Regional Environmental Change (2024) 24:171
https://doi.org/10.1007/s10113-024-02340-2

ORIGINAL ARTICLE

Co-production of sustainability indicators in a vulnerable South American agricultural frontier

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Received: 17 January 2024 / Accepted: 9 November 2024

Abstract
Deforestation linked to agricultural activities is a major sustainability concern. Planning towards sustainable agricultural landscapes in the (sub-)tropics requires indicators that capture the many aspects of social-ecological cost and benefit of agriculture. Agricultural production strategies are developed using the best available data and knowledge such as high-yield locations, distance to storage facilities, or certification bonuses. However, there is often a divide between sustainable production data generated by the scientific community and current data that are of interest to actors, such as those in the agribusiness sector. Here, we describe how the harmonization of crop production, conservation, and social data used by scientists and agribusiness is possible using a participatory exercise based on knowledge co-production (i.e., generation of knowledge in a collaborative way) of socio-economic and environmental indicators (such as agricultural production, logistics, or the location of indigenous communities). This was made available through an online decision support platform that facilitated the generation of sustainable entrepreneurial strategies. We tested this exercise for the social-environmentally vulnerable Argentine Chaco dry forest, subject to some of the highest rates of deforestation globally, mainly due to soybean production. The cooperation between participants of this exercise built a knowledge exchange network that was key for informing decision-makers and highlighted information gaps including agricultural productivity, accessibility of regions, and the vulnerability of rural communities. Our exercise may be applicable to other agricultural commodity frontiers and showcases the value of including actors' priorities in the design of indicators to ensure their policy impact and to achieve food systems' sustainability.

Keywords Co-design · Gran Chaco ecoregion · Investment strategies · Online-decision support tool · Soybean-trading companies · Actors

Introduction

Agricultural commodity production frontiers comprise areas of intensive agricultural production that tend to be located at interfaces with remote, natural, or semi-natural ecosystems. Thus, they face several sustainability

Communicated by Jacqueline Loos

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Published online: 28 November 2024

challenges, due to overlapping and colliding interests of agricultural production and conservation actions (Buchadas et al. 2022; Foley et al. 2011; Pendrill et al. 2022). A principal and important challenge for planners in these regions is defining management strategies to ensure a balance between production of high-value commodities and the preservation of rich biological and culturally diverse livelihoods (Fischer et al. 2006). This challenge is particularly important, because a substantial proportion of global farming and agricultural commodity production occurs in regions of high biodiversity and rich cultural livelihoods (Benton 2007) that also experience highest global rates of deforestation, defaunation, and social inequalities (Gardner et al. 2019; Hansen et al. 2013; Motta 2017; Oldekop et al. 2020).

To address these sustainability challenges, regional spatial planners need concise, purpose-driven data to make informed and effective strategic and management decisions. In this context, scientists play a crucial role in providing relevant information to regional planners and decision-makers (Meah 2019). However, there is a divide between the type of available scientific data and data needs of actors, such as spatial planners, NGOs, agricultural producers, and enterprises (Núñez-Regueiro et al. 2020; Rasmussen et al. 2017). For example, meanwhile spatial governmental planners may need quality of life or employment data (European Commission 2021), agricultural producers may need precision agriculture data boosted by AI (Artificial Intelligence), such as proximate humidity sensor measurements or yields (Rozenstein et al. 2024). Thus, there is an opportunity to foster multi-way interactions and processes of knowledge co-production to improve the socio-political impacts of decision-making (Fazey et al. 2014; Howarth & Monasterolo 2017; Young et al. 2014). Knowledge co-production is the integration and generation of information across disciplines, while ensuring a balanced weighting and influence of actors representation (Staffa et al. 2021; Tengö et al. 2017). It also supports the development of local and regional adaptation policies and their efficiency (Boon et al. 2019; IPBES 2022). Although current actors of knowledge co-production tend to include governmental planners, Non-Governmental Organizations (NGOs), and indigenous or local communities (Albuquerque et al. 2021; Euskirchen et al. 2020; Tengö et al. 2014), little progress has been made in understanding the decisions of enterprises that invest in the purchase of agricultural products and, therefore, their influence on global and local markets and potential regional-scale conversions of land cover and land use (Chambers et al. 2021; Malek & Verburg 2020). Moreover, the Sustainable Development Goal (SDG) 17, which focuses on strengthening partnerships for sustainable development, highlights the importance of improving science-industry collaboration as key factor in achieving the SDGs (Österblom et al. 2020).

There is, therefore, an emerging need to integrate knowledge across disciplines, sectors, and actors to address sustainability challenges in the production of agricultural commodities (Allen et al. 2019; Care et al. 2021; Fazey et al. 2014; Raymond et al. 2010). The first step in this process is to bridge the gaps between data generation, actors' data priorities, and communication between scientists and various actors (Balvanera et al. 2020; Cash et al. 2003; Zheng et al. 2019). Previous studies have shown that dynamic processes, such as participatory approaches, which facilitate the integration of disciplines and communication in the co-production of knowledge and knowledge networks, lead to coherent results accepted by all actors, with positive policy impacts (Cash et al. 2003; Lang et al. 2012; Toomey 2023). Moreover, bottom-up approaches that include local and relevant knowledge in decision-making processes legitimate knowledge co-production and ensure the acceptance of planning strategies (IPBES 2022). Thus, the aim of this study is to test the relevance and value of interdisciplinary knowledge integration and transdisciplinary communication and collaboration using a participatory exercise to advance the contribution of science to sustainability challenges in agricultural production frontiers.

We collaborated in an interdisciplinary participatory exercise between scientists, technicians, conservation NGOs, governmental bodies, agricultural producers, and soybean trading enterprises that developed and prioritized cross-sectional and customized data, filling the need for spatial information by trading enterprises. The main goal was to inform the planning of sustainable sourcing of agricultural commodities within the purchasing strategies of agricultural trading enterprises in a major global deforestation frontier, the Argentine Chaco ecoregion. This region represents a complex social-ecological system, characterized by remaining forest cover that is home to local-rural communities, as well as intensive soybean and livestock production (Baumann et al. 2022; P. D. Fernández et al. 2024; Levers et al. 2021). Balancing conservation and agricultural production is challenging in this context (Kuemmerle et al. 2017) especially when communication barriers (i.e., lack of common language), limited contemporary participation in meetings, or trust issues exist between different regional actors. Nonetheless, recent global demands for sustainable agricultural production are influencing the inclusion of biocultural diversity and ecosystem services in the planning of the agricultural strategies in this region (TNC 2021). Thus, to overcome these challenges, regional actors from the conservation and agricultural production sectors are then faced with the need for interacting and co-producing knowledge to achieve a sustainable agricultural production.

The data generated from the participatory exercise were used to develop relevant sustainable economic and social-environmental indicators. These indicators were centralized in an open online platform (see SI 1) and facilitated the generation of entrepreneurial strategies to leverage sustainable produce sourcing according to actor's interests. This resulted in a novel contribution to scientific knowledge, as researchers were previously unaware of the data needs and priorities of trading enterprises. The large collaborative effort enabled researchers and NGOs to develop and customize data relevant to trading enterprises, while adhering to conservation legislation, such as land-use zonation. A strength of our exercise was the inclusion of trading companies in knowledge co-production which has so far seldomly being done in participatory processes. In this work, we described the participatory process in the form of workshops (see the "Co-production of sustainable agriculture indicators (workshops)" section) that highlighted essential information for commodity production trading companies in their sourcing and purchasing strategies. Additionally, we shared insights that may contribute to informing policy strategies and guiding future scientific studies to prioritize regional management approaches for sustainable agricultural production in commodity frontiers.

Study area

Deforestation in South America is a global phenomenon mainly driven by the production of agricultural commodities (e.g., palm oil, soybeans) and with important impacts on the environment and local livelihoods (Armenteras et al. 2017; Maxwell et al. 2016; Pendrill et al. 2019). This translates into significant challenges associated with balancing agricultural activities in the continent and the preservation of the biological and cultural diverse livelihoods (Leclère et al. 2020). The Gran Chaco is a dry forest that encompasses around 1 million km^2 located between Bolivia, Paraguay, Argentina, and Brazil (Olson et al. 2001) (Fig. 1).

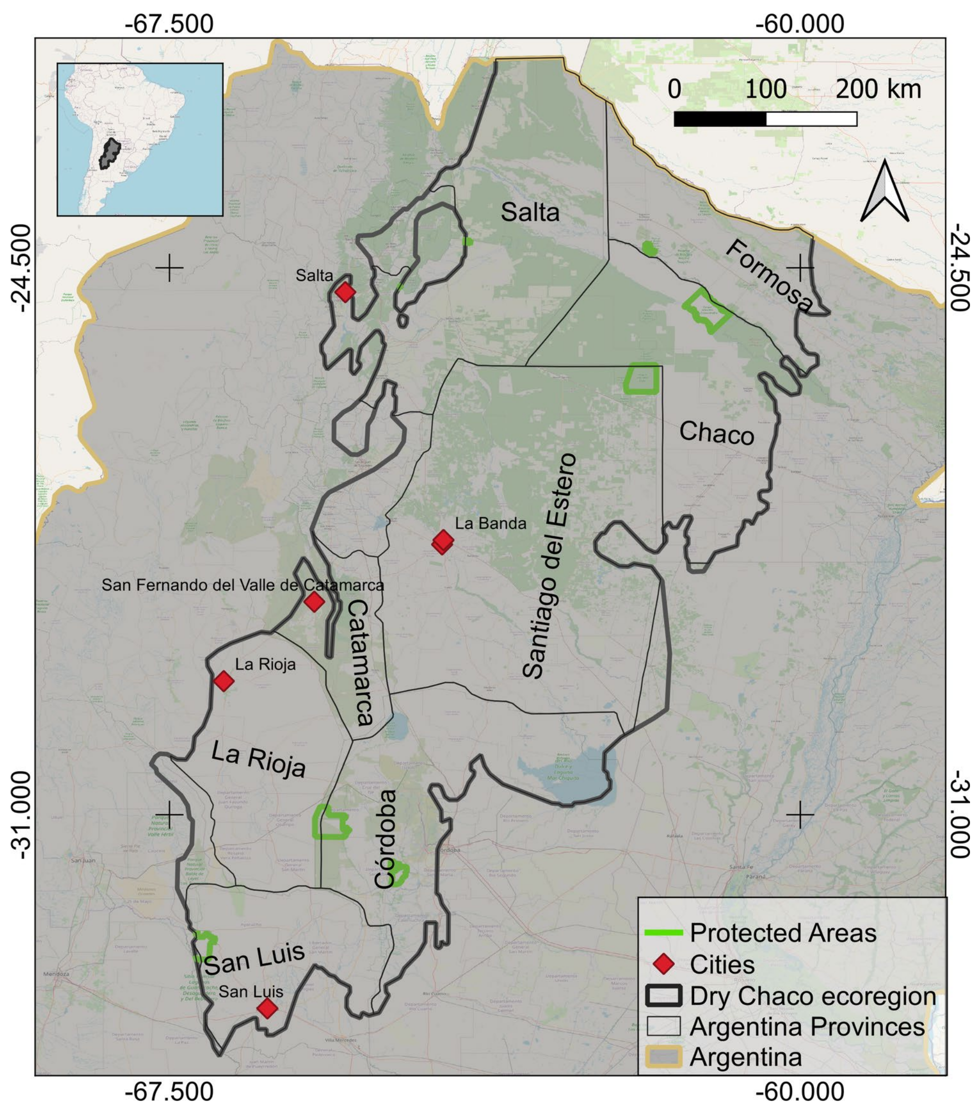

Fig. 1 The Argentine Chaco study area (Olson et al. 2001) with some reference features. The base map uses Open Street Maps

It holds rich biodiversity and is home to a diverse array of indigenous communities (Kuemmerle et al. 2017; The Nature Conservancy (TNC) et al., 2005). However, it has also experienced one of the highest deforestation rates of the world in this century (Hansen et al. 2013), mainly due to the production of soybean and cattle ranching activities (Baumann et al. 2022). Global trading companies have established business in the region with special focus in Argentina, where soybean production and exports are the third largest in the world (FAOSTAT 2019). The Argentine Chaco experienced a rate of forest loss of 4700 km^2 per year between 1977 and 2010 (Piquer-Rodríguez et al. 2015), and currently has 3,000,000 ha under cultivation for soybean production in areas that were originally forest or grasslands (i.e., 54% of its cultivated area in 2019–2020) (INTA 2020; Piquer-Rodríguez et al., 2018). In Argentina, there is also a legal zoning in place that limits regions to specific levels of agricultural activities or protection within three traffic-light-colored zones: (1) red areas under protection, (2) yellow areas where only sustainable land uses are allowed, and (3) green areas where deforestation for any land use is legally allowed (the Forest Law 26331, 2009).

Methods

Drawing on findings of the project Agroideal ® in the Argentine Chaco (www.agroideal.org, The Nature Conservancy (TNC 2019), see SI), which during 2018 and 2019 brought together participants from academia, trading enterprises, banks, technical organizations, oil chamber, governmental and non-governmental organizations in twelve workshops (see the “Co-production of sustainable agriculture indicators (workshops)” section), this paper addresses how to co-develop relevant data to fill in knowledge gaps to inform sustainable decision-making in the context of agricultural commodity production. The project Agroideal ® in the Argentine Chaco developed an online public platform to be used as an intelligent territorial tool to promote the sustainable planning of the agricultural commodity sourcing of trading companies (hereafter: traders). It centralized solid information about agricultural productivity, territorial accessibility, the social context, and the environment of the Argentine Chaco (see SI1 for more information on the functioning of the platform). By building on the results of the twelve workshops, which were used to prioritize the data available in the online platform, our work presents findings and discusses the role of transdisciplinary approaches under the following themes: (1) knowledge co-production, (2) identification of data gaps for academia and administrations based on the needs of agribusiness enterprise, and (3) lessons learned to provide accessible and relevant information to potential users and policy makers.

Participants in the co-production process

Approximately 50 people from 35 different organizations participated in different stages of the knowledge co-production process that involved personal and virtual meetings, interactions by email, surveys, platform testing, and workshops (Fig. 2). There were two original working groups of (1) NGOs and social-environmental experts (i.e., academics, technical organizations, government and agricultural producer consortia) and (2) traders, but both were integrated into a common working group after the first separate meeting to ensure interconnectedness, integration of positionalities, engagement, and commitment (Howarth & Monasterolo 2016; Staffa et al. 2021). Twenty-nine organizations participated during the first year in several meetings and 20 organizations did it in the second year. These included NGOs (e.g., The Nature Conservancy, Fundación Vida Silvestre-FVSA, ProYungas), academics (e.g., National University of Tucumán-CONICET), one bank, national oil chamber, governmental sector (i.e., the National Agroindustry Ministry of Argentina), traders (e.g., Cargill, Dreyfus, Bunge), and technical organizations such as agricultural technology organizations (National Institute of Agricultural Technologies, INTA in Spanish), consortium of agricultural producers (e.g., AAPRESID), technical companies (e.g., Agroideal), agro-consulting (e.g. Terea Argentina), and RTRS-Round Table on Responsible Soy Association Argentina (Fig. 2). The active participation of both, the business and academic sectors, enabled the identification of the most relevant indicators for the development of sustainable and productive investment plans with a balance between economic and conservation objectives to avoid biases (Engler et al. 2019). The authors of this article held various roles, primarily as organizers (NGOs) and as expert researchers within the working group (see details below and SI1).

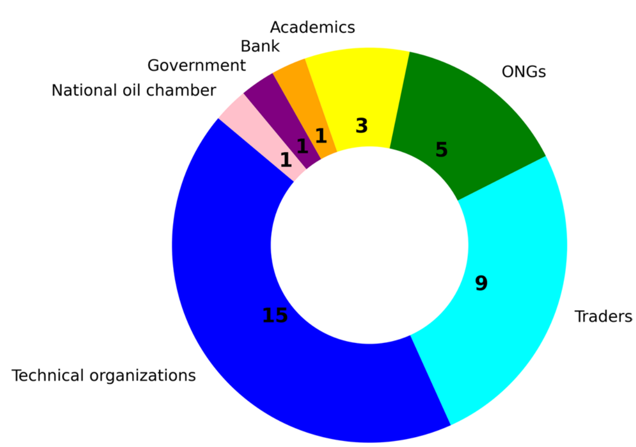

Fig. 2 Representation (in total number) of the different sectors that participated in the Agroideal.® workshops in Argentina 2018–2019

Co-production of sustainable agriculture indicators (workshops)

Workshops lasted one full day and were held every 2–3 months, during 2018 and 2019. Workshop participants were invited based on their thematic expertise (i.e., environmental, social, or economic) or their practice experience (i.e., decision-makers in administration or industry). Invitations to participate were done by organizers to include all traders present in the area, as well as relevant actors from the environmental sector with affinity to the topic and technical power to produce and retrieve data, such as FVSA or CONICET (National Research Council). Initial participants suggested the participation of other institutions that were not originally present such as INTA (who were key in the development of soybean productivity data) or the UNJU (National University of Jujuy), key in developing the social vulnerability indicators (see SI 2). The majority of participants remained involved for the 2 years (29 participants in 2028 and 20 in 2019). Participants were first split in two groups: (1) traders and (2) NGOS and social-environmental experts, but after a first meeting both groups were merged into one single working group that stayed working together and mixed during the project (Fig. 3). Each workshop was goal oriented (Fig. 3) and adopted a semi-structured approach, with a structured questionnaire to gather objective individual perspectives at the beginning, and then opened discussions to maximize interactions (for questionnaires, see SI3-1:4) (Norström et al. 2020). Discussions were analyzed on site by organizers and during breaks leading to decisions for the next steps at the end of the meetings. Datasets were often sent to participants for review before the subsequent meeting, where justified decisions regarding data inclusion in the platform would be made. Workshops' design ensured several feedback rounds between the meetings within one phase, but also between phases (Fig. 3, see feedback forms in SI 3). Results and discussions were drafted as a workshop summary which was then shared with participants to review and comment on. The workshops to identify important indicators for their inclusion in the platform had four phases (with the number of workshops between brackets) and covered the following topics (Fig. 3):

Phase 1: Preparatory workshops (4 workshops):

The four workshops were structured around these *objectives*: (1) show the existing Brazilian system (Agroideal Brazil) and share feedback, (2) consult existing layers (i.e., spatial data) and indicators (see SI 3), (3) generate and present new indicators, (4) present the final system.

The main *goals* of these workshops were as follows: (1) selection of important data to be included as layers or indicators in the platform due to their relevance for all participants (i.e., social, environmental, and productive information, see SI 2), (2) detection of data gaps for either enterprises, academia, or administration sectors because important differences in data relevance between academics or NGOs and traders became apparent. Researchers from CONICET, INTA, universities, and NGOs generated or provided information directly on demand to fill detected data gaps based on actors' views and needs (see the "Data needs included in the platform" section), (3) data sharing agreements and data publication: participants agreed that existing data (e.g., biological corridors), or data which were generated for this

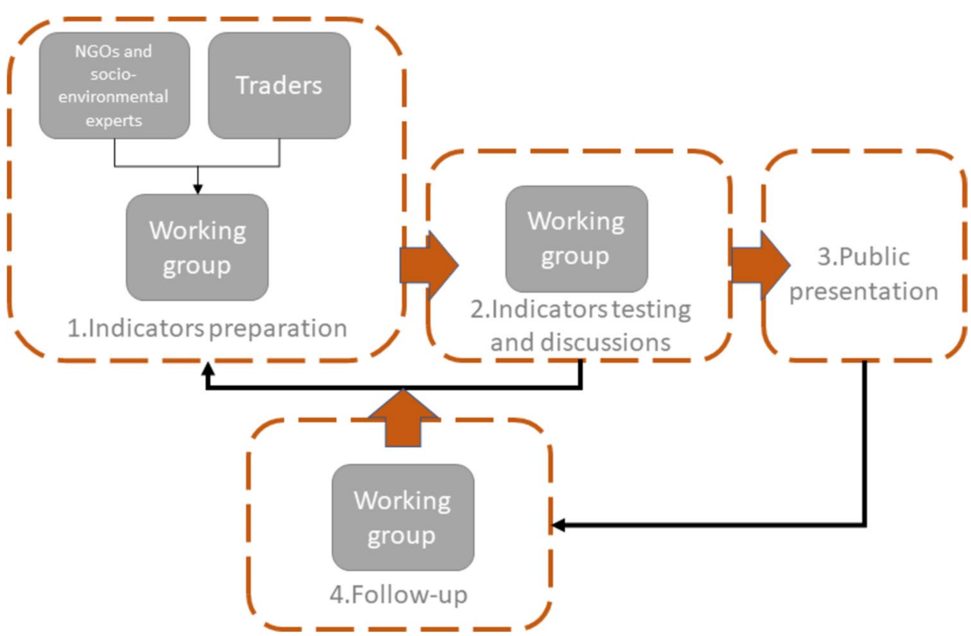

Fig. 3 Schematic representation of the workshops' iterative structure in 4 phases

project (e.g., distances to the Port of Rosario), would be available in the platform for the generation of strategies (see SI 2). The metadata to include in the newly generated data was also agreed among the participants. All participants collaborated in sharing existing information either from academia (e.g., yield productivity, see SI 2) or from traders (e.g., soybean storage) and by allowing its publication in the platform.

Phase 2: Testing and discussion workshops (4 workshops):

The main *goals* of these workshops were as follows: (1) validation of potential new data to be included/considered in the platform based on the relevance of the institution generating the information (i.e., reliance and prestige), data currency (i.e., generation date), and potential for actualization, (2) internal data testing and adjustments of a trial version in an online platform prototype. Traders were asked to test the online platform according to their decision-making needs to detect inconsistencies. Then, participants adjusted the social-environmental and economic indicators based on discussions about specific strategies developed in the platform.

Phase 3: Public presentation workshop (1 workshop):

Results from workshops on indicator co-production were disseminated using the final online platform in August 2019 (Fig. 3). The first version of the platform Agroideal® for the Argentine Chaco was then launched in Buenos Aires, with 31 participants and broadcasted through several media. Afterwards, the platform was presented to a broader potential target audience (e.g., investors, research organizations, and developers of related platforms such as Trase – https://trase.earth/).

Phase 4: Follow-up workshops (3 workshops):

In-person and virtual meetings with the working group continued periodically to improve the information available (Fig. 3). The main goal of these workshops was to continue discussing and testing new datasets that were useful to the participants and informed by the feedback received from the public presentation. It was decided that a future second update of the Agroideal® project should incorporate novel information such as multi-thematic social census data. The platform counted with 866 visits with a return rate of 1.5 (i.e., once someone visited the online platform, they returned one and a half times), in July 2020. Currently, Agroideal® is under structural revision from national partners EMBRAPA-The Brazilian Agricultural Research Corporation (Brazil) and INTA (Argentina) and the website was momentarily not available at the time this manuscript was written.

Results of the data co-production process

The results of the workshops are described in a coherent form for the first time in this article. They describe data needs on the planning of sustainable agricultural production strategies that were detected by participants. These data were co-produced by the NGOs and academic participants and included in the online platform. The results of this co-designed exercise were unique because they arise from integrated participatory bottom-up approaches from the beginning of the project, which is seldomly done in large interdisciplinary consortia.

Data needs included in the platform

The Agroideal® platform for the Argentine Chaco comprised 39 layers of data (December 2021) distributed among Protected and Special Areas, Political and Administrative boundaries, Agriculture, Infrastructure and Vegetation Cover categories, and 22 indicators (13 of Economic opportunity and 9 of Social-environmental risk) (Table 1, SI 2). All data in the platform can be displayed as **layers**, but only those layers that were most relevant for participants to determine economic opportunities and social-environmental risk were included as **indicators**, meaning that it is data that can be used to calculate risks and opportunities in strategies (SI 2). In this manner, the indicators contribute to making sustainable agricultural decisions in the region by being integrated into strategies that minimize the social and environmental impacts of investments in soy. Traders can adopt regional development strategies that simultaneously account for the fulfillment of their economic objectives, as well as, their social-environmental commitments (see SI 1 for a traffic color representation of risk strategies Fig. S2). To the best of our knowledge, the platform was used by approximately 400 actors to locate sources of soybean wholesale, according to the strategic priorities of businesses (as of December 2021). The platform may also be used to select land for sustainable development taking into account user preferences or local zoning legislation. The platform provides balanced information on environmental conditions, zoning regulations, society characteristics, and economic-development data (see SI 1 for details on the platform function and data content).

The analysis of workshop discussions identified four dominant key data needs for decision-making in enterprises, administration, and for researchers and NGOs to ensure the delivery of sustainable decisions in agricultural commodity production (SI 2): (1) soybean productivity data (important for traders), (2) regional accessibility data

Table 1 Final set of indicators identified and developed by the working group. Their integrated use with the set of blocked layers (see SI 2) makes then a compendium of indicators that can be used for the sustainable planning of an agricultural region. Note that areas transformed between 2008 and 2017 do not comply with several commodity certification standards. Inquiries about data availability should be sent to http://siga.proyungas.org.ar/ or siga@proyungas.org.ar

INDICATORS	Data/layers
Socio-environmental risk	
Environmental	Vegetation cover, biological corridors, and areas of conservation importance, priority areas for conservation, potential hydric erosion (exceeding 30 tn/ha/year), agricultural or pasture areas transformed between 2008 and 2017, soybean and other crops in the rotation cultivated on Categories III areas of the Forest Law deforested between 2008 and 2017, low yield and high variability risk
Social	Indigenous communities: location and vulnerability, social vulnerability
Economic opportunity	
Logistics	Distance to Rosario's port, workforce population
Special areas	Areas with restauration potential
Agricultural production	Soybean area (2000/2001, 2006/2007, 2017/2018, 2018/2019, 2019/2020), soybean yield, attainable soybean yield, coefficient of variation of attainable soybean yield
Soy expansion	Agricultural or pasture areas transformed before December 2007, corn or cotton planted area (2000/2001, 2006/2007, and 2017/2018), area of other crops in rotation with soybean (2018/2019, 2019/2020)

(important for traders), (3) location and vulnerability of indigenous communities (important for NGOs and the scientific community), and (4) social vulnerability (important for NGOs and the scientific community). More specifically, a total of 22 indicators encompassing environmental, social, logistics, agricultural production, and soybean expansion variables were agreed upon by participants as crucial for informing sustainable agricultural decisions in the region. Consequently, these indicators were incorporated into the platform (Table 1 and SI 2).

It is important to remark that data about protected and connectivity areas was included by default in the platform to ensure compliance with national conservation regulations (Table 1 and SI 2). For example, soy produced in areas converted from native forests prior to December 2007, when the Forest Law was passed (Law 26,331, 2007), fulfill Round Table on Responsible Soy Association (RTRS) certification requirements. Unfortunately, despite the aim to include a balanced range of data, not all trader sustainability requirements, including compliance with soybean certifications (such as RTRS), could be included in the first version of the platform; but further revisions will integrate additional data (see below). Overall, our study showed that the participatory exercise led to great inclusion and representation of actors' views in potential decision-making, through compromise and agreement.

Information gaps and co-produced data

Important information gaps at detailed spatial scales and across the Argentine Chaco were identified by the working groups and subsequently generated or customized by the technical-scientific working group (i.e., CONICET, INTA, and Agrosatellite) in the form of indicators (Table 1 and SI 2). Data gaps were detected in preparatory workshop (the "Co-production of sustainable agriculture indicators (workshops)" section) by using questionnaires where actors (i.e., traders, NGOS, government, and scientists) informed of their data needs after the academic sector presented existing spatial data for the study region (see questionnaires in SI 3).

The most relevant data gaps that were detected and that lead to the generation of data for actors comprised:

1) Soybean productivity data:

Used for the identification of potential areas for soybean cultivation, using indicators of *Actual soybean cultivated area* and *Attainable and potential soybean yields (SI 2)*. The comparison of these indicators identifies locations where it is possible to increase productivity to maximum achievable yields, considering:

a. *Actual soybean cultivated area:*

The company Agrosatellite produced an accumulated crop cover map of soy, corn, and cotton cover in the summers of 2000–2001, 2006–2007, and 2017–2018 using a visual classification of Landsat images. Data from 2018–2019 and 2019–2020 used cropland maps of INTA (INTA 2020) comprising two layers (soybean, and corn and cotton) with indicators of accumulated area under soybean production and accumulated area of potential soybean expansion which can occur on areas growing corn and/or cotton.

b. *Attainable and potential soybean yields:*

Experts from INTA (Buenos Aires Norte) and the University of Buenos Aires estimated attainable and potential soy yields. Attainable soybean yield refers to the maximum achievable yields under rain-fed conditions, considering inter-annual variability in climate and soil conditions, soybean varieties, and land management (e.g., sowing date) as inputs for the CROPGRO model (Hoogenboom et al. 2015) in the CASANDRA platform (Rolla et al. 2016). Potential soybean yield was estimated in a similar way; however, water limitation was not considered.

2) Regional accessibility data:

Used for the identification of transportation costs of agricultural produce. It used indicators of distance by road to soybean storage facilities (*silos*) and to the distribution port of Rosario (SI 1). Distances were based on the 2010 road network and a network analysis of average distance in km (Piquer-Rodríguez et al., 2018) from any cell centroid of the Chaco grid (12×12 km^2) to soybean storage facilities in semi-concentric ranges of 20, 100, 200, and 300 km and to the port of Rosario, that is the main export hub for commodities in Argentina (Table S1).

3) Location and vulnerability of indigenous communities:

Used for the identification of *socially sensitive areas* where to avoid production strategies by visualizing and making available information on living conditions and educational background of communities in one single index of vulnerability. Current locations of indigenous communities from the National Institute of Indigenous Affairs - (INAI, in Spanish) were complemented using other sources (i.e., provincial organizations and local specialists) and new field surveys (García Moritán & Malizia 2022). Updated locations included 680 mapped communities with major concentrations in the provinces of Formosa, Chaco, and northeast of Salta (70%). The ProYungas Foundation (NGO) calculated vulnerability per community using non-hierarchical cluster analysis (k-means) of the variables detailed in Table S1.

4) Social vulnerability:

Used to identify *socially sensitive areas* for the entire Argentine Chaco. The ProYungas Foundation (NGO) calculated social vulnerability at the scale of census radii in 2010 (c. 300 homes per radii for 8152 radii) using non-hierarchical cluster analysis (k-means) to ordinate 16 vulnerability variables shown as important in a Principal Components Analysis (Table S1). Radii in group 4 experienced highest vulnerability conditions (i.e., highest average values of vulnerability variables).

Applicability of integrated co-produced data

The integration of a broad range of co-produced thematic datasets (see SI 2) that allowed the visualization of strategic planning scenarios offered a high and versatile visual application/result covering the needs of different users, in terms of developing sustainability strategies. For example, having an integrated and transdisciplinary dataset could minimize social and environmental impacts of investments in soy, because soybean trading companies could adopt regional development strategies that simultaneously accounted for the fulfillment of their economic objectives, but also their social-environmental commitments (see SI 1).

An important outcome of this integrated co-production exercise was that users other than traders, including societal or conservation NGOs, could also benefit from publicly available data to answer questions, such as "Among the departments (i.e., second-order political division in Argentina) with the greatest cultivated area and yields of soybean, which ones exhibit the highest levels of compromised connectivity in priority conservation areas?" or" Which areas require more intensive monitoring to minimize the social risk associated with the presence of indigenous communities?".

To address the first question, data on departments with the largest area of soybean cultivation in the Chaco ecoregion and spatial data on biological corridors and priority areas for conservation could be integrated (Fig. 4). These layers of information revealed that the majority of departments with greatest areas of soybean cultivation in the Chaco (2018 – 19) overlapped with areas that are crucial for conservation. In response to the second question, analysis of data on the number of indigenous communities in the target departments revealed that these communities are present in all ten departments with the highest areas of soybean cultivation (2018–2019), with a particularly high concentration in the department of General San Martin, Salta (Fig. 4). These findings (Fig. 4) enable, for example, the prioritization in the allocation of funding for sustainable development projects within these departments, informing decisions on where to protect biological corridors or implement measures for social cohesion to reduce vulnerability. Answering these questions was not possible before because such data was not publicly available. This information is now accessible through the Agroideal® platform that currently integrates conservation and agricultural production data, accessible to a variety of stakeholders involved in agricultural frontiers.

Discussion and recommendations

In order to create opportunities that inform adaptive governance and facilitate resilient decision-making, it is important that integrated transdisciplinary approaches are used for the

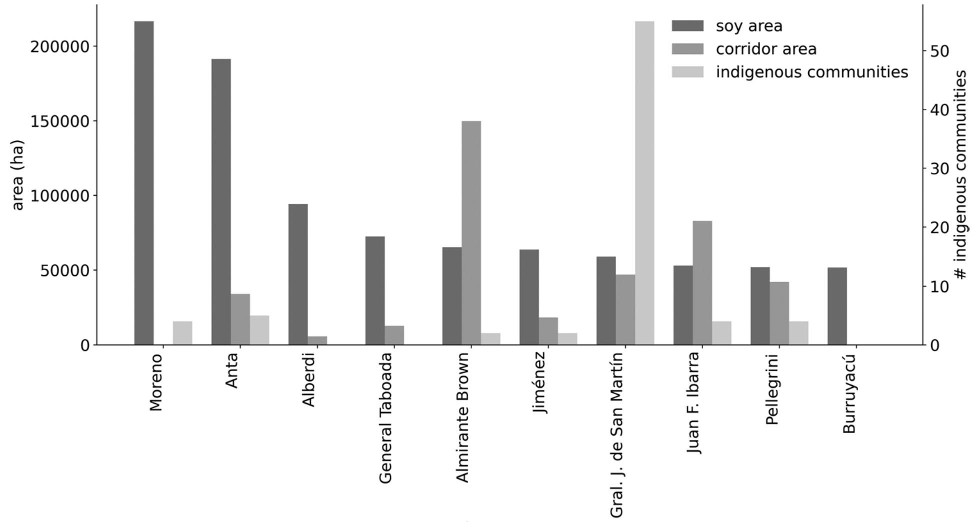

Fig. 4 Areas of soybean cultivation and biological corridors with priority areas for conservation (left y axis in ha) and the number of indigenous communities (right y axis), in the 10 departments with the greatest areas of soybean cultivation in the Argentine Chaco Ecoregion

study of complex systems and their interactions (Cosens et al. 2021). In this context, knowledge co-production is key in addressing sustainability challenges to support sustainable transformations from an inclusive approach (Norström et al. 2020; Staffa et al. 2021).

Here, we have demonstrated that by forging transdisciplinary knowledge co-production through the inclusion of views of industry decision-makers (i.e., traders), researchers, NGOs, and policy makers, the generation of consensual indicators for sustainable agricultural production is possible. The results from the participatory workshops held in Argentina identified four key information gaps detected by participants and then included in an online spatial planning platform used for sustainable decision-making of agricultural activities in the Argentine Chaco. In this section, we discuss lessons learnt and suggest recommendations for consideration when designing participatory exercises for knowledge co-production in dynamic agricultural settings.

Lessons learned from knowledge co-production workshops

From a management perspective, we demonstrated how participatory exercises can be used for the co-production of knowledge in building decision-making tools that support the sustainable management of a South American agricultural commodity production frontier. By including actor's knowledge and data priorities, key weaknesses, that potentially hamper current policy design and applicability, can be addressed and the usability of data be optimized (Kirchhoff et al. 2013; Lambin et al. 2014). From a scientific perspective, we showed how the inclusion of different types of knowledge (i.e., actor's views) is important to ensure the legitimacy of the research exercise (Fernández 2016; Game et al. 2015; Sala & Torchio 2019; Tengö et al. 2014). This proactive and participatory exercise was a win–win process for the diversity of actors involved and proved effective in bringing together different sectors that play an important role in shaping the landscape of an ecoregion with one of the highest global deforestation rates (Buchadas et al. 2022; Hansen et al. 2013). The participants generated essential information to feed decision-making processes for traders and strengthened cooperation among the participating organizations (Table 2). On the one hand, participants learned about priorities in decision-making at the enterprise and political level, a key step for influencing evidence use into practice (Oliver & Cairney 2019). On the other hand, participants also got to understand interests of researchers and their methodological approaches, important in bridging science-policy interfaces (Table 2). Moreover, the co-production process promoted research and scientific-knowledge exchange networks between the participating organizations. Participants stayed in contact during the duration of the workshops and reached out to peers with questions during the generation of data, for example. These networks were facilitated by the constant presence of scale-crossing brokers (Rölfer et al. 2023), ensuring a trust-building process among participants that allowed for the acceptance and integration of diverse perspectives, due to the construction of effective and safe professional relationships (Boon et al. 2019; Staffa et al. 2021). Such actively built up networks, arising from participatory approaches and shared conceptualizations, are more likely to last long and be fruitful (R. J. Fernández 2016).

Overall, scientists benefited from shared knowledge on the enterprise investment priorities that improved their understanding of the regional land-use systems and allowed them to witness the application of their research findings in the development of trader strategies (Table 2). Similarly, traders gained from this participatory exercise, because they felt "the platform was important in the long-term planning of

Table 2 Summary of main benefits gained per actor group

Actor	Benefit	Description
Traders	Data, knowledge	• Learning about priorities in decision-making at the political level • Obtainment data which contributed to strengthening their strategical planning • Understanding interests of researchers and their methodological approaches
Technical organization	Knowledge, application	• Learning about priorities in decision-making at the enterprise and political level • Understanding interests of researchers and their methodological approaches • Application of their technical work/results
Government	Data, knowledge	• Learning about priorities in decision-making at the political level • Obtainment data which contributed to their strategical planning • Understanding interests of researchers and their methodological approaches
Academia	Knowledge, application	• Learning about priorities in decision-making at the enterprise and political level • Acknowledgement of data needs from enterprises for decision-making • Application of their research findings
Conservation/social NGOs	Knowledge, application	• Learning about priorities in decision-making at the enterprise and political level • Application of their technical work/results

the company" and "it helped strengthening the analyses and evaluations of the commercial team, because it integrates information on production and environment" (Bunge Brasil, pers. comm. 2020). See Table 2 for a summary of main benefits gained per actor group.

Learning outcomes related to participatory exercises

A number of learning outcomes arose from the participatory exercise, principally from the organization of the meetings, selection of participants, and dealing with different stakeholder interests, including finding compromises. For example, we found that *funding* should not be underestimated when organizing participative transdisciplinary workshops, because the iterative process required multiple meetings that involved actor-time and financial support for the attendance in person (9 meetings) and online (3 meetings) and costs associated with the generation of data and specific indicators by research institutes and technical companies. Creating groups of actors with similar information needs and decision contexts increased the efficiency of interactions (Kirchhoff et al. 2013). The financial investment was worth it because of the formation of a non-hierarchical team of actors (thanks to regular in-person contact), that was able to communicate transparently after understanding the socio-cultural context of participants, reached consensus in their decisions and

Table 3 Recommendations for participatory knowledge co-production in commodity agricultural productive regions which can bridge barriers in knowledge co-production

Barriers in knowledge co-production	Main recommendation for knowledge co-production	Description
Diversity of participants	ENSURE the DIVERSITY of PARTICIPANTS	Ensure the transdisciplinary and cross-sectorial participation of actors, with special emphasis on regional-level government and purchasing departments of trading companies
Data needs vs. data availability/accessibility	PROMOTE BOTTOM-UP CO-DESIGN	Facilitate the co-design and co-production of tools and data, including the acquisition and integration of social data and commodity productivity data
Communication, participation, and trust	SEEK IN-PERSON PARTICIPATION	Invest in and facilitate recurrent in-person meetings to ensure fluid communication and active participation of actors that represent a diversity of disciplines
	BUILD-UP LOCAL CAPACITY	Broaden actor's use of tools, by building local capacity with trader marketing departments and local sectors, such as farmers and administrative departments

facilitated the generation of ideas (Scheffer 2014; Toomey 2023) (Table 3).

The selection of *participants* was prioritized to include a varied array of actors (government, academia, NGOs, industry), which ensured transdisciplinary collaborations, with a particular requirement for the presence of representatives from trading companies (Toomey 2023) (Table 3). While the platform primarily addressed the needs of trading companies, incorporating perspectives from a wider spectrum of government entities in future iterations would enable the integration of regional-scale policies and potential investments. In our exercise, only two participants represented local government. Yet, ensuring government representatives participation in such events it is a known challenge (Tschanz et al. 2022). Thus, the policy impact of the platform could be improved, by securing greater participation from government sectors.

Importantly, we suggest a greater emphasis on the holistic needs of *industry* that would also ensure greater long-term engagement of companies (i.e., "highway" sensu (Österblom et al. 2020), by ensuring cross-company participation, including purchasing decision-makers (e.g., marketing teams) and agricultural value-chain responsible (e.g., sustainability teams). In our exercise, workshops tended to be attended by a sustainability representative of trading companies, but not a marketing delegate. Although trader participants were in constant, but remote, contact with their marketing team, their in-person presence would have increased the agility of some decision-making, such as prioritization of data (Table 3).

Dealing with actor's data interests, compromise resolution, and risk perception

Finding compromises in participatory processes is a key challenge that scientists face. In our case, while there was a clear consensus in the inclusion of common data in the online platform (e.g., protected areas, soybean yield, and native forest legal protection), other datasets not included in the platform were subject to discussion. For example, traders demanded data on soy production efficiency, such as potential soybean yield (see the "Data needs included in the platform" section), accessibility to ports and storage facilities by road (see the "Data needs included in the platform" section), and environmental conditions, such as soil erosion due to hydrological processes or deforestation, related to dates relevant to their own corporate soybean sourcing policies and sustainability certification schemes (e.g., 2007 for RTRS certification, see SI 2). These datasets were developed by the working group to cover these detected data needs. Accessibility by railroad was an interesting dataset for traders, but was not included at the time of discussions because it would have required the development of scenarios of future access by railroad that was outside the scope of the project. Still the knowledge co-created was very valuable for participants because it signaled a diversity of priorities in developing sustainability approaches (Table 2). A follow-up study which is both critical and evaluative in the form of an online survey to understand the usage of the online data and the platform is planned as soon as the platform is up again.

Risk perception plays an important role in co-production processes that involve trade and can limit participation and action-taking (Miller & Wyborn 2020). Through the use of traffic-light color coding (see SI 1) to emphasize the strengths of specific data types, participants who initially regarded certain data (e.g., social data) as risky came to accept its inclusion in the platform. During the data selection process we observed, social data perceived as highly relevant for academics and NGOs, yet was perceived as potential triggers of conflicts, community vulnerability, or sensitive situations, by trading companies. For example, we found there were contrasting views among trading companies on the prioritization of the use and inclusion of social data in company strategies, due to the perception by industry of the risk posed by soybean production to indigenous community vulnerability. Indeed, the topic of risk perception is complex because data that may be perceived as a risk, such as environmental and social data, have the potential to become an opportunity under sustainable production or purchasing strategies via a contribution to the work force or the delivery of ecosystem services, such as pollination, soil retention, and water purity (Brosi et al. 2008; Morales-Reyes et al., 2018).

Conclusions

Recent global demands for sustainable agricultural production influence the integration of bio-cultural diversity and ecosystem services into agricultural purchasing strategies. Consequently, actors who previously operated in isolation are now compelled to collaborate to address these sustainability requirements within agricultural production and procurement chains. This paradigm shift has revealed new knowledge gaps, specifically in the necessity for actors to incorporate social-environmental data into their agricultural production or purchasing strategies. Simultaneously, it presents an opportunity for the development and implementation of indicators that support the sustainable planning of productive regions.

We participated in an interdisciplinary participatory exercise between scientists, technicians, conservation NGOs, governmental bodies, agricultural producers, and soybean trading enterprises that developed and prioritized cross-sectional data in an online platform to inform the planning of sustainable sourcing of agricultural commodities for trading enterprises in a major global deforestation frontier, the Argentine Chaco ecoregion. Throughout this process, we identified several barriers to effective knowledge co-production, including data needs, communication issues, involvement levels, trust, and the integration of diverse actors in participatory exercises. These barriers are not exclusive to this context but are relevant to other agricultural regions as well, and can be alleviated through the insights derived from our study.

Here, we propose several recommendations for co-productive participatory exercises in the development of sustainability indicators for agricultural commodity production. These recommendations include ensuring the diversity of participants, particularly those with decision-making authority, seeking in-person participation, promoting bottom-up co-design processes, and building local capacity (Table 3). Yet, these recommendations are not a definitive list and are focused on attending the challenges in agricultural commodity production regions, where decision power and agency are often urgent due to the drastic consequences of unplanned developments (Kuemmerle et al. 2017). We hope that these recommendations can serve as a stimulus for further discussion and refinement.

Sustainable agricultural production requires integrated, multi-actor perspectives to address complex sustainability challenges in agricultural production frontiers characterized by high deforestation. In this context, and to enhance the contribution of legitimate knowledge while ensuring the efficiency of local spatial planning, participatory co-production processes should be supported and integrated into political strategies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-024-02340-2.

Acknowledgements The authors thank the editor and two reviewers for previous suggestions on this manuscript as well as Flavia Pinto (TNC) for comments on a first version of the manuscript. We used openai's AI assistant for proofreading some sections of this work. This research contributes to the Global Land Program (glp.earth). Open Access funding was enabled by Projekt DEAL.

Funding Open Access funding enabled and organized by Projekt DEAL. We acknowledge funding from the National University of Tucumán (Argentina), grant number PICT 2015–0521; the Geo.X, the Research Network for Geosciences in Berlin and Potsdam, Grant/Project-number: SO_087_GeoX; and SDGNN-ZEU Justus-Liebig-Universität Gießen.

Declarations

Research involving human participants and/or animals This research did not include any vulnerable group of participants, neither dealt with animals.

Consent to participate All authors consent publishing the content of this work.

Conflict of interest Project sponsors funded the trips, meals, and accommodation of the authors to attend the in-person meetings in Argentina.

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