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RESEARCH ARTICLE

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Co-production of agroecological innovations to improve sustainability in South American fruit farms

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Abstract

1. Agricultural intensification and expansion are the main drivers of biodiversity loss that continue to increase this century, especially in South America. International markets and global policy provide incentives and frameworks to address this, but these are unlikely to be effective unless farmers on the ground are enabled and motivated to respond to them by developing long-term solutions that fit their production systems and local contexts.
2. Here, we use a multi-actor transdisciplinary approach to co-design and test agro-ecological innovations suitable for intensive, exporting South American fruit farms. We focus on highly biodiverse regions experiencing habitat loss in the Mediterranean and dry tropical forest regions of Chile and Brazil, respectively. The innovations were designed to support local biodiversity without compromising productivity or quality.
3. Fourteen farmers participated throughout the project, covering a total of 4178 ha of intensive table grape, mango and cherry production. All were under pressure from buyers to report action on biodiversity.
4. Farmers worked with researchers and industry representatives through an iterative process of dialogues and workshops to select, co-design and implement three agroecological innovations: perches for birds of prey, cover crops and native hedgerows. Farmers became engaged in monitoring their effectiveness and redesigning them to suit local contexts.

5. We develop an extensive set of resources for ongoing dissemination, including an online sustainability metric to report the practices carried out. Eight farms continued to implement at least one agroecological innovation beyond the end of the project, motivated by its fit to their management system and their ability to report positive actions in their supply chains.
6. *Policy implications*. Our model of knowledge co-production demonstrates how transdisciplinary research in agriculture, fully localised in a particular food-producing context, can enable farmers in the global South to engage with biodiversity conservation in response to top-down market signals incentivising sustainability. We argue that many top-down efforts to enhance the sustainability of food supply chains, whether through market incentives, voluntary codes or trade regulations, require locally based knowledge co-production, in which multiple stakeholders from agriculture and the food industry can benefit from working with locally based researchers.

KEYWORDS
agroecological practices, ecological intensification, fruticulture, sustainable agriculture, transdisciplinary research, translational ecology

1 | INTRODUCTION

Agriculture is widely accepted to be the main cause of biodiversity loss (Díaz et al., 2019) and one of the main causes of terrestrial greenhouse gas emissions (Tubiello et al., 2022). To minimise these contributions to problematic environmental change, global food systems require the transformation of agricultural practices to reduce the use of agrochemicals and minimise landscape impacts (Foley et al., 2011; Hughes et al., 2023; Meehan et al., 2011), while simultaneously closing yield gaps to avoid unnecessary and inefficient use of land (Leclère et al., 2020).

Currently, the changes occurring in food systems at the global level do not appear to be moving in this direction. Rather than declining, the use of pesticides and fertilisers continues to increase in many regions, including South America, and at a global scale in the case of fertilisers (Ritchie et al., 2022a, 2022b). Open global markets are promoting agricultural intensification in many places to provide different products year-round, and this intensification is often accompanied by ongoing expansion into native vegetation (Garrett et al., 2018; Potapov et al., 2021; Rodríguez García et al., 2020).

South America is the global region that experiences these trends most rapidly during this century (Potapov et al., 2021; Ritchie et al., 2022b). Two examples where a dual intensification and expansion process is currently occurring are the dry tropical forest area of Brazil known as the 'Caatinga' and the central Mediterranean zone of Chile. Due to their climatic conditions and the availability of water from managed rivers, their main valleys have become important nuclei of agricultural expansion and development. Both areas have increasing production volumes and areas for fruits such as cherries, table grapes, apples, avocados and walnuts in the case of central Chile (Pefafur, 2023), and mangoes and table grapes in the case of the São Francisco Valley in the Caatinga (Leão, 2021). Salazar et al. (2021) recently quantified the change in land use from 1985 to 2018 in an area of 846,400 ha of the São Francisco River basin, around the cities of Petrolina and Juazeiro in northeast Brazil, whose economies are heavily focused on fruit export. They showed that native Caatinga vegetation had decreased by 20.2% during this period, at a rate of −5203 ha/year, at least partly driven by the expansion of fruit production.

Both these areas of Chile and Brazil also have a globally significant ecological and conservation value, due to the diversity and uniqueness of their flora and fauna, with high rates of endemism. The Brazilian Caatinga, for example, has more than 1000 vascular plant species, 31% of which are endemic (Albuquerque et al., 2012). In Chile, an even greater 57% of the 4758 vascular plant species are endemic (Ormazabal, 1993). The Mediterranean region of Chile is classified as a biodiversity hotspot (Myers et al., 2000) and one of the most endangered Mediterranean biomes (Underwood et al., 2009). This coexistence of high biodiversity and opportunities for agricultural growth presents a great challenge for these regions.

With the emergence of global sustainability goals that include biodiversity and the continued evolution of global food markets and consumer demands (Schwarzmueller & Kastner, 2022), it is expected that biodiversity will be increasingly incorporated into agricultural management frameworks for export markets (Dalin & Outhwaite, 2019). Indeed, the Kunming-Montreal Global Biodiversity Framework, agreed under the Convention on Biological Diversity in December 2022, specifies this as a target for urgent action over the decade to 2030 (Target 15): *legal, administrative or policy measures … to ensure that large and transnational companies …: Regularly monitor, assess, and transparently disclose their risks, dependencies and impacts on biodiversity, including with requirements*

… *along their operations, supply and value chains* (Convention on Biological Diversity, 2022). In this way, involvement in the global market could be a positive driver towards another Target (10) of the Kunming-Montreal Global Biodiversity Framework, which specifically calls for agricultural areas under agriculture *to be managed sustainably …… including through a substantial increase of the application of biodiversity friendly practices, such as …… agroecological and other innovative approaches* (Convention on Biological Diversity, 2022). By demanding more sustainable produce, global consumers could become key motivators of transformed sustainable agricultural systems, including preventing expansion into natural habitats, through support for zero-deforestation commitments, for example (Beck-O'Brien & Bringezu, 2021; Levy et al., 2023; Villoria et al., 2022). However, sustainable management practices and certification schemes related to biodiversity are currently not exerting much influence on many South American farmers, because other high-value markets are available that are not making these demands (Zhao et al., 2021).

A complementary mechanism to drive a transformation towards sustainable agriculture is to embed the 'functional' role of biodiversity in the production system itself. This mechanism is, arguably, less dependent on market signals and incentives. A significant body of scientific knowledge has characterised the role biodiversity plays in resilient and productive agricultural systems, for example, by maintaining nutrient cycling in soils, clean water supplies and crop yields through pollination and pest regulation services (reviewed by Garibaldi et al., 2021; Kremen & Merenlender, 2018). The changes in management practice required to achieve this have been well described and tested in some parts of the world, under various labels, including 'agroecological practices', 'diversified farming systems', or 'ecological intensification' (see, e.g., Kleijn et al., 2019; Rosa-Schleich et al., 2019; Wezel et al., 2014). Here, we use 'agroecological practices', which we consider a relatively simple and widely recognised concept that keeps the focus on the farm scale. These practices are small steps towards a wider agroecological transition, recognised by Hughes et al. (2023) as an important lever for action to minimise the impacts of agriculture on local biodiversity in both high- and low-income countries while maintaining food security. Currently, there are major gaps in knowledge about how agroecological practices might work in the rapidly intensifying regions of the Global South, especially for fruit production (van der Meer et al., 2020).

Agroecological practices are known to have highly context-dependent effects (Karp et al., 2018; Scheper et al., 2013) and therefore must be designed for specific farming systems and ecological contexts. The participation of farmers in the design process is crucial, as they are the final users who will make the decision on whether to adopt (or not) practices in their farms (Kleijn et al., 2019). There is increasing interest in co-designing agroecological practices with farmers, drawing on well-established processes of knowledge co-production developed over decades in sustainability science (e.g. Aare et al., 2021; Bezard et al., 2023; Sachet et al., 2023). We propose that such co-production is important to ensure that the practices benefit biodiversity but also fit within economically viable food production systems, rather than representing a cost to producers and requiring additional economic incentives, such as agri-environment schemes (Batáry et al., 2015), unlikely to be available in the Global South.

Co-production of knowledge, in which relevant stakeholders participate in generating new knowledge alongside researchers from the early stages of the project, is a core aspect of a transdisciplinary approach that increases the impact of science and makes evidence from research more relevant, useful and usable in practice (Dilling & Lemos, 2011; MacLeod et al., 2022; Norström et al., 2020). The literature suggests that there are different methods, principles and indicators with which co-production has been interpreted and applied (Hickey, 2018; Lemos et al., 2018). Research focusing on the practice of co-production can help us understand what works and what does not work in different contexts and can critically inform different ways to reduce costs and scale up varied approaches to co-production (Lemos et al., 2018). By engaging multiple stakeholders in research on agroecological practices for farms in regions of South America with current conflict between biodiversity and economic development goals (Zabel et al., 2019), co-production can help overcome the challenges of developing sustainable solutions for the global food system (Pohl et al., 2021).

Here, we present initial results from a transdisciplinary project aiming to co-produce knowledge on agroecological practices suitable for conventional, intensive, exporting fruit farms, linking South American countries to the global food market that demands year-round fruit supply. Transdisciplinary research to co-produce agroecological knowledge with farmer participation is scarce in many regions, especially with a focus on evidence-based design and implementation of practices (Sachet et al., 2021). This study is unique in geographic scale and specific context. Our specific objectives are: (i) to co-design new agroecological practices ('agroecological innovations') that would be implemented by farmers and persist beyond the lifetime of the project; (ii) to co-design and promulgate resources suitable for farmers and other actors in the supply chain to understand and communicate their use of the selected agroecological practices. By describing the process, we hope to help other researchers and practitioners using transdisciplinarity in similar contexts, with the aim of fostering and supporting a transition to biodiversity-friendly sustainable agriculture in these regions.

2 | MATERIALS AND METHODS

2.1 | Study participants

This case study took place during a 4-year participatory project, *Sustainable Fruit Farming in Caatinga* (SUFICA). The main actors were Waitrose, a UK supermarket, Primafruit, a UK fruit supplier specialising in year-round supply with operations in the Global South and exporting fruit farmers from the Caatinga region in Brazil and the Mediterranean central region of Chile. In total, 14 farmers participated in the project, covering a total of 4178 ha of intensive table grape, mango and cherry production (Table S1). Four farms from Brazil and four from Chile were involved in the project from the outset. An additional six farmers joined the Brazilian group following a workshop in May 2018, after individual visits to each farm. Participants were selected and invited from among the main Primafruit suppliers in each country, based on their willingness to participate in a co-production process.

All farmers were under pressure from buyers to report action on biodiversity. In both regions, all farmers must already meet the requirements of certain certification schemes to export to European markets (Comexstat, 2023; Dorr & Grote, 2009). Some of these schemes, for example, the Global GAP Biodiversity add-on, include voluntary biodiversity-related criteria for conventional farmers (Global GAP, 2023). However, in response to larger narratives and incentives in European markets to address biodiversity as part of sustainable agriculture, our industry partners wanted to go beyond these requirements and engage farmers more closely in biodiversity management. Their goals were as follows: (a) to prepare the sector for forthcoming increases in the stringency of biodiversity requirements; (b) to build capacity to meet biodiversity certification requirements in fruit-producing regions; and (c) to promote best practices for biodiversity management in current and potential future supplier farms. To achieve these goals, a Waitrose fresh produce representative contacted researchers, requesting expertise in biodiversity management and certification, suitable for perennial fruit crops grown under irrigation in Brazil and Chile.

2.2 | Underlying conceptual model

We use a three-level hierarchical model (Salthe, 2010, 2012) adapted from Rocha and Rocha (2018) to depict how multi-sector stakeholders engaging in knowledge co-production are embedded within and responding to incentives, opportunities and constraints from the global food market (Figure 1).

The SUFICA project partnership came about when incentives from the upper level first impacted food industry actors at the lower level, determining criteria for a high-quality and sustainable supply of fruits that included improved consideration of biodiversity. In our hierarchical model (Figure 1), the institutions involved in international markets ('Global food market'; upper level) impose top-down restrictions, opportunities and incentives on the individual stakeholders that supply the goods (lower level). In this context, 'regulatory constraints' include policies, trade regulations and market conventions. 'Opportunities' and incentives include consumer choices, differential prices and various motivations to improve sustainability; the latter increasingly consider the impacts of biodiversity on food supply chains.

Our co-production process involves interactions between stakeholders at the lower level, which comprises individual players in the

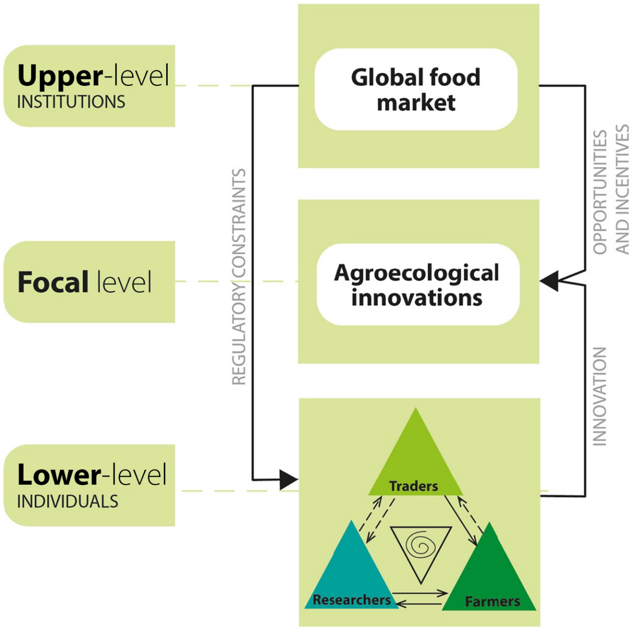

FIGURE 1 A three-level hierarchical model illustrating the relationship between global food markets and the emergence of agroecological innovations. These innovations are then tested by farmers, with regulations, restrictions, opportunities and incentives from global food markets imposing constraints (upper level). The participatory process, involving farmers, traders in the food industry and researchers, plays a crucial role in the decision-making about the adoption of agroecological practices in agriculture (focal level). Within the 'interactive space' (lower level), knowledge co-production occurs among farmers, traders and researchers, leading to the co-design, co-implementation and usability of agroecological innovations. This bottom-up mechanism promotes the emergence of agroecological innovations that are both scientifically sound and practical for implementation (adapted from Rocha & Rocha, 2018; Salthe, 2010, 2012) Image designed by Germana Gonçalves de Araujo.

food industry ('traders'), researchers and farmers, promoting (bottom-up) the emergence of agroecological innovations (focal level) in farms (Figure 1). 'Agroecological innovations' are practices recently introduced into agricultural management systems that have the potential to embed the functional role of biodiversity in food production landscapes for the long term. A long list of examples is provided in Table 1. By connecting biodiversity directly with food production, agroecological innovations represent an area of shared interest between farmers and biodiversity researchers, around which both parties can exchange knowledge.

Our interpretation of co-production draws on research-implementation concepts in conservation science (MacLeod et al., 2022; Sutherland et al., 2019); co-production theory (Norström et al., 2020; Wyborn et al., 2019); and usability of science (Dilling & Lemos, 2011; Lemos et al., 2018). We apply the concept of 'interaction spaces', arenas in which various stakeholders (here, researchers, traders and farmers in the food industry) interact, collaborate and learn together (Toomey et al., 2016).

TABLE 1 List of agroecological practices with the potential to improve biodiversity and support ecosystem services on farms, presented to participants during the selection phase (translated into Portuguese or Spanish, as appropriate). Practices are grouped according to components of the farming system relevant to biodiversity: crop management, small natural habitats and large natural areas. All listed practices were presented in Brazil, 14 in Chile (excluding 3, 5, 9–12, 18 and 21–23). The practices finally selected and implemented on farms are shown in bold (*hedgerows implemented in Chile only). The concerns of farmers, which influenced their opinions on acceptability and feasibility, are summarised.

	Agroecological practice	Related concerns raised by farmers
Crop management		
1	Planting to maintain soil cover	Does not fit current management (predetermined strategy of production); risk of attracting pests
2	**Plant cover crops to increase soil protection and biocontrol**	Does not fit current management (predetermined strategy of production); risk of attracting pests; water use
3	Use a push-pull system for insect pest control	Risk of attracting pests
4	Conversion to organic farming	Too expensive and time consuming
5	Exclude ants that protect pests	Do not know how to manage this
6	Add compost to soil	Time consuming; costly
7	Add animal manure to soil	Not enough manure available; needs previous preparation
8	Use vegetation cover/green manure	Already use prunings of vines
9	Replace inorganic fertilisers with organic ones	Determined by current management
10	Use less inorganic fertilisers	Determined by current management (predetermined strategy of production)
11	Release natural enemies (biocontrol)	Reduce costs and risk of contamination with agrochemicals
Small natural habitats		
12	Drains with vegetation	Costly and require irrigation
13	Windbreaks	Some species attract undesirable animals
14	Buffer strips	
15	Plant flower strips	Costly and require irrigation
16	**Plant hedgerows with native vegetation***	Costly; require irrigation; seedling availability
17	Restore habitats along watercourses	Absent from within or nearby farm area; actions influenced by Forest Code in Brazil[a]; not specifically regulated in Chile
18	Create/restore small reservoirs for wildlife	May also attract undesirable animals
19	Add bird nest boxes	Undesirable or not useful; not worth paying for and requires maintenance
20	**Add bird perches**	Do not know the technique; grape damage is not that significant
21	Add nest boxes for wild bees	Grapes do not need pollination
Large natural areas		
22	Create/restore wetlands	No wetlands within the farm
23	Preserve natural wetlands	No wetlands within the farm
24	Preserve native vegetation	No natural vegetation—Permanent Protection Area (APP) or Legal reserve—within or nearby some small or medium farms; large farms have protected areas already, as mandated under the Forest Code[a]

[a]Brazilian law 12.651, 25 May 2012. http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm.

2.3 | Co-production process: Underlying principles

This project follows general principles highlighted by Norström et al. (2020) that contribute to high-quality co-production: (1) context-based: targeting fruit farmers from specific regions in Brazil and Chile; (2) pluralistic: in which practitioners of different sectors of society—researchers, food industry (Waitrose supermarket and Primafruit) and exporting farmers—jointly co-design, co-implement and co-disseminate results to scale up impact; (3) goal-oriented: aiming to adapt and improve the use of agroecological practices in agriculture; and (4) interactive: bringing together academics and non-academics (practitioners) from different sectors of the fruit supply chain (Tress et al., 2005). Following definitions in Tress et al. (2005), our research is both interdisciplinary (scientists and research fields working in a way that forces them to cross subject boundaries and co-create new integrated knowledge) and transdisciplinary (between scientists and stakeholders, connecting interdisciplinary knowledge to other types of knowledge, considering the dialogue among all stakeholders).

The exchange of information and insights is influenced by three dimensions of the knowledge system, involving the knowledge (K), values (V) and practices (P) of each stakeholder (Clément, 2006). Recognising these different elements of knowledge systems, and allowing them explicitly to influence decision-making, helps the interacting parties to understand one another and enables co-produced knowledge arising within the iterative 'research-implementation space' (Figure 1) to move beyond that space (Lemos & Morehouse, 2005).

2.4 | Co-production process: Phases, activities and outcomes

Throughout the co-production process, we adopted a variety of participatory methods, combining online and face-to-face actions, such as surveys (a semi-structured questionnaire), question-oriented interviews (in person or online), presentations and mediated group meetings and individual conversations (Table S2). All interactions and communications with stakeholders were conducted in the appropriate local language, either Spanish or Portuguese. The adhesion of the farmers to each participatory method and their participation were measured by counting the number of farmers who responded effectively and engaged in the co-production process, respectively (Table S2).

The phases and timeline of the co-production process are shown in Figure 2, comprising a. Defining and designing the study; b. Selecting target farmers; c–e. Identifying, selecting trials and implementing agroecological innovations; f. Summarising main results; and g. Disseminating the results. These phases were sequential but did not have strict time boundaries. Each phase lasted from several months to over a year (or 3–13 months). The relative time allocations would differ according to circumstances. In our case, the 2020–2021 COVID pandemic occurred towards the end of the selection phase (d) but before the implementation phase (e), causing some delay and changes to the partnership. Our transdisciplinary approach, involving academic and non-academic actors working together from the outset, was stressed throughout the project (shown by coloured triangles indicating 'Actors', Figure 2). Interdisciplinarity is supported by combining expertise in conservation, agroecology, forest engineering, entomology and agronomy, which comes not only from the core team of researchers but also from the participating actors (shown by blue and green blocks, on the left of Figure 2).

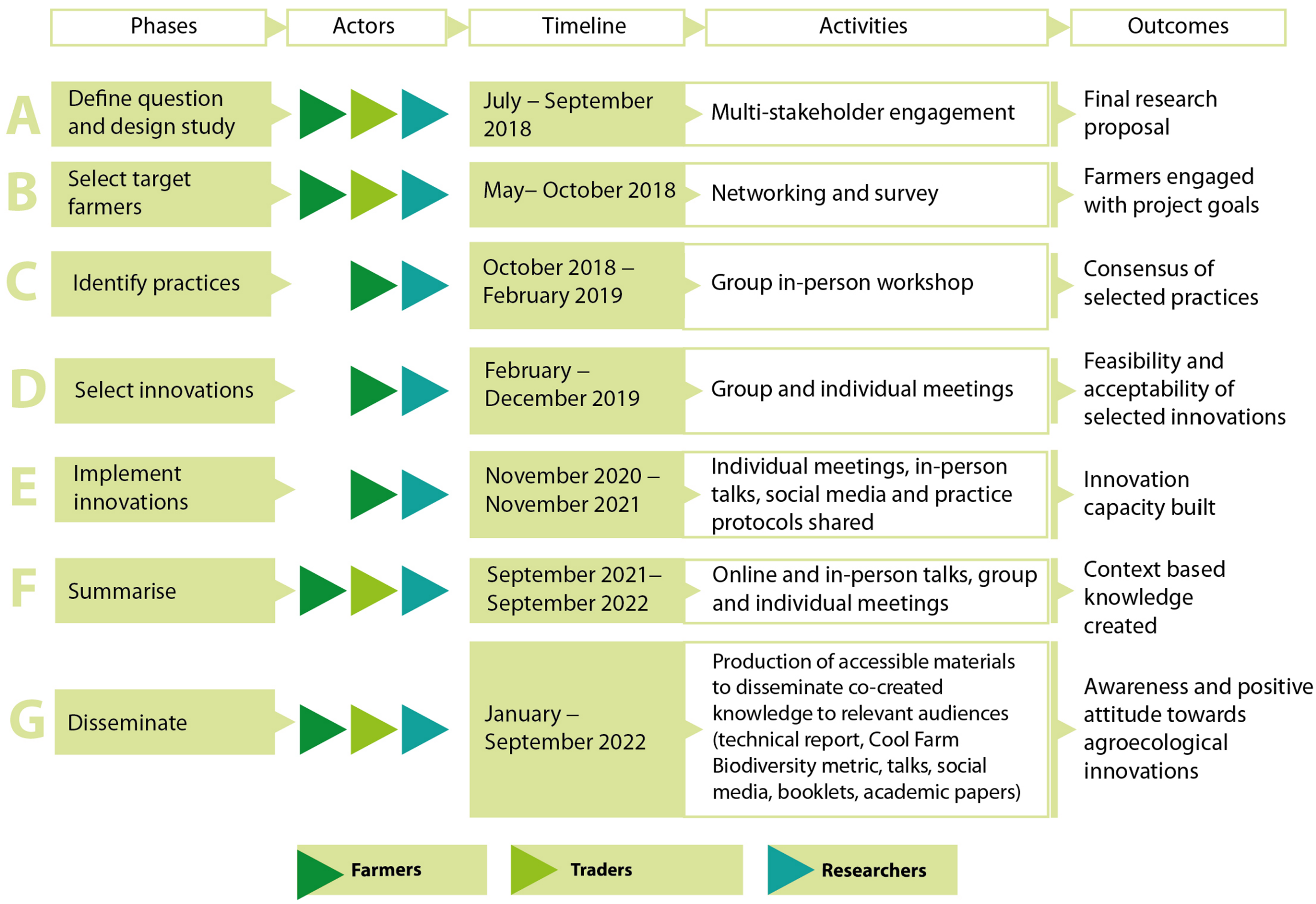

FIGURE 2 Timeline phases, activities and outcomes of the knowledge co-production process. The transdisciplinary dimension (green space, on the left) is denoted by the participation of non-academic and academic actors in each phase, while the interdisciplinary dimension (blue space, within green space) comprises the theoretical input to the project by core research team and stakeholders. Image designed by Germana Gonçalves de Araujo.

During the participatory process, the project provided inputs, logistic and economic support, time and space for interactions to take place, with the overall aims to co-design, co-produce and co-disseminate knowledge about agroecological practices (Toomey et al., 2016; Wyborn et al., 2019). Our research was approved by the Ethics Committee for People Research (CEP) of the Brazilian Ministry of Health before any of the following steps began (Brazil CAAE: 91416918.5.0000.5546).

In order to recruit and engage local farmers in each country and integrate academic and non-academic actors, 10 in-person meetings (10 meetings of up to 5 days each) were held, seven in Brazil and three in Chile. In each country, during the first in-person meeting, the purpose and design of the project were presented to the local farmers, the relationship between farmers was established, and the participants were introduced to each other, so they could get to know who would interact with whom and in what settings. Three of these (two in Brazil and one in Chile) were group meetings, with a higher number of farmers attending the latter group meetings than the first, due to newly engaged farmers joining the network. To avoid fluctuation in the number of participating farmers, and as requested by the farmers themselves, all other in-person meetings were individual meetings between researchers and farmers, conducted during farm visits. During the periods of the COVID-19 pandemic (in 2020 and 2021), in-person activities were impossible, and farmers faced other problems that caused them to change priorities regarding farm management. In between the in-person meetings, participatory online methods were also used, such as social networks (a WhatsApp® group for the project), email, a project website and video calls (Figure 2).

2.5 | Identifying, selecting and implementing agroecological innovations

The selection of agroecological innovations followed a prioritisation process during a second group meeting in person in Brazil (Figure 2). The same results were obtained during a group online meeting with farmers in Chile. To co-define and co-select the agroecological innovations to implement, the researchers provided a list of 24 agroecological practices relevant to farms in Mediterranean and semi-arid regions, for which evidence synthesised by the Conservation Evidence project (Conservation Evidence, 2023) or from the primary scientific literature, indicated potential beneficial effects on biodiversity and/or crop production (Table 1).

The list, or a subset of the list, was presented to farmers and traders in the food industry during in-person group meetings. The core research team mediated the process, in which farmers (owners, managers and employees) worked in small groups to discuss and make decisions about which of the listed agroecological practices they would be prepared to implement and why. Participants were invited to add additional agroecological practices or innovations of interest to the list, but none were added.

After these discussions, the farmer participants answered two questions about each practice, either in a short survey on paper (Brazil) or using an online poll (Chile).

1. Do you currently use this on your farm? Yes/no.
2. Would you be willing to try it? Yes/No.

Agroecological innovations were prioritised for further consideration according to the following two criteria:

- Practice not widely implemented in SUFICA fruit farms (that is, a minority of respondents answered 'yes' to question 1)
- Farmers would be willing to use the practice (that is, a majority of respondents answered 'yes' to question 2).

The research team compiled a written summary of scientific evidence on the effectiveness of a subset of the most promising practices according to these criteria to inform our deliberations and to discuss with farmers (practices 2, 3, 16, 20 and 21; Table 1). We prepared slide decks and other materials illustrating this evidence to present to farmers during individual meetings. Subsequent conversations with individual farmers improved our collective understanding of the acceptability (potential risks and benefits) and feasibility (costs, logistics and acceptability) of the different agroecological practices. Stakeholders provided information on the potential barriers to participation in the co-production process (Table S1) and to the implementation of agroecological innovations on their farm.

Further discussion refined the list to a set of practices generally considered useful for the local context in both countries (numbers 2, 15, 16, 20 and 21; Table 1). Finally, table grape farmers applied more specific criteria related to production in their farms, excluding practices 15 and 21, as grape productivity is not influenced by pollination. Dialogues were conducted to build a consensus based on the balance between factors that affect acceptability and feasibility (Table 3). At this point, a consensus was reached in each country regarding how many and which practices to implement following the discussion of the result among all the participants.

Once agroecological innovations were selected, researchers worked with farmers, agronomists and food industry traders to develop detailed protocols and specifications for implementation, suitable for the specific context (Appendix S1). Cover crop seed mixes were selected on the basis of seed availability and suitability for local site conditions. In Brazil, the implementation of cover crops was overseen by a local agronomist employed by the project. Cover crop seed mixes and native hedgerow plants were paid for by the SUFICA project. All materials and the construction of the bird perches were provided by farmers in Brazil or by the SUFICA project in Chile.

The researchers chose randomised experimental and control sites on each farm, matching fields by crop, variety and management. The placement of bird perches was also informed by conversations with farmers, who told us in face-to-face meetings where they experienced the greatest loss of grapes to birds. They designed

TABLE 2 Involvement of farmers from Brazil (Chile) through the co-production process, indicated by the level of participation in specific actions. The percentage of the total number of farmers involved in the entire process is shown at each level. As the participatory process progresses, all levels of participation are achieved, while the number of participants decreases.

Level of participation	Action	Number of farmers involved	Farmer participation (%)	Number of food industry traders
Inform	Answer on-site and online surveys	10 (4)	100 (100)	2 (5)
Make decision	Co-select practices	10 (4)	100 (100)	2 (5)
Implement	Co-design and implement selected practices on farm	5 (4)	50 (100)	1 (3)
Monitor	Provide observational data	5 (4)	50 (100)	0 (3)
Interpret results	Comment or make suggestions about the practices tested	5 (4)	50 (100)	1 (3)
Disseminate results	Join a community of practice, provide data to Cool Farm Biodiversity Metric, attend capacity-building/training events, explain to employees	10 (4)	100 (100)	1(5)

methods for monitoring before and after biodiversity responses. Most of these activities were carried out through in-person meetings, in which researchers visited each farm, and individual online meetings and communication tools (Figure 2; Table 2). The farmers carried out and paid for ongoing management tasks for all three innovations with the technical support of SUFICA.

3 | RESULTS

Participatory methods ('Activities', Figure 2) generated a progressive increase in the level of farmer participation (Table 2). These methods maintained frequent contact to build trust with stakeholders, while overcoming possible logistic barriers to dialogue and the exchange of information along the transdisciplinary dimension of the project (Table 2). Both the transdisciplinary and interdisciplinary dimensions were achieved through participatory activities. The interdisciplinary dimension was developed mainly through online meetings of the core research team, held every 14 days (109 meetings total). Food industry traders and agronomists also attended these meetings when their specific expertise was required, especially during the early stages (Figure 2).

Their involvement moved from being information providers (informants) to participating in actions. Some farmers were primarily involved in providing information and making decisions, and less involved in implementation. This does not mean that there was a substitution of participants, but five of the 10 Brazilian farmers involved in the project changed their previous decision to implement agroecological innovations. This was mainly a result of the immense challenges faced during the pandemic by exporters, who rely on a large workforce to manage and pick fruit.

We asked farmers in both countries about which agroecology practices they currently used and which ones they are willing to use, using the list previously summarised by researchers (Table 1). At the end of the selection phase, two agroecological practices—bird perches and cover crops—were selected as innovations for implementation in Brazil (Figure 3). In Chile, the selected practices were bird perches, cover crops and native plant hedgerows. These practices are described in resources prepared for farmers, describing how to implement each selected innovation and explaining its feasibility and advantages based on scientific evidence (Appendix S2).

Throughout the planning and decision stages, all stakeholder groups were encouraged to exchange information and insights. All opinions are based on their own knowledge systems, including knowledge (K), practices (P) and values (V), and were equally respected (Figure 4). Most farmer decisions are influenced mainly by their previous experience (P dimension), although the scientific information provided by the researchers very likely influenced the practices selected; value dimension involves the economic aspects of expectations and acceptance, based on costs and market prices, for example, but it also includes wider value sets, such as intrinsic values of nature.

In the end, five farms in Brazil and four farms in Chile implemented bird perches, four farms in Chile implemented native vegetated hedgerows, while three farms in Brazil and three in Chile implemented cover crops (Figure 5). The selected practices were considered usable by our participating farmers. In the case of bird perches and hedgerows, they do not interfere with crop management, as they can be placed in spaces never used for production. Bird perches were considered particularly cheap and easy to instal. For cover crops and bird perches, farmers were interested in the potential to improve pest control, by increasing the activity of natural enemies (predatory arthropods and birds, respectively). Farmers were less confident in cover crops, several having concerns about their potential to also attract pests, despite the expected positive benefits to soil and biodiversity.

In Chile, bird perches were automatically monitored using motion-sensitive camera traps mounted on poles. The selected results of these cameras can be seen in an online dissemination video shared with farmers (Arellano, 2023). In Brazil, all five farmers provided observational data on the use of bird perches themselves, following a simple 10-min observation protocol suggested by researchers. The results were shared in person or online (e.g. email and text messages). Farmers submitted a total of 38 timed observations; nine showed that birds used perches, of which three involved a target bird of prey ('gavião'). During this observation

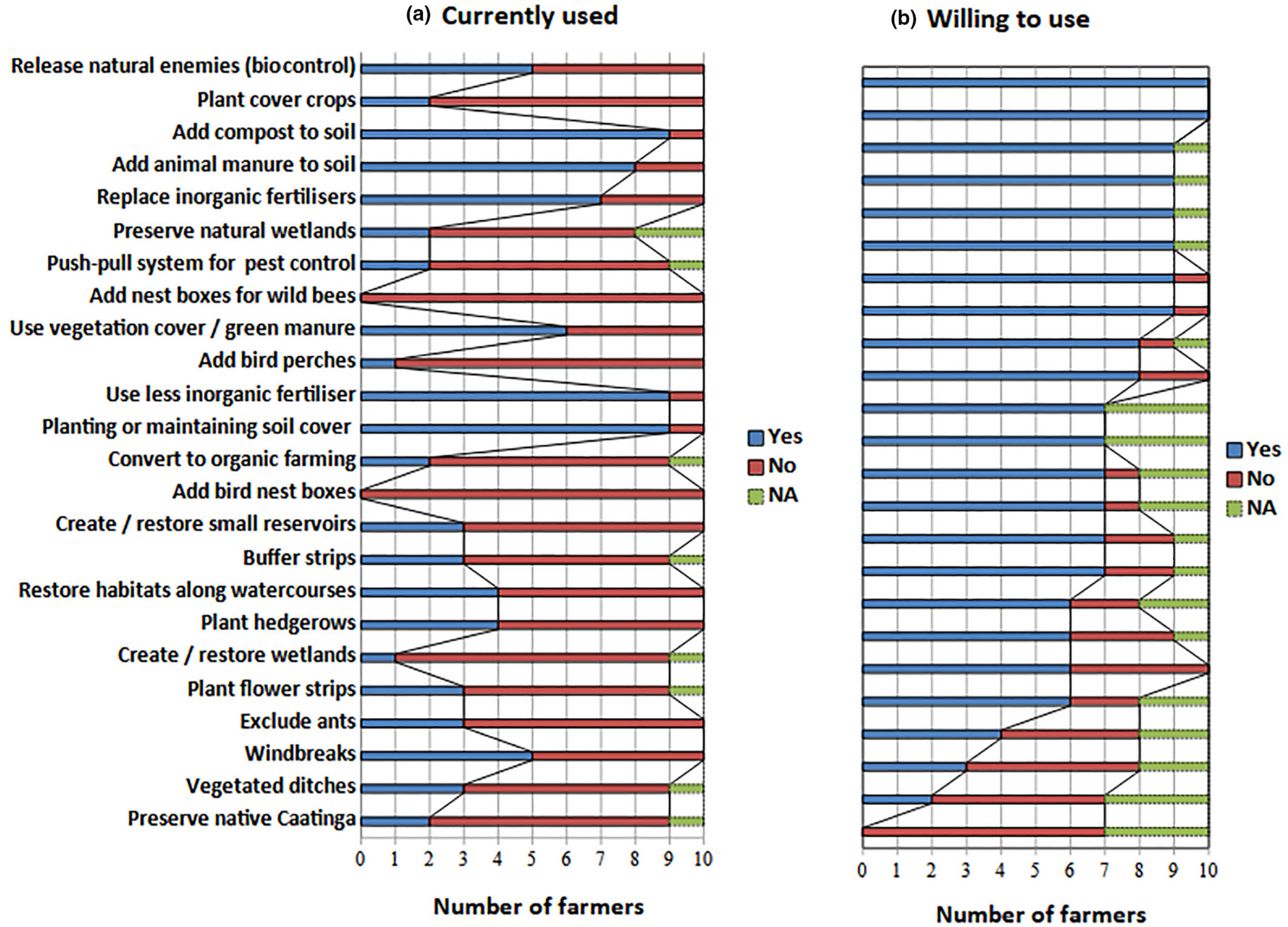

FIGURE 3 Example of responses from Brazilian farmers ($n=10$) during the selection of agroecological innovations. Farmers indicated which agroecological practices they used or did not use (a) and which they would be willing to use (b). Practices ordered according to the number of farmers willing to use the practice (answering 'yes' to Question 2, right). We assumed that practices that few farmers already used but many would be willing to use had the highest chance of being implemented as innovations. Chilean farmers followed the same selection process and implemented the same practices, except for planting native hedgerows.

period, several Brazilian farmers suggested a redesign to improve the landing area to accommodate the foot size of local birds. A farmer erected a redesigned perch, demonstrating adaptive management of the innovation in situ and strong engagement with the aims of the project. The researchers monitored the effects of cover crops and hedgerows on biodiversity since farmers were unwilling to do so due to the lack of employment. One farmer noted some benefits on grape size.

From interactions with farmers who implemented agroecological innovations through the co-production process, there are indications of changes in their perception of risks before and after the implementation. These have not been formally analysed, but we summarise them in Table 3.

3.1 | Dissemination and lasting benefits

The co-produced knowledge was co-disseminated through a variety of resources, including support to a community of practitioners, written and oral content, online and in-person talks and meetings (Table 4). The SUFICA project team worked with farmers to develop and test an online sustainability metric for biodiversity suitable for Mediterranean and semi-arid or dry tropical environments, the Cool Farm Biodiversity Metric (methods reported elsewhere). This industry-led tool, used in global supply chains, is available online (Cool Farm Tool, 2023) and translated into many languages, including Spanish and Portuguese. It explicitly includes the practices considered, shortlisted and tested in this project, and gives our farmers the opportunity to report and receive recognition for their action on biodiversity, through agroecological innovations.

4 | DISCUSSION

The transdisciplinary research reported here set out to co-produce knowledge on agroecological practices suitable for conventional, intensive, exporting fruit farms in South America, engaging with

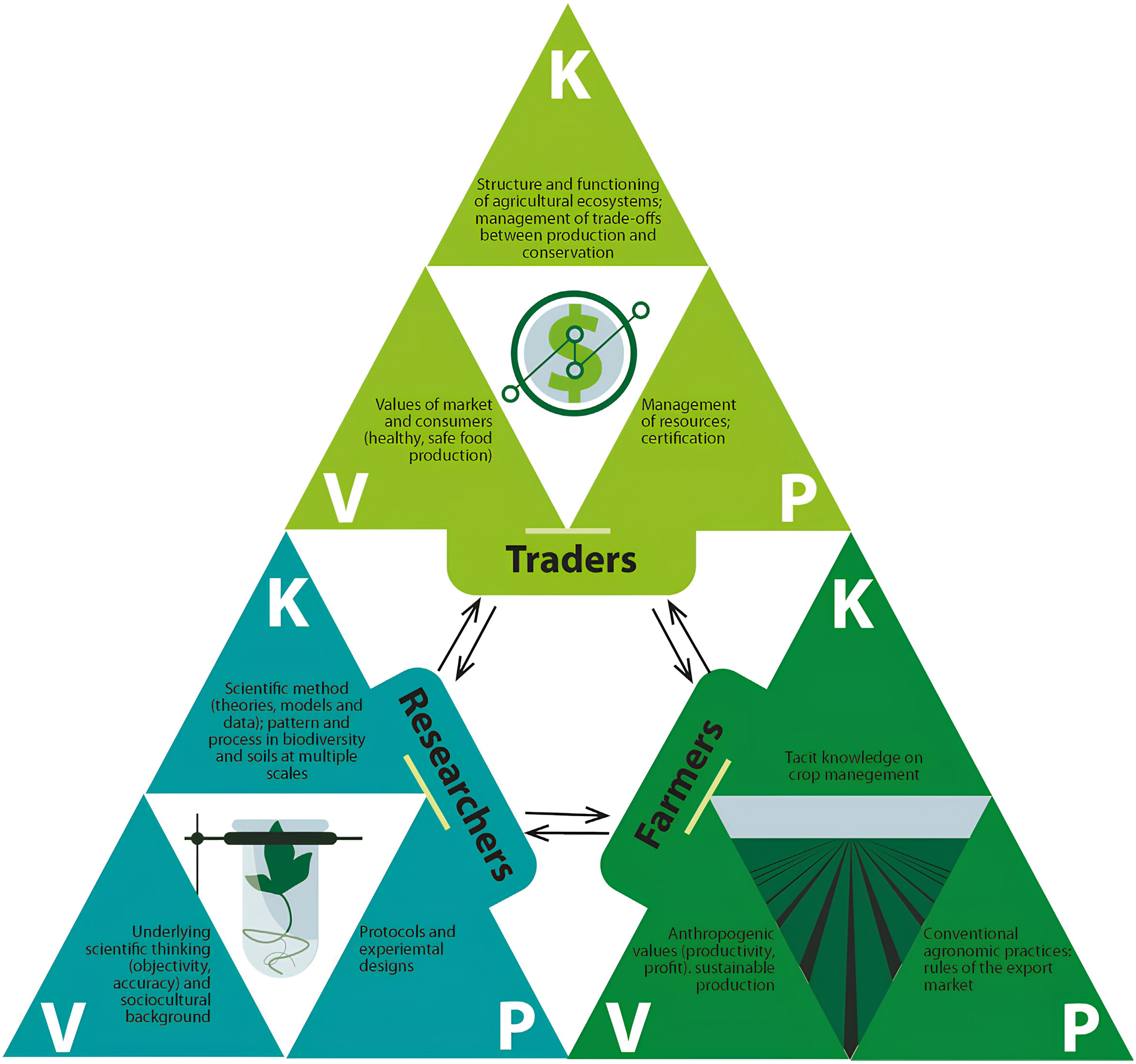

FIGURE 4 Iterative knowledge exchange among stakeholders in the research-implementation space, describing the dimensions of knowledge systems (K = knowledge, P = practices and V = values) that influence co-produced knowledge (adapted from Rocha & Rocha, 2018). Triangles show the three dimensions (KV-P) for each stakeholder; arrows represent the directions of knowledge exchange. Image designed by Germana Gonçalves de Araujo.

actors at the local level, linked to international supply chains. We succeeded in co-designing and implementing a set of three agroecological innovations with participating farms in two countries, Chile and Brazil, and developed an extensive set of resources for ongoing dissemination of what was learned. (531–536).

The co-production process provided an organisational structure in which the perspectives of all participants were integrated in decision-making from the beginning, despite researchers assuming mediation, especially in defining the scope of the project. The project can be conceived as having begun with the establishment of a linear, bidirectional interaction across a 'research-implementation gap' between fruit consumers, traders, farmers and researchers. Such a linear model of interaction between science and society, in which objective knowledge is generated by science and subsequently transferred for use in decision-making, is not expected to be effective in changing the attitude of users or driving transformative change (Lemos et al., 2018; Mauser et al., 2013). In response, the team of researchers changed activities into an integrated 'research-implementation space', involving a multi-actor group that included farmers in a knowledge co-production process (represented by the lower level in Figure 1), following Mauser et al. (2013) and Toomey et al. (2016).

FIGURE 5 Agroecological innovations implemented in farms. Bird perches in use by the target species: (a) 'gavião' (*Parabuteo unicinctus*) in Chile, taken with a camera trap; (b) 'carcará' (*Caracara plancus*) in Brazil, photographed by a participating farmer and shared on WhatsApp; (c) cover crops between rows of grapes implemented in Brazil; and (d) native hedgerows in Chile. Photo credits: (a, d) Nadia Rojas-Arévalo, (b) an anonymous participating farmer and (c) Patricia Oliveira-Rebouças.

The project has provided a list of evidence-based, context-based and cost-effective agroecological practices for fruit farms that can be tested in other semi-arid regions of South American countries. Our project engaged influential traders and farmers representative of the fruit-producing sector in the region, who can be seen as knowledge 'brokers'. We expect this strategy to drive wide dissemination of our results, scaling up the generated knowledge to a far greater number of farmers than were initially involved in the project (Lemos et al., 2018; Lemos & Morehouse, 2005).

Our co-dissemination activities can be expected to continue to have an impact well beyond the completion of the project. We made information available in different formats, not only targeting the brokers but also presenting findings in research papers and using both oral/video and written materials, as well as an online software tool already used by suppliers and embedded in supply chains (the Cool Farm Tool Biodiversity metric). This range of formats helps to overcome the inaccessibility (language, jargon and reading time) of primary scientific information and knowledge. In a review of several case studies, Djenontin and Meadow (2018) indicate that making co-produced information available in different forms, based on a sound understanding of stakeholders' needs, increases the usability of the science produced and maintains the results of a project.

Declines in the quality of participation towards implementation and evaluation phases, as we found here, are frequently observed in well-structured projects, and can be caused by many factors (Djenontin & Meadow, 2018). The difficulties of maintaining face-to-face communication, especially during the COVID pandemic, may have weakened the bonds between farmers and the objectives of the project, in addition to the limited time and internet access available to interact directly with the full intercontinental range of project participants.

Our approach involved a multidirectional dialogue between participants to inform the selection and implementation of agroecological innovations (Figure 4). This helped the interacting parties understand one another and enabled co-produced, usable knowledge to be perceived by users of the knowledge on the ground (Lemos & Morehouse, 2005). Tacit knowledge of agronomic practices and economic values explicitly influenced decision-making about the practices to be implemented. Furthermore, some published studies probably had substantial impacts on the final selection of practices. For bird perches, Peisley et al. (2017) demonstrated a strong positive benefit to grape production through reduced grape damage near the perches in a similar, but not identical, production system in Australia. For cover crops, two meta-analyses focused on cover crops in Mediterranean agricultural systems demonstrated multiple benefits to soil, biodiversity and pest control without a penalty in terms of crop yield (Shackelford et al., 2017; Winter et al., 2018).

At the time of writing, 1 year after the completion of the project, all Chilean farmers who implemented innovations continue with hedgerows and bird perches, while two continue with an adaptation of cover crops to protect the soil during winter. Four of the Brazilian farmers in the implementation stage have retained their bird perches. To our knowledge, cover crops were not retained in subsequent years in Brazil, although one farmer who perceived benefits to the soil remains open to the idea. This lack of continuation among Brazilian farms probably reflects the cost of seed, management and concerns about the water demand from cover crops. This indicates that, in addition to providing learning opportunities, the co-production process provides capacity building and practical gains. The combination of these types of outcomes has the potential to affect resource management decisions (Djenontin & Meadow, 2018).

TABLE 3 Main barriers to the adoption of agroecological innovations pointed out by farmers participating before and after co-implementation. The opinions noted come from nine farmers (five in Brazil and four in Chile) and suggest changes in perception in response to co-production.

Agroecological innovation	Before implementation	After implementation
Cover crop	Fear of attracting pests Risk of increased frost damage	Pests were not attracted
	There is not enough knowledge about suitable plant species	Successful test of the selected plant species
	Not able to buy seeds of the selected plants	Seeds are available to buy
	Not willing to pay additional costs	Costs were not as high as previously thought
	Does not fit the current management scheme	Can be adapted, but irrigation and work effort are needed
Bird perches	Not expecting this to be effective	Target birds in Brazil occasionally seen, but other birds used the device; in Chile, there was evidence of use and rat consumption by the target predators
	No previous test in the region	Farmers suggested adaptations to the device (e.g. shape of landing area)
	Does not know how to build the device	Researchers provided a guide model, using wood that is easy to find. Farmers were able to construct
	Unnecessary additional cost	Not a high cost, some think it is not worth it
	Does not fit the current management	Easy to adapt
	Fruit damage is confined to field edges and not economically very significant	Did not seem to influence current fruit damage, according to farmers[a]
Hedgerows	Does not know the value of having native species Fear of attracting pests Cost of implementation Poor knowledge of planting techniques for native vegetation (trees and shrubs) Irrigation requirements	Selected native species were easy to establish Problems with shrubs and the use of heavy equipment Preference for native trees with low water requirements No competition with main crops Now they can report the action for different certification standards

[a]Unfortunately, researchers were unable to collect data on this, largely due to COVID lockdowns during the project.

TABLE 4 Resources developed to co-disseminate co-produced knowledge, incorporating the knowledge systems of each stakeholder group, as they apply agroecological innovations.

Type of resource	How co-disseminated knowledge can be used
Individual technical reports provided to each farm	For *farmers* to demonstrate their action on biodiversity and sustainability to food industry traders, consumers and during certification audits
Scientific information freely and openly shared, such as online brochures, using plain language understandable to farmers, for example https://sufica.org/publications/	To support *farmers* to implement and monitor agroecological practices, with locally relevant information, including plant species, design specifications
Talks in easy understandable format (in person, or freely available online)	To help *industry traders* provide locally relevant technical advice and guidance on agroecological practices to other farmers in the same regions
Online reporting tools for example www.coolfarmtool.org	To help *industry traders* monitor, benchmark and compare farms in their supply chain, for their efforts relating to biodiversity management

Analysing the interaction between the components of the research knowledge system and stakeholders, the farmer's decision to adopt agroecological practices is mainly influenced by instrumental values (Chan et al., 2016), especially in the global South, where there are lower levels of livelihood security (Pascual et al., 2023). The same emphasis arises from our project, in which we adopted an 'ecological intensification' perspective (Foley et al., 2011; Kleijn et al., 2019), focussing more on the ecosystem service benefits of agroecological innovations for soil quality, pollination and pest control, rather than on positive impacts for biodiversity conservation and sustainability. Although the additional benefits derived from it can be as or more important than the means of reaching them (Ghijselinck et al., 2023;

Pascual et al., 2023). Being immersed in the web of rules and requirements of the international market, farmers and traders tend to view the conservation of biodiversity as a way of meeting specific objectives of production according to acceptable standards, rather than seeing the intrinsic value of biodiversity. One possible consequence is that farmers are less inclined to make efforts to adopt new agroecological practices, if they could be replaced by something capable of performing better or cheaper (Hughes et al., 2023). In our context of intensive, exporting, South American fruit farms, so-called 'conventional' practices based on synthetic inputs, are still the mainstream of industrial agriculture, while agroecology is based on knowledge and often requires more time and effort to implement (Maughan & Anderson, 2023; Sachet et al., 2021).

5 | CONCLUDING REMARKS

The ultimate measures of success for this project are likely to differ between the participating stakeholder groups, according to their underlying motivations and knowledge systems. Our research was motivated by an original demand from industry to improve biodiversity management and address concerns about biodiversity decline in intensive fruticulture regions, primarily to inform sustainability reporting, as part of good environmental and social governance. Farmers who participated were mainly motivated to gain or retain access to international high-value markets by being able to demonstrate that they are meeting externally imposed sustainability goals, including biodiversity management, with minimal or no cost to the quality or quantity of what they can produce. From the perspective of researchers, our ultimate goal is to inform a transformational change in global food systems, moving towards greater long-term resilience and sustainability, with lower impacts on local biodiversity. The difference between these motivations could be conceived as the research-implementation gap.

The processes of interaction among stakeholders in research-implementation spaces, demonstrated here (Figure 1), can help to reconcile these divergent perspectives of scientists and other stakeholders (Maas et al., 2021). We present some evidence of this happening from the perspective of farmers (Table 4), although we did not intend to study changing perceptions. During the process, the researchers involved have also learned a significant amount about the agronomic challenges of incorporating agroecological practices into intensive farming systems in dry tropical or Mediterranean systems. We have also generated substantial datasets on the biodiversity in these systems (not reported here) and its potential responses to agroecological practices.

Previous analysis by Chambers et al. (2021) shows that co-production requires careful facilitation to bridge diverse perspectives, values and identities, and that multi-scalar and long-term engagement are essential for achieving outcomes. Our co-production model demonstrates how transdisciplinary agriculture research, fully localised, with 'feet on the ground' in South American fruticulture regions, can be integrated with international supply chains and global markets, with the potential to enhance impact on very large scales and in the long term.

It is our contention that many efforts to enhance the sustainability of food supply chains implemented top-down (from the upper level in Figure 1), whether through market incentives, voluntary codes or trade regulations, can benefit from knowledge co-production such as that demonstrated here, with multiple stakeholders working together at the local level in the source countries. The main outcomes of such work are to interpret the sustainability requirements correctly and efficiently for each local context, to embed them in scientific understanding and to ensure that actors in the food supply chain (farmers, industry traders) are empowered and enabled to implement them and evaluate their effectiveness for the long term. This must be true not only for biodiversity aspects of sustainability but also for addressing climate change adaptation and mitigation. We therefore call for sustained funding of transdisciplinary research such as ours, and we are very pleased that major science funders around the world are increasingly recognising this.

In this project, our proposed solution to agroecological innovations (focal level, Figure 1) is more of a 'bottom-up' solution to improve sustainability, designed for specific farming systems. To drive transformational change at scale, farmers around the world, including those involved in local and international markets, must clearly see benefits to their production systems in ways that resonate with their knowledge system, including values. This will require local and global governance focused on driving sustainability (Dilling et al., 2015).

AUTHOR CONTRIBUTIONS

Fabiana Oliveira da Silva, Eduardo C. Arellano, Blandina Felipe Viana and Lynn V. Dicks conceived the ideas and made equal contributions to writing the manuscript; Fabiana Oliveira da Silva, Vinina Silva Ferreira, Patricia Oliveira-Rebouças, Natalia B. Zielonka, Liam P. Crowther, Nadia Rojas-Arevalo, Andrés Muñoz-Sáez and Valentina P. Jimenez collected and analysed the data. Eduardo C. Arellano and Lynn V. Dicks acquired the funding. All authors have read and agreed to the published version of the manuscripts.

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CONFLICT OF INTEREST STATEMENT

Eduardo Arellano and Lynn V. Dicks are both members of the Science Advisory Council for the Cool Farm Alliance, in a voluntary capacity.

DATA AVAILABILITY STATEMENT

There are no data associated with this document that are not recorded in the document itself.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Details of participating farms Brazil and Chile.

Table S2. Mixed participatory methods used to engage farmers in the co-production process developed in Brazil (Chile).

Appendix S1. Example of a letter that explained the implementation protocol for one of the farms, specifying the design of the bird perches.

Appendix S2. (a) Booklet 'Guide for actions of Ecological Intensification in fruit and vineyards at central Chile', an example produced during the project and shared with farmers (Spanish): (b) Booklet example produced during the project and shared with farmers (Portuguese): https://doi.org/10.17605/OSF.IO/BA9YJ.

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