project and the organizations they represented, including among others Christian Fritz from AREC, Christina Schlangen from ÖSF, Elisabeth Schwaiger and Hedwig Bartl from UBA, Martin Kappel from the Young Farmers Association, Barbara Köcher-Schulz and Michael Langanger from AMA, and Andreas Baumgarten from AGES among others. All participating organizations are listed in Table S1 in Supporting Information S1. We all thank the members of the international consortium for feedback and discussions during the project.

References

Bell, S., Berg, T., & Morse, S. (2016). Rich pictures: Sustainable development and stakeholders – The benefits of content analysis. *Sustainable Development*, *24*(2), 136–148. https://doi.org/10.1002/sd.1614

Binder, C. R., Feola, G., & Steinberger, J. K. (2010). Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. *Environmental Impact Assessment Review*, *30*(2), 71–81. https://doi.org/10.1016/j.eiar.2009.06.002

Bruckmüller, E., Hanisch, E., Sandgruber, R., & Weigl, N. (2002). Geschichte der österreichischen Land-und Forstwirtschaft im 20. *Ueberreuter*.

Chambers, J. M., Wyborn, C., Klenk, N. L., Ryan, M., Serban, A., Bennett, N. J., et al. (2022). Co-productive agility and four collaborative pathways to sustainability transformations. *Global Environmental Change*, *72*, 102422. https://doi.org/10.1016/j.gloenvcha.2021.102422

Chambers, J. M., Wyborn, C., Ryan, M. E., Reid, R. S., Riechers, M., Serban, A., et al. (2021). Six modes of co-production for sustainability. *Nature Sustainability*, *4*(11), 983–996. https://doi.org/10.1038/s41893-021-00755-x

Checkland, P. B. (1989). Soft systems methodology. *Human Systems Management*, *8*(4), 273–289. https://doi.org/10.3233/HSM-1989-8405

Chopin, P., Mubaya, C. P., Descheemaeker, K., Öborn, I., & Bergkvist, G. (2021). Avenues for improving farming sustainability assessment with upgraded tools, sustainability framing and indicators. A review. *Agronomy for Sustainable Development*, *41*(2), 19. https://doi.org/10.1007/s13593-021-00674-3

EC. (2022). Home—Eurostat. Retrieved from https://ec.europa.eu/eurostat

EC & DG AGRI. (2015). *The monitoring and evaluation framework for the common agricultural policy 2014-2020*. Publications Office. Retrieved from http://bookshop.europa.eu/uri?target=EUB:NOTICE:KF0415328:EN:HTML

EC DG AGRI. (2024). European commission | Agri sustainability compass. Retrieved from https://agridata.ec.europa.eu/extensions/compass/compass.html

Einarsson, R., Cederberg, C., & Kallus, J. (2018). Nitrogen flows on organic and conventional dairy farms: A comparison of three indicators. *Nutrient Cycling in Agroecosystems*, *110*(1), 25–38. https://doi.org/10.1007/s10705-017-9861-y

European Court of Auditors. (2020). Special Report 05/2019: Sustainable use of plant protection products: Limited progress in measuring and reducing risks.

FAO. (2022). FAO statistical database. Retrieved from https://www.fao.org/faostat/en/#home

Folberth, C., Sinabell, F., Schinko, T., Hanger-Kopp, S., Lappöhn, S., Mitter, H., et al. (2024). Integrating global comparability and national specificity in agricultural sustainability indicators through stakeholder-science co-evaluation in Austria—Supplementary materials. *Zenodo*. https://doi.org/10.5281/zenodo.14014894

Forbord, M., Schermer, M., & Grießmair, K. (2012). Stability and variety – Products, organization and institutionalization in farm tourism. *Tourism Management*, *33*(4), 895–909. https://doi.org/10.1016/j.tourman.2011.08.015

Gavrilova, O., Jonas, M., Erb, K., & Haberl, H. (2010). International trade and Austria's livestock system: Direct and hidden carbon emission flows associated with production and consumption of products. *Ecological Economics*, *69*(4), 920–929. https://doi.org/10.1016/j.ecolecon.2009.11.015

Gennari, P., & Navarro, D. (2019). The challenge of measuring agricultural sustainability in all its dimensions. *Journal of Sustainability Research*. https://doi.org/10.20900/jsr20190013

Glötzl, M., Schwaiger, E., Sonderegger, G., & Süßenbacher, E. (2011). Ökosystemleistungen und Landwirtschaft: Erstellung eines Inventars für Österreich. *Umweltbundesamt*.

Grant, M., Gilgen, A. K., & Buchmann, N. (2019). The rich picture method: A simple tool for reflective teaching and learning about sustainable food systems. *Sustainability*, *11*(18), 4815. Article 18. https://doi.org/10.3390/su11184815

Gudbrandsdottir, I. Y., Olafsdottir, G., Oddsson, G. V., Stefansson, H., & Bogason, S. G. (2021). Operationalization of interorganizational fairness in food systems: From a social construct to quantitative indicators. *Agriculture*, *11*(1), 36. https://doi.org/10.3390/agriculture11010036

Hakkarainen, V., Mäkinen-Rostedt, K., Horcea-Milcu, A., D'Amato, D., Jämsä, J., & Soini, K. (2022). Transdisciplinary research in natural resources management: Towards an integrative and transformative use of co-concepts. *Sustainable Development*, *30*(2), 309–325. https://doi.org/10.1002/sd.2276

Halpern, B. S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J. L., et al. (2022). The environmental footprint of global food production. *Nature Sustainability*, *5*(12), 1027–1039. https://doi.org/10.1038/s41893-022-00965-x

Hamm, M. W. (2009). Principles for framing a healthy food system. *Journal of Hunger & Environmental Nutrition*, *4*(3–4), 241–250. https://doi.org/10.1080/19320240903321219

Hanger-Kopp, S., Lemke, L. K.-G., & Beier, J. (2024). What qualitative systems mapping is and what it could be: Integrating and visualizing diverse knowledge of complex problems. *Sustainability Science*, *19*(3), 1065–1078. https://doi.org/10.1007/s11625-024-01497-3

Hendrickson, M. K., & James, H. S. (2016). Power, fairness and constrained choice in agricultural markets: A synthesizing framework. *Journal of Agricultural and Environmental Ethics*, *29*(6), 945–967. https://doi.org/10.1007/s10806-016-9641-8

Huber, R., Bartkowski, B., Brown, C., El Benni, N., Feil, J.-H., Grohmann, P., et al. (2024). Farm typologies for understanding farm systems and improving agricultural policy. *Agricultural Systems*, *213*, 103800. https://doi.org/10.1016/j.agsy.2023.103800

ILO. (2022). Ilostat - The leading source of labour statistics. *ILOSTAT*. Retrieved from https://ilostat.ilo.org/

Jung, M., Boucher, T. M., Wood, S. A., Folberth, C., Wironen, M., Thornton, P., et al. (2024). A global clustering of terrestrial food production systems. *PLoS One*, *19*(2), e0296846. https://doi.org/10.1371/journal.pone.0296846

Karner, K., Schönhart, M., Sinabell, F., & Mitter, H. (Eds.). (2022). *Resilience of the Austrian agricultural and food system—insights from the AT-Agri-SSPs*. https://doi.org/10.22004/ag.econ.329605

Lemke, L. K.-G., Beier, J., & Hanger-Kopp, S. (2024). Exploring procedural justice in stakeholder identification using a systematic mapping approach. *Environmental Science & Policy*, *162*, 103900. https://doi.org/10.1016/j.envsci.2024.103900

Lynch, J., Donnellan, T., Finn, J. A., Dillon, E., & Ryan, M. (2019). Potential development of Irish agricultural sustainability indicators for current and future policy evaluation needs. *Journal of Environmental Management*, *230*, 434–445. https://doi.org/10.1016/j.jenvman.2018.09.070

Magrini, A., & Giambona, F. (2022). A composite indicator to assess sustainability of agriculture in European union countries. *Social Indicators Research*, *163*(3), 1003–1036. https://doi.org/10.1007/s11205-022-02925-6

Malek, Ž., & Verburg, P. H. (2020). Mapping global patterns of land use decision-making. *Global Environmental Change*, *65*, 102170. https://doi.org/10.1016/j.gloenvcha.2020.102170

Mancini, L., Valente, A., Barbero Vignola, G., Sanyé Mengual, E., & Sala, S. (2023). Social footprint of European food production and consumption. *Sustainable Production and Consumption*, *35*, 287–299. https://doi.org/10.1016/j.spc.2022.11.005

Musacchio, A., Re, V., Mas-Pla, J., & Sacchi, E. (2020). EU Nitrates Directive, from theory to practice: Environmental effectiveness and influence of regional governance on its performance. *Ambio*, *49*(2), 504–516. https://doi.org/10.1007/s13280-019-01197-8

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., et al. (2020). Principles for knowledge co-production in sustainability research. *Nature Sustainability*, *3*(3), 182–190. Article 3. https://doi.org/10.1038/s41893-019-0448-2

OECD. (2023). OECD statistics. Retrieved from https://stats.oecd.org/

Opancar, C. (2014). AKIS and advisory services in Austria—Report for the AKIS inventory (WP3) of the PRO AKIS project. Retrieved from https://430a.uni-hohenheim.de/fileadmin/einrichtungen/430a/PRO_AKIS/Country_Reports/Country_Report_Austria_02_06_2014.pdf

Power, A. G. (2010). Ecosystem services and agriculture: Tradeoffs and synergies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2959–2971. https://doi.org/10.1098/rstb.2010.0143

Quemada, M., Lassaletta, L., Jensen, L. S., Godinot, O., Brentrup, F., Buckley, C., et al. (2020). Exploring nitrogen indicators of farm performance among farm types across several European case studies. *Agricultural Systems*, *177*, 102689. https://doi.org/10.1016/j.agsy.2019.102689

Rasmussen, L. V., Coolsaet, B., Martin, A., Mertz, O., Pascual, U., Corbera, E., et al. (2018). Social-ecological outcomes of agricultural intensification. *Nature Sustainability*, *1*(6), 275–282. https://doi.org/10.1038/s41893-018-0070-8

Regulation (EU). (2023). 2023/956 of the European parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism (text with EEA relevance), 130 OJ L (2023). Retrieved from http://data.europa.eu/eli/reg/2023/956/oj/eng

Scown, M. W., & Nicholas, K. A. (2020). European agricultural policy requires a stronger performance framework to achieve the Sustainable Development Goals. *Global Sustainability*, *3*, e11. https://doi.org/10.1017/sus.2020.5

Sinabell, F. (2014). Eine Auswahl von Nachhaltigkeitsindikatoren für die österreichische Land-und Forstwirtschaft im internationalen Vergleich. Retrieved from https://www.wifo.ac.at/publication/118689/

Sinabell, F. (2018). *Eine Auswahl von Nachhaltigkeitsindikatoren für die österreichische Land-und Forstwirtschaft im internationalen Vergleich. Aktualisierung 2018*. WIFO Studies.

Sinabell, F. (2022). *Agriculture and forestry in Austria in a new agricultural policy environment* (Vol. 14). WIFO Reports on Austria. Retrieved from https://ideas.repec.org//a/wfo/repoau/y2022i14.html

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology, `Translations' and boundary objects: Amateurs and professionals in Berkeley's museum of vertebrate zoology, 1907-39. *Social Studies of Science*, *19*(3), 387–420. https://doi.org/10.1177/030631289019003001

Statistics Austria. (2022). Agrarstrukturerhebung 2020. Retrieved from https://www.statistik.at/fileadmin/publications/SB_1-17_AS2020.pdf

Statistics Austria. (2023). Economic accounts for agriculture at national level. *Statistics Austria*. Retrieved from https://www.statistik.at/en/statistics/agriculture-and-forestry/agricultural-and-forestry-economy-and-prices/economic-accounts-for-agriculture/economic-accounts-for-agriculture-at-national-level

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., et al. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

Tubiello, F. N., Wanner, N., Asprooth, L., Mueller, M., Ignaciuk, A., Khan, A., & Moncayo, J. (2021). *Measuring progress towards sustainable agriculture*. FAO. https://doi.org/10.4060/cb4549en

Umweltbundesamt. (2022). 13th environmental control report (13. Umweltkontrollbericht. Umweltsituation in Österreich). Umweltbundesamt. Retrieved from https://www.umweltbundesamt.at/studien-reports/umweltkontrollbericht/ukb2022

Weitz, N., Strambo, C., Kemp-Benedict, E., & Nilsson, M. (2017). Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. *Global Environmental Change*, *45*, 165–173. https://doi.org/10.1016/j.gloenvcha.2017.06.006

Wiedmann, T., & Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, *11*(5), 314–321. https://doi.org/10.1038/s41561-018-0113-9

Wuepper, D., Le Clech, S., Zilberman, D., Mueller, N., & Finger, R. (2020). Countries influence the trade-off between crop yields and nitrogen pollution. *Nature Food*, *1*(11), 713–719. https://doi.org/10.1038/s43016-020-00185-6

Zaehringer, J. G., Schneider, F., Heinimann, A., & Messerli, P. (2019). Co-Producing knowledge for sustainable development in telecoupled land systems. In C. Friis & J. Ø. Nielsen (Eds.), *Telecoupling: Exploring land-use change in a globalised world* (pp. 357–381). Springer International Publishing. https://doi.org/10.1007/978-3-030-11105-2_19

Zhang, X., Ozturk, L., Folberth, C., Chivenge, P., Martinelli, L. A., Mabhaudhi, T., et al. (2022). Sustainable agriculture Matrix (SAM) consortium: A transdisciplinary and transnational network to guide the pursuit of sustainable agriculture. Fall Meeting 2022. Retrieved from https://agu.confex.com/agu/fm22/meetingapp.cgi/Paper/1098892

Zhang, X., Yao, G., Vishwakarma, S., Dalin, C., Komarek, A. M., Kanter, D. R., et al. (2021). Quantitative assessment of agricultural sustainability reveals divergent priorities among nations. *One Earth*, *4*(9), 1262–1277. https://doi.org/10.1016/j.oneear.2021.08.015

Zhen, L., & Routray, J. K. (2003). Operational indicators for measuring agricultural sustainability in developing countries. *Environmental Management*, *32*(1), 34–46. https://doi.org/10.1007/s00267-003-2881-1