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RESEARCH ARTICLE

# Case study analysis of innovative producers toward sustainable integrated crop-livestock systems: trajectory, achievements, and thought process

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## Abstract

Integrated crop-livestock systems (ICLS) are more complex to properly manage than specialized farming systems due to multiple interactions between crops, livestock, and grassland. Despite individual and structural barriers to adopting sustainable ICLS, some innovative producers have successfully conducted integrated production practices. In this context, a research gap exists in understanding the motivations and incentives for transitioning to such systems. This study aims to address ICLS adoption barriers by analyzing the trajectory, achievements, and thought processes of 15 producers practicing ICLS. Our objectives were to (1) highlight producers' perceptions of ICLS levers and barriers and (2) identify turning point factors that enabled producers to overcome the barriers. We used a unique set of cases in three continental regions (southern Brazil, the northern Great Plains region in the United States, and southern France) and conducted semi-structured interviews. Interviewees emphasized that ICLS imply dealing with barriers ranging from mindset change to operational adaptations, but they also emphasized the rewarding nature of ICLS when properly managed. All their trajectories had important turning points, such as programs or initiatives, human influence, and broader social and economic reasons that resulted in shifts in their production practices and thought processes. The cases also highlighted that integrating crops and livestock positively impacted family producers' business outcomes, soil health, and livelihood options. Still, individual barriers, including operational management, and structural barriers, including stakeholder awareness and commitment, must be overcome. Encouraging initiatives that offer a systemic approach and promote knowledge exchange can address part of ICLS adoption barriers. Initiatives must embrace a broader innovation ecosystem, having extension teams in close contact with researchers and stakeholders to assist producers in providing support for a more sophisticated level of management that ICLS require. Overall, we found commonalities in consciousness and proactiveness in remarkable cases that could inspire broader sustainability transitions.

**Keywords** Farm trajectory · Mixed crop-livestock farming · Sustainable intensification · Social-ecological systems · Integrated crop-livestock system · Turning points

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## 1 Introduction

Integrated crop-livestock systems (ICLS) allow synergisms from coupling biogeochemical cycles that provide the diversity necessary for proper ecosystem functioning (Sanderson et al. 2013; Franzluebbers et al. 2014; Hendrickson 2020). They are complex production systems regarding spatio-temporal land use, financial planning, and objectives compared to specialized systems or natural ecosystems (de Faccio Carvalho et al. 2021a). The phenomenon of agricultural specialization relates to economies of scale, which encourage producers to enlarge and specialize their systems to reduce the unitary price of inputs to match a lower price of outputs, triggering

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the decoupling of livestock and crop production (Ryschawy et al. 2012). This phenomenon is occurring worldwide, as exemplified by Aguilar et al. (2015), who showed a decline in crop diversity in the United States, and Schut et al. (2021), who reported an increase in specialization and farm sizes in the European Union.

However, the trend toward specialization has negative implications because specialized farming systems can be less resilient to climate and economic shocks (Bell et al. 2021). The reintegration of crop and livestock production will undoubtedly play a strategic role in global needs to increase *both* the intensification *and* sustainability of food production as ICLS can increase resilience, economic benefits (e.g., mitigating risks due to climate and price variability), social benefits (e.g., for communities in close relationships with food production), and environmental benefits (e.g., nutrient cycling, the efficiency of natural resource use) (Franzluebbers et al. 2014; Moraine et al. 2017; Kumar et al. 2019). The opportunity to share resources (i.e., human, capital, infrastructure, land, water) between work units (i.e., crop and livestock) at the farm level allows producers to tactically adjust their allocation across or between enterprises in response to fluctuations in price or climate (Bell et al. 2021).

However, implementing ICLS within commercial agroecosystems requires a more sophisticated level of management, openness to systems thinking vs compartmentalization, acquisition of knowledge and skills, and available workforce (Garrett et al. 2017). In these contexts, producers face major challenges in ICLS adoption across the world (Prokopy et al. 2019; Garrett et al. 2020).

ICLS farms can be characterized along two axes. The first axis is the level of diversification, and the second is the degree of integration between crop and livestock enterprises. In the case of the level of diversification, Martin et al. (2020) showed that using multi-species of livestock by keeping two or more animal species on the same farm has the potential to improve sustainability if practices such as appropriate stocking rates are observed. These authors reviewed the use of multi-species livestock to enhance resource use efficiency, reporting that it also requires more skills (e.g., more versatility and flexibility of workers) and workload reorganization to ensure that complementarities and facilitation occur rather than competition of resources. Increasing the level of crop diversity in rotations and land use maintains or increases crop productivity while reducing relative economic risk (Archer et al. 2020). The diversification of crops in ICLS can also provide more livestock feed sources and reduce the cost of bringing outside feed sources depending on market and seasonal climatic conditions (Bell et al. 2021). Martel et al. (2021) applied a tool with 10 indicators regarding food self-sufficiency, fertilizer autonomy, and land use and found that increased integration is related to higher environmental and economic performance.

The adoption of ICLS is impacted by both individual factors (such as experience, information, attitudes, beliefs, and values) and structural factors (including culture, markets, governance, and ecology) that can be important barriers (Cortner et al. 2019). To cope with the challenges of implementing sustainable practices, exemplary projects address specific practices and strategic redesign of agroecosystems towards ICLS (Price et al. 2009; Moraine et al. 2014). Still, ICLS projects face many barriers to implementation due to a common lack of resources including trained advisors, adapted tools, time, and budget (Moojen et al. 2023). Besides projects, some producers benefit from other initiatives, including developing and interacting with producer and advisor networks, as well as with broader contexts to support the (re)integration of crops and livestock into more sustainable systems (Sulc and Franzluebbers 2014; Gil et al. 2015; Cortner et al. 2019; de Faccio Carvalho et al. 2021a). Fedele et al. (2019) studied transformative adaptation and summarized its six characteristics: restructuring, path-shifting, innovative, multiscale, systemwide, and persistent. These characteristics align with the transitions toward ICLS, as sustainable practices fundamentally need design and intention of holistic perspectives that recognize context, interactions, and the ability to differentiate short- vs long-term impacts.

This paper addresses the research gap in understanding the motivations and incentives for transitioning to ICLS systems. Our analysis thus focuses on analyzing (1) farm trajectory, (2) achievements, and (3) thought processes among innovative producers as critical to the dynamics in aspirational change toward ICLS. The "farm trajectory" encompasses key transitional practices and technical and learning conditions in the transition pathway of an operation (i.e., farm or ranch) (Chantre et al. 2015). Ryschawy et al. (2013) analyzed the importance of assessing farm trajectories that exemplify suitable "paths to last" in ICLS. Within a farm trajectory, we highlight the importance of transformative periods of changes that may occur as "turning points" (Bakker et al. 2023). By "achievements," we mean direct and tangible results experienced by each producer that manifest advancement and change within their system. By "thought processes," we refer to the way producers conceptualize and understand agroecosystems connected to their motivations related to decision-making processes. Given that ICLS adoption has not only technical but also behavioral (*sensu* human psyche) components, a mindset change is often a key first step within ICLS transitions to emerge (Moojen et al. 2022a). Overall, these innovative producers could provide inspiration for more producers to transition to more sustainable systems (Garrett et al. 2020). In addition, considering their experiences and perspectives helps identify pathways to scale up effective sustainable ICLS initiatives worldwide.

To contribute to mainstreaming such ICLS niche, we also aim to address barriers to ICLS adoption by analyzing producers' perceptions of ICLS levers (i.e., boosters) and barriers, identifying trajectories and turning points that made them interested in ICLS as a way to improve sustainability. This study should help ICLS research and extension projects when organizing participatory projects that aim to encourage ICLS. Besides, it could help to develop outreach systems that inspire producers seeking to transition to ICLS. For that, we chose a unique set of innovative producers' cases in Brazil, France, and the United States (Fig. 1) with data obtained from interviews (Section 2) to present results illustrating transitional pathways and achievements in ICLS and add discussion related to each topic in the literature for integrated systems (Section 3).

## 2 Materials and methods

We designed a unique aggregation of cases from southern Brazil, the northern Great Plains region of the United States, and the Occitanie region in southern France because of a collaborative network of researchers aligning these geographies. By virtue of that network, a unique opportunity to understand trends of similarity and/or difference across larger global scales became an important question. In this case, the three regions represent not only a diverse range of agroecosystems, making their combined diversity helpful for understanding ICLS trends and contexts at a larger scale (Fig. 2), but also varied social, cultural, and economic conditions valuable to contextualize such a unique scale of analysis.

The northern Great Plains region experiences lower precipitation and has a relatively shorter growing season than the other two locations. The predominant livestock raised in this region is beef cattle, while the main crops grown include wheat, corn, soybeans, sunflowers, field peas, beans, flax, and canola. Within this region, five types of ICLS can be found: crop residue grazing, cover crop grazing, swath grazing, non-harvested crop grazing, and perennial crop reintroduction (Kumar et al. 2019). Southern Brazil is a subtropical area with higher precipitation among the regions studied. The region has as livestock mainly beef and dairy cattle. The crops grown all year long (usually 2 harvests in 1 year) are soybean, corn, wheat, and rice predominately. This region typically has ICLS characterized by annual rotation of pastures and crops within a no-till system at the farm level, where the pasture is grazed for meat or milk production (de Moraes et al. 2014). The Occitanie region, as in southern Brazil, has a growing season all year long, but the water resource can be a key challenge in designing ICLS. In the region, livestock is also mainly beef and dairy, while the crops are mostly wheat, barley, and corn. The ICLS occur in the region at the farm and territorial levels, mainly with crops in valley areas and foothill areas with livestock (Moraine et al. 2014; Ryschawy et al. 2022).

### 2.1 Sampling and interviews

In each data collection region, the team of authors organized a purposive sample of agricultural producers strategically identified for their innovation and implementation of ICLS. A purposive sample is not meant to provide full coverage of representativeness as in a statistical analysis, but rather a more robust explanation about unique and complex relationships within a system. As such, the analysis builds three case studies via a common and standardized set of questions

**Fig. 1** Integrated crop-livestock systems from Occitanie region in southern France, southern Brazil, and the northern Great Plains region of the United States. Photo credit: first author.


**Fig. 2** Geographical context of integrated crop-livestock systems research locations and annual average precipitation (mm), growing season, most common crops, and livestock enterprises in each region. Map image: https://www.google.com/maps.

that enable insights across a broad socio-geographic scale. The intent is *not* direct analytical comparison (i.e., are ICLS working better/worse in one region vs another), but rather a demonstration of what insights can emerge from looking not only *within*, but also *across* landscape scales.

We contacted representatives working in alternative advising networks to help us identify producers who utilized management strategies that they believed would enhance the sustainability of their operations. These producers believed that the implementation of ICLS would help them achieve their sustainability goals. We selected fifteen producers ($n$ = 15), five from the northern Great Plains in the United States of America (US), five from the state of Rio Grande do Sul in southern Brazil (BR), and five from the region of Occitanie in France (FR) (Table 1) to exemplify innovation trends in ICLS in a multi-regional context. All operations selected occurred as (1) a structure of family-owned and managed production businesses; (2) evidence of changes towards ICLS; and (3) status among local and regional counterparts as remarkable examples addressing both the mental and practical shifts necessary for change. In this design, the case selection process does not claim a full representation of the entire population of ICLS producers in the regions studied but emphasizes patterns, motives, and trends among producers across cases at larger socio-geographic sales.

Data collection for each case study included individual interviews, carried out between 2017 and 2022, primarily in-person and one-third online when conditions prevented in-person sessions. While large-scale global events (e.g., the COVID pandemic, climate shifts) occurred during this time span, the atemporal focus of the data collection makes the aggregation of the cases meaningful. Because of the trajectories of ICLS transitions, a 5-year timespan, on average, does not constitute a full transition period for most integrated producers. Five interviewers, three authors plus two interns, conducted the in-depth interviews that lasted 1 h and 40 min

**Table 1** Interviewed producers from three global regions, crops they grow, and livestock they raise.

| Producer | Crops | Livestock | Tillage practice |
|---|---|---|---|
| *Northern Great Plains/United States of America* | | | |
| US1 | Spring wheat, winter triticale, oats, corn, sunflowers, peas, hairy vetch, alfalfa, cover crops | Beef cattle, sheep, poultry, swine | No-till |
| US2 | Corn, soybeans, sunflower, alfalfa, corn for silage, cover crops | Beef cattle, bison | No-till |
| US3 | Spring wheat, corn, soybean, sunflower, cover crops | Beef cattle | No-till |
| US4 | Corn, corn for silage, sunflowers, flax, soybeans, wheat, cover crops | Beef cattle | No-till |
| US5 | Wheat, yellow peas, radish, millet, pinto beans, sunflower, buckwheat, flax, soybeans, cover crops | Beef cattle | No-till |
| *Southern/Brazil* | | | |
| BR1 | Soybean, cover crops | Beef cattle | No-till |
| BR2 | Soybean, rice, cover crops | Beef cattle, sheep | No-till |
| BR3 | Soybean, corn, cover crops | Dairy cattle, beef cattle | No-till |
| BR4 | Corn, cover crops | Dairy cattle | No-till |
| BR5 | Soybean, triticale, white oats, cover crops | Beef cattle | No-till |
| *Occitanie/France* | | | |
| FR1 | Wheat, meslin, pea, vetch, trees, cover crops | Beef cattle, sheep | Till |
| FR2 | Wheat, triticale, temporary grassland, alfalfa, corn silage, mixed crops, mixture of cereals, cover crops | Dairy cattle, beef cattle | No-till |
| FR3 | Corn, soybean, sunflowers, wheat, faba bean, rapeseed | Dairy cattle | Till |
| FR4 | Corn, durum wheat, barley, temporary grassland, faba bean, corn silage, cover crops | Dairy cattle, beef cattle | Till |
| FR5 | Sunflower, alfalfa, cover crops | Beef cattle, swine | Till |

on average. The questions were open-ended and related to (a) producers' farm trajectory (e.g., Fig. 3), (b) current system and practices, (c) producers' achievements, (d) thought processes, (e) results with ICLS, and (f) future plans. All interviews were recorded with consent from the respondents. The recorded interviews (25 h total) were transcribed in each original language (French, English, and Portuguese). Some producers' quotes were translated to English and identified as a country (US, BR, FR) + number, e.g., FR1 (Table 1).

### 2.2 Analysis

The transcripts were coded in MaxQDA 20.2.2, and a qualitative content analysis was performed according to Elo and Kyngäs (2008). The coding identified commonalities and synthesized recurring themes across the data (Welsh 2011). Several rounds of coding enabled category consolidation in common themes, super themes, and main categories (Table 2).

## 3 Results and discussion

Our study offers a unique qualitative in-depth analysis of experiences and perceptions from innovative producers in Brazil, France, and the United States who have ICLS and are applying practices such as pasture management, lowering input dependence, and soil health, that they believe to be helping on enhance their farming sustainability. Each region differs in terms of cultural, political, and environmental factors but provides interesting commonalities. Our results indicate that adopting and managing ICLS involves a range of barriers, which are not only related to the classical technical farm practices but include changes in mindset and operation up to the gates and system changes beyond the farm gates. Although, when properly managed, producers perceived rewards from the system synergies and emphasized yielding benefits. The case studies showed evidence of positive implications from adding sustainable practices into their businesses and lives. We argue that these practices should be viewed at the system level, recognizing context and interactions. We also identify emerging themes in ICLS development that matter to coping with ICLS adoption barriers.

We believe that the use of a study case may be viewed as an important limitation of our study. Yet, we had rich, in-depth interview data from multiple individuals, including remarkable cases from each country. With that said, we hope that future studies using more generalizable data will incorporate mixed methods—including sustainability parameters for example—to allow further interpretations.

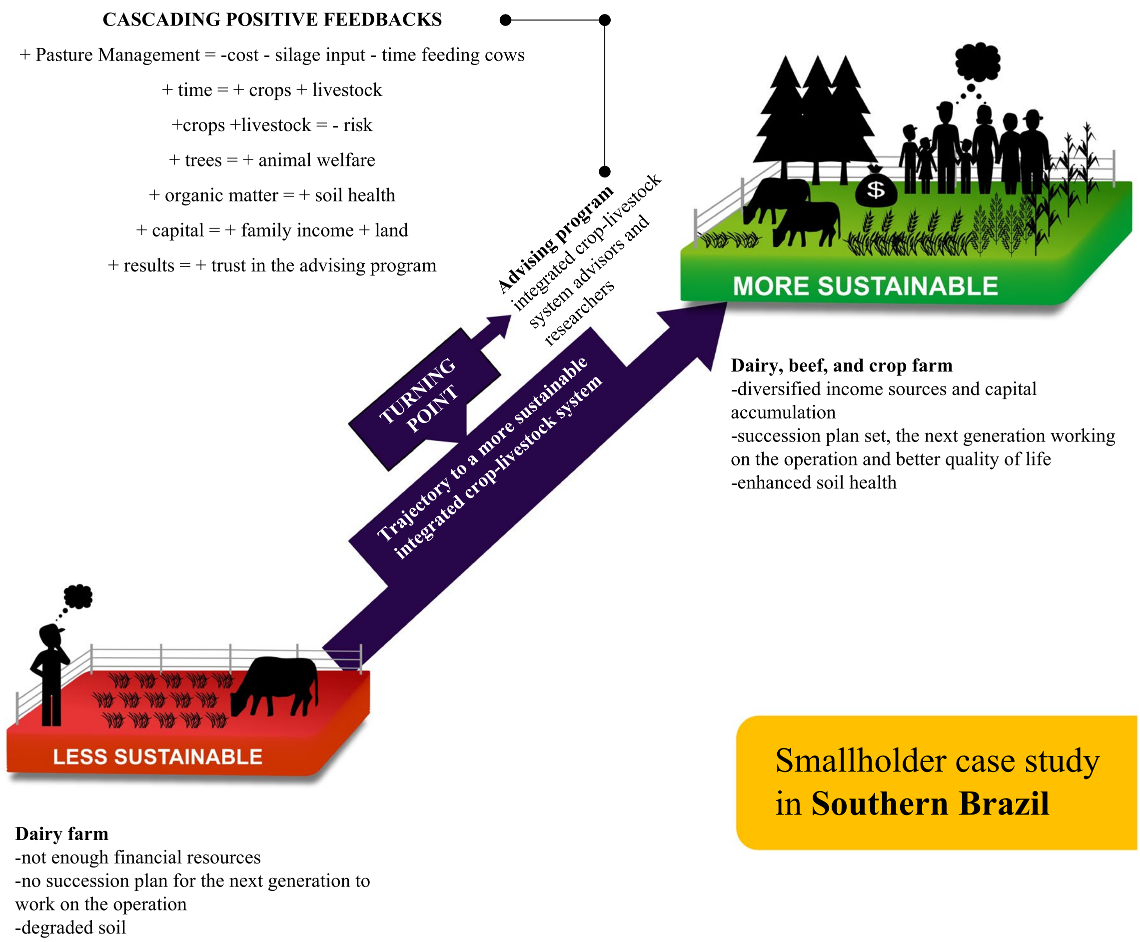


**Fig. 3** An illustrative example of a farm trajectory to a more sustainable integrated crop-livestock system from a smallholder producer interviewed in Brazil. A turning point in their trajectory was participating in an advising program that generated cascading positive feedback.

### 3.1 Innovative ICLS producers bucking agricultural specialization

Specialization is a trend that directly causes a loss of biodiversity (e.g., pollinators, soil microorganisms, wildlife), interferes with proper ecosystem functioning, and increases financial risk (de Faccio Carvalho et al. 2021a). Despite this trend toward increased specialization, we showed some cases that are transitioning towards ICLS in three regions worldwide. All the producers interviewed were already engaged in ICLS and had experienced a turning point that changed the direction of their systems, which is why they were strategically selected. Our sample represented producers who are ICLS information seekers, risk takers, and sources of inspiration for researchers and among some of their peers. By being information seekers, they were all aware of ICLS concept benefits and implications, by being risk takers, their protagonist and proactivity attitude in dealing with barriers was evidenced in their trajectories and examples. The feedback from producers' practical experience showed that the process of changing made them search for new ways of working and thinking (Coquil et al. 2018). Therefore, transitions challenge producers that are diverging from the status quo by going against the specialization trend (as BR5 expressed; see Section 3.3). As in regenerative agriculture, the transitions towards ICLS require a commitment to change connected with attitudes for improving the practices over a journey (Cusworth and Garnett 2023). These authors also recognize integrating livestock in cropping areas as one of the five practices towards regenerating natural ecological functions.

### 3.2 Core ICLS findings, by region

Globally, ICLS have declined in most regions including US and FR, but in some parts, as in Brazil, it has persisted and even reemerged (Garrett et al. 2020). In our attempt to explore ICLS cases in three agroecological geographies, our collaborative working group enabled the multi-case study approach. Further dialogue and data collection coordination

**Table 2** Example of category consolidation in common themes, super themes, and main categories about perceived drivers of integrated crop-livestock systems (ICLS). *n* number of quoted passages (producers may be quoted several times on the same subject). Regions: the northern Great Plains in the United States of America (US), the state of Rio Grande do Sul in Brazil (BR), and the region of Occitanie in France (FR). When there is "FR FR," for example, it means that two different producers from France responded about the same subject.

| Category | Super themes | Theme | Codes | *n* | Region |
|---|---|---|---|---|---|
| Drivers to ICLS | Cover crops | Benefits | Cover crops enhance wildlife habitat | 1 | US |
| | | | Cover crops bring versatility | 3 | US FR |
| | | | Cover crops are an investment to restore degraded land | 3 | US FR FR |
| | | | Cover crops help with less winter feed costs and reduce input costs | 5 | BR US US |
| | | | If there is a weed problem (e.g., in organic system), the crops can be used for animal feed | 1 | FR |
| | | | Cover crops are profitable with livestock as financial returns on livestock pay cover crop bills | 15 | BR BR US US US US US FR |
| | | | Cover crops can be a protein source for feeding livestock | 3 | US |
| | | Mix of species | A mix of cover crops can improve resistance to drought | 1 | US |
| | | | Allows longer rotations (e.g., including perennials) | 1 | FR |
| | | | Different cover crop species (i.e., up to 23) from other groups (warm and cool season grasses, legumes) | 17 | BR US US US US US FR FR |
| | | | The diversity of species mimic native prairies | 6 | US |
| | ICLS advantages | Livestock importance to ICLS | Livestock as an alternative for areas not suitable for cropping | 4 | US US FR |
| | | | Opportunity to graze stalks and stubble after crop harvesting | 6 | US US US |
| | | | Livestock can be more resilient (less risk) than cropping | 5 | BR US US |
| | | | Livestock brings flexibility to the farm's cash flow | 4 | BR BR US |
| | | Livestock importance to soil in ICLS | Livestock do not imply soil compaction when properly managed | 6 | BR BR BR BR US |
| | | | Livestock enhances soil health | 14 | BR BR US US US US FR BR US |
| | | | Adding animal manure helps to fertilize cropping areas | 5 | FR FR FR |
| | | | Biodiversity enhances nutrient cycling | 3 | U FR |
| | | | Adding legumes to pasture mix allows nitrogen fixation | 4 | BR FR FR |
| | | | A higher % of organic matter results in fewer inputs needed | 3 | BR US |
| | | | System fertilization (i.e., planning the fertilization for the entire ICLS, not just the crop separated from the pasture) | 7 | BR BR |
| | | | Looking at the whole system is important for soil health | 2 | BR US |
| | | | Increase of organic matter due to grazing | 3 | BR BR US |
| | | | Livestock recycling nutrients reduces the need for inputs | 2 | BR |
| | | Complementarities of crops and livestock | Sharing equipment, nutrients, and human resources | 4 | BR US US |
| | | | Increasing system autonomy | 13 | FR FR FR FR FR |
| | | | Diversification of activities | 6 | US US US US |
| | | | ICLS have good short-term results and, looking for long term, can have even better results | 3 | BR BR |
| | | | Perennial pastures add carbon to the system | 6 | BR BR US |
| | | | Trees are ICLS components that can provide natural soil protection, fertilization, provide insects, fungi, and wild animals' habitat | 5 | FR |
| | | ICLS partnerships positive points | In partnerships, livestock producers do not have crop risk | 2 | US |
| | | | Landscape integration can be an alternative of ICLS | 6 | FR |
| | | | Opportunity of increasing carbon stocks in exchanges of straw-manure | 1 | FR |
| | | | In partnerships, crop producers do not need to own cattle | 1 | US |

allowed us to focus on commonalities among each region due to the nature of the data that emphasized rich and explanatory depth rather than statistical representativeness across all producers. As a result, our ability to more fully analyze the distinctions between some cultural and economic differences among regions was limited. Therefore, in this section, we will focus on how the producers interviewed addressed different strategies for achieving ICLS goals in each region of our study.

#### 3.2.1 Brazil ICLS: pasture management through advising

The five cases from southern Brazil had individual advisor specialized in ICLS in common. Advising occurred either by participating in public extension programs (i.e., individual advising + group activities) or privately. All Brazilian producers had livestock and crop production decoupled, but once advising started, they transitioned to integrated crops and livestock at farm level. During the interviews, all addressed the changes that resulted from having an advisor for supporting them from planning stage, transitioning towards ICLS up to monitoring the performance of the system. The role of advisors in this case of fostering ICLS is broader than prescribing punctual solutions, as it should encompass facilitating knowledge exchanges and approaching strategic and systemic implications of farming decisions (Moojen et al. 2023). In Fig. 3, we briefly illustrated part of the "cascading of positive feedback" that started with the BR3 producer's farm since they started to participate in an advising program named PISA (The Integrated Production in Agricultural Systems - referred as PISA, a Portuguese acronym for *Produção Integrada em Sistemas Agropecuários*). It shows how pasture management can have a direct impact on benefiting multiple dimensions of farming practices; the pasture management and cascading feedbacks are further described in (de Faccio Carvalho 2013; de Faccio Carvalho et al. 2021b).

The producers emphasized that with advising they could benefit by learning mainly about (i) pasture management (for improving animal performance, beneficiating the crop phase, having a low-cost animal feed, improving soil quality by working to increase organic matter and root production); (ii) fertilizing pastures (most Brazilian producers only fertilize crops and not the pasture); and (iii) ICLS farm design (looking for long-term systemic benefits). Soil health was a top priority for the Brazilian producers, and all had been practicing no-till for decades. The livestock are mainly (sometimes only) grass-fed, raised on grasslands and cultivated pastures (i.e., usually Sudan grass and ryegrass). One of the producers illustrated the point this way:

> The advisor brought the university [knowledge] into my operation. Things that we thought were correct, [because] the neighbor did like that, and as my father did like that. Today, with [the advising program] and with the advisor inside the operation, they brought the [proper ICLS] knowledge. It is with the knowledge that we progressed...Another thing is the [grazing] management that [the advising company] taught us -- the straw left after grazing. (i.e., they used to overgraze before) -BR1

In Brazil, ICLS is also addressed as an opportunity to restore degraded pastures, a land "spare effect," and to add diversification by reconnecting grazing livestock into monocropping areas; with a political fostering by electing ICLS in the technical pathways recognized as greenhouse gas mitigation option (Cortner et al. 2019; de Faccio Carvalho et al. 2021a).

#### 3.2.2 US ICLS: soil improvement through conservation agriculture

The five cases from the US had a significant focus on soil health, mainly related to the inclusion of cover crops and adopting no-till practices. They all mentioned researchers, institutions (e.g., Soil Conservation Districts), and programs (e.g., mentorship programs) as sources of knowledge. During the interviews, they addressed (i) cover crop management (all producers used a diverse mix of species, and four of them used the cover crops for grazing); (ii) stopping tillage (for reducing soil erosion, increasing carbon stocks, increasing resilience to drought); (iii) the importance of adding livestock (to increase soil health and lower winter feed costs). One example related to cover crop mix was:

> So, I think that we really need to look very closely at how the prairies function and mimic that in our cropping operations every chance we get. (…) So instead of a monoculture of one crop at a time. We can put 15-20 of those species back. So, you get 15-20 percent of what was maybe there instead of 1 percent, and that is synergism. But those plant roots really enhance the biology in a short period (…) we're starting to work with nature instead of against nature, and the results are really positive" –US3

ICLS is commonly used for soil health improvement by grazing cover crops in crop landscapes (Sulc and Franzluebbers 2014). Although the strategies seem distinct from one another, they all address core principles of restoring ecosystem function and considering each land's sustainable potential (Liebig et al. 2017; de Faccio Carvalho et al. 2021a).

#### 3.2.3 France ICLS: achieving self-sufficiency by reducing inputs

The five cases from southern France focused primarily on self-sufficiency (i.e., less dependence on external inputs) in their production systems, both on crop inputs and livestock feed. During interviews, recurring themes were (i) searching for ways to increase self-sufficiency in animal feeding (by diversifying the system and having on-farm protein sources mainly for dairy production—e.g., combining protein-rich fodder such as alfalfa, some mixed crops in particular cereal-protein for grain or silage), (ii) direct sales (for getting immediate feedback from consumers and increasing economic margins), and (iii) transitioning into organic (by making a progressive transition, guided by training and a mindset change). Three producers had organic systems (i.e., no chemicals), and two mentioned the challenge of managing weeds in organic systems, so tillage was still a major component of their management. To illustrate a reason behind autonomy search, one producer mentioned:

> Non-autonomous systems, as we can see, are the most fragile. After years of drought, there are more people who are not self-sufficient, but in a normal year, we have to be self-sufficient. You are dependent on others; otherwise, the others make room for you, and you decide nothing more (…) protein autonomy is our preoccupation for the moment- FR2

The shift from high external input fodder systems to more autonomous systems is an opportunity to optimize the relationship between animal demand and the available on-farm feed resources (Bonaudo et al. 2014).

## 3.3 Experiences and perceived levers toward ICLS: from synergies to mindset

We highlighted five main themes perceived as levers towards ICLS (Fig. 4): cover crop inclusion into crop rotations, soil conservation, added benefits from livestock, open mindset, and multi-level synergies. Each main theme grouped the main points addressed during the interviews.

### 3.3.1 Cover crop inclusion into crop rotations

Cover crop inclusion into crop rotations was highlighted as a sustainable practice for (i) providing soil cover through living plants (i.e., not just straw in no-till areas), (ii) increasing plant diversity in rotations, (iii) restoring degraded lands, (iv) feeding animals (i.e., can be a protein source, reduce winter feed costs), (v) enhancing wildlife habitat, and (vi) lengthening crop rotations (e.g., instead of annual rotations, by including perennial pastures it is possible to have longer rotations). The diversity provided through implementing mix of cover crops was mentioned as capable of "mimicking prairies" and improving drought resistance. Specifically looking into the diversity of plants, FR4 stated:

> The rotations are summer/winter, but it is still cereals after cereals. So why not put some diversity back? —FR4

### 3.3.2 Soil conservation by no-till practices

Most producers pointed out soil health concerns. Soil health was considered a priority by US3 and by FR1:

> Our farming operation is based on soil health, soil health drives everything. —US3
> So, the logic is to preserve the soil, to restore the organic matter, to make the crop associations and to optimize in the cereal-livestock system. —FR1

BR3 addressed soil management as the starting point toward sustainability:

> The first thing is to start at the base, which is the soil. Most people make mistakes because they want to do things by running over and don't start by the soil [management]. —BR3

A common point emphasized by all interviewees from Brazil and the United States as well as one in France emerged describing the use of no-till as a beneficial soil conservation practice. They stressed the importance of stopping tillage practices to (a) improve soil health, (b) avoid soil erosion, (c) reduce the dependence on subsidies (i.e., only in the French context), (d) enhance biological properties, and (e) increase resilience to drought periods (i.e., more soil water content available). Three producers illustrated their experiences from no-till:

> Whatever rainfall falls, I'm going to infiltrate them because of the organic matter levels we have, we're going to be able to store. So, I don't have to worry about a drought anymore. —US1
> We took tillage out, and when we did that one thing, that's when everything turned around. It affected our machinery lines, it affected our financial lines, it affected our crop production, it affected our inputs, and it affected our soil health, and all of those things in a very, very positive way. —US3
> Just from the no-till, we noticed the earthworms, and the condition of the soil are a lot better now. — US5

Looking to improve soil health was a common strategy for producers in all the regions studied. The use of no-till is one soil health practice considered an environmentally friendly way to protect soils from erosion and compaction, conserve moisture, and reduce production costs (Holland 2004). Other soil health practices such as crop diversification, and ICLS, when combined with no-till, can not only

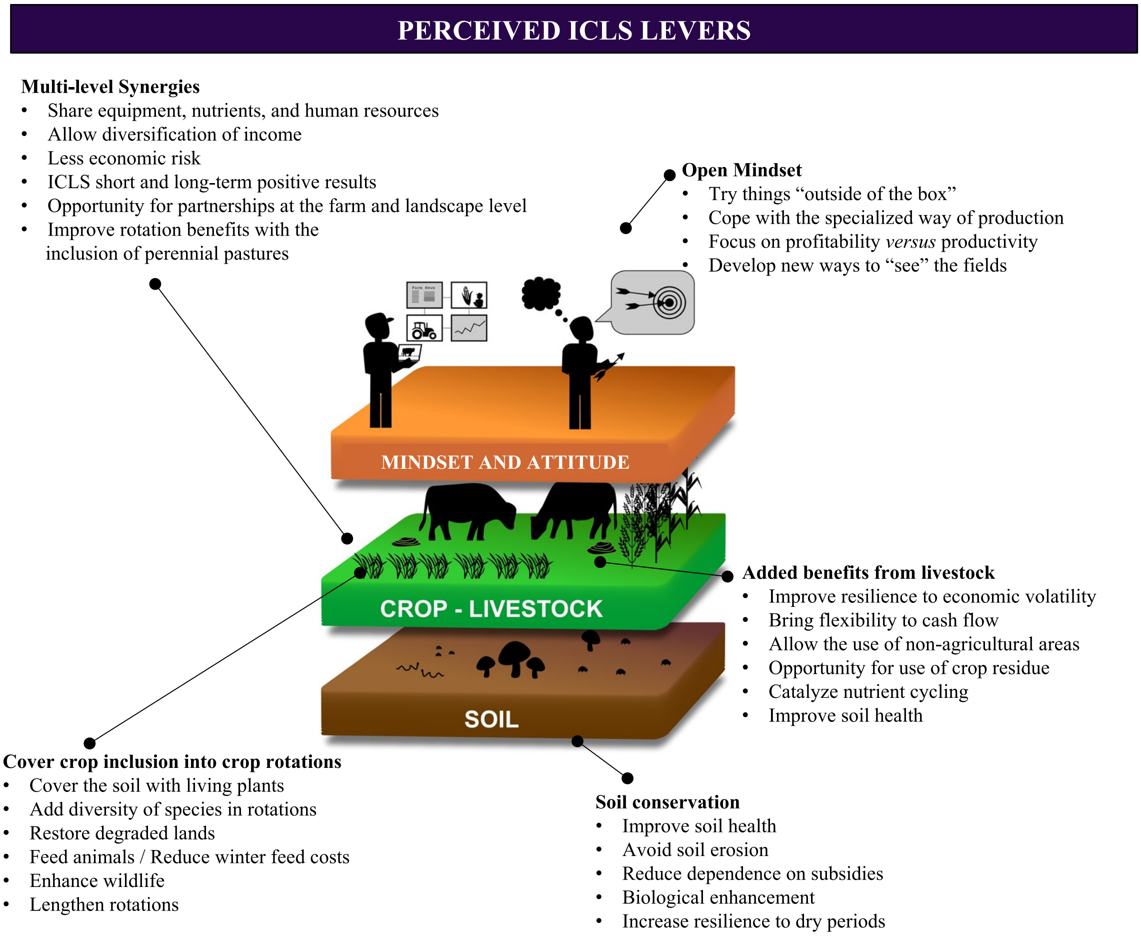


**Fig. 4** Producers' perceptions of levers towards sustainable integrated crop-livestock systems (ICLS).

be beneficial in the long term, but they also have short-term positive impacts on soil quality by increasing the particulate organic matter fraction of the soil carbon stock (Martins et al. 2017). Moreover, under controlled grazing intensities (i.e., avoiding overgrazing or under-grazing), soil aggregation (i.e., physical aspect), nutrient availability (i.e., chemical aspects), and soil microbial activity (i.e., biological aspect) are also significantly improved when compared to cash crop rotation without livestock (de Faccio Carvalho et al. 2010; Deiss et al. 2020).

#### 3.3.3 Livestock importance to promote sustainable systems

Producers feel including livestock is critical to improving system stability. They mentioned that livestock (i) increase resilience to economic volatility, (ii) bring flexibility to cash flow, (iii) serve as an alternative for production in non-agricultural areas (i.e., rangelands, rocky or sloped areas), (iv) allow the use of crop residue, (v) help in nutrient cycling by both the practice of adding manure and by directly grazing, and (vi) improve soil health. To illustrate livestock benefits, producers mentioned their experiences:

> The organic matter is starting to increase, which is very difficult for the agriculture of grains. In areas where livestock is used, it is much easier to improve the organic matter. —BR5
> We try to keep cattle on the land as it is building soil health. —US2
> I spread manure in my plot, and we end up with very living soil. —FR5
> If cattle graze it [cover crops], that's a good thing. Because then you get the manure, and you get the biology in the manure that put back in the soil what's missing. —US3

However, BR3 stressed the importance of livestock presence being well monitored:

> From the moment we started proper grazing management, the animals are recycling nutrients. In addition to defecating and urinating, every bite the

animal gives to the plant at the right time will generate many more leaves and many more roots. —BR3

Studying the effect of adding a trophic level to crop systems, de Albuquerque Nunes et al. (2021) and Martin et al. (2020) showed that livestock inclusion increases system stability and profitability. Livestock enhances resilience since livestock production is a less risky activity to conduct with increased climate variability and has less exposure to the price volatility of feed resources—when animals are grass-fed (Szymczak et al. 2020). Also, when grazing, ruminants catalyze nutrient cycling by breaking down complex plant molecules into more bioavailable forms helping to maintain or even improve soil fertility (Deiss et al. 2020). Livestock transforms most of the ingested forage into urine and feces, so, in integrated systems, they are only responsible for 5% of the exportation of nutrients (i.e., in meat production) compared to 95% exported by grain production (Alves et al. 2019). Improved grazing management also represents a considerable mitigation opportunity for greenhouse gas emission intensities in ICLS (de Souza Filho et al. 2019). Altogether, livestock provides multiple unique benefits to agroecosystems, allowing ICLS to be more efficient in food production compared to specialized systems.

Interviewees said ICLS land use included both the use of livestock in non-agricultural areas (i.e., rangelands, areas not mechanizable) and in agricultural areas (i.e., rotations over space-time, using the grains and residues to feed animals). One land use strategy highlighted during the interviews was the inclusion of perennial pastures into crop rotations. Perennial vegetation can enhance the provision of a wide range of goods and services to society, such as water quality regulation and preservation of habitats (Asbjornsen et al. 2014). Including perennial pastures in no-till crop rotations can also reduce weed infestation, which can result in either a reduction or elimination of herbicides—reducing the costs considerably—without crop yield loss (Dominschek et al. 2021). Also, Hendrickson et al. (2014) found that on transitions from perennial pasture grazed to annual crops, no-till is not only a compatible alternative, but it was also the best option in the following crop yield. Another land use strategy is the inclusion of annual winter-planted cover crops, which do not compete with cash crops since they are usually planted after crop harvesting (Roesch-McNally et al. 2018). This strategy reflects the reality both in temperate regions, where only one crop is grown per year due to severe winters, and in subtropical regions, where large production areas can remain unproductive during the winter despite a potential use (de Moraes et al. 2014). ICLS can also restore vast areas of degraded pastures (Bonaudo et al. 2014; Cortner et al. 2019; Pontes et al. 2021), meaning that there is a large area globally that has the potential for ICLS adoption.

#### 3.3.4 Open mindset

A fourth lever towards ICLS perceived by producers was an open mindset for (i) trying things "outside of the box," (ii) coping with the narrow commonsense way of specialized production, (iii) setting profit goals, and (iv) developing new ways to "see" the fields (i.e., less homogeny, some degree of weed infestation). For example, BR5 stated "for profitability, I think in the medium term using less input, from utilizing the same input twice [reference to nutrient recycling]." Also illustrated as "you have to think about the margin and not productivity"—FR2. The production-centric logic has dominated agricultural thinking for a long time, and it directly impacts the producer's mindset and practices (Šūmane et al. 2018). Church et al. (2020), studying producers who adopted cover crops, found they were more likely to be systems thinkers and tended to understand connections and contemplate alternative perspectives in their decisions. Therefore, transitions towards ICLS require a change from an emphasis on yields to focusing on the profitability of the whole system (i.e., gross margin per land unit) by integrating intensification options, along with environmental sustainability at the farm system level (Jaurena et al. 2021). In order to analyze whole system impacts, multicriteria analysis as the methodology IDEA (Zahm et al. 2019) and whole-farm modeling like MIDAS (Pannell 1996) can be tools to help, and, recently, serious games are gaining importance as tools with a pedagogical role on training producers with ICLS (Etienne 2003; Martin et al. 2011; Salvini et al. 2016; Jouan et al. 2020; Moojen et al. 2022b). But still, the lack of robust platforms for producers and advisors to plan and evaluate the performances of the ICLS that are user-friendly remains a barrier, as most of the tools only focus on productive and/or financial analysis of each component (either crop or livestock). Interactive whole-farm optimization models seem a promising participatory way to support system analyses (Mössinger et al. 2022).

#### 3.3.5 Multi-level synergies

Producers highlighted a variety of synergies appeared from connecting crop and livestock components in ICLS, including (i) sharing equipment (e.g., machinery), infrastructure (e.g., buildings), nutrients, and human resources; (ii) diversification of income and reducing economic risk; (iii) positive results in both the short term (e.g., more productivity) and long term (e.g., more stability); (iv) opportunity for partnerships at farm level and landscape level (e.g., the crop producer does not need to own and manage cattle and livestock producer does not need to own machinery and manage crops); and (v) including perennial pastures for livestock in rotations to improve soil quality benefiting subsequent crop production. To illustrate operational synergies, two producers noted:

> The way to generate real profit is by taking the waste stream of one enterprise [i.e., crop or livestock] to fuel the profit of another. So, like our grain business, because I try and add value to everything, most of the grain we raise, if it is not for the consumption of our livestock, it's for cover crop seed. —US1
>
> It's much more flexible; it allows you to wipe out a few mistakes, plots, where the potential is not there [e.g., due to weed infestation], it will become fodder. —FR1

The wide variety of crop-livestock synergies mentioned are aligned with the current literature regarding ICLS (Lemaire et al. 2014; Asante et al. 2019). The diversification of income with the inclusion of livestock into crop systems can, on average, double the overall gross margin, being important both in wet years to increase the economic gain and to avoid economic loss in years with low rainfall (de Oliveira et al. 2014; de Albuquerque Nunes et al. 2021). Another study in tropical Brazil showed higher levels of profitability and return on investment and lower payback periods and economic risk in ICLS compared to specialized systems (dos Reis et al. 2020). In France, Ryschawy et al. (2012) showed lower sensitivity of ICLS gross margins to variation in input and sales prices. These authors also underlined that ICLS are mostly found in unfavored areas, where "economic results are limited by soil and climatic conditions," which highlights the importance of fair comparisons to interpret the results from crop and livestock operations.

## 3.4 Experiences and perceived barriers towards ICLS: from mindset to beyond gates

As barriers towards ICLS, we identified three main themes (Fig. 5): changing mindset, inside the gate, and beyond farm and ranch gates.

### 3.4.1 Changing mindset

The adoption of ICLS goes beyond a single additional technology that only copes with a specific objective (e.g., new herbicide) or an incremental adaptation (e.g., adding an irrigation system). ICLS imply a transformative adaptation from specialized systems that shifts the appearance, process, products, finances, and vision of the system (Fedele et al. 2019; Cortner et al. 2019). Therefore, ICLS require a mindset-changing process that starts with a disruption from a specialized to an integrated and systemic way of thinking (Moojen et al. 2022a). The producer mindset was perceived as a lever (see Section 3.2) but also as a barrier. Changing the mindset from simplified, specialized systems (e.g., monocropping) towards a systems-thinking approach in ICLS presents challenges because of decision-making complexity. The interviewees indicated that (i) most of their peers are not aware that their current systems are unsustainable; (ii) most of the advisors still practice "old models" (i.e., only focus on the short-term increase of productivity); (iii) they did not have many examples of neighboring producers to provide inspiration (i.e., the challenge of being pioneers); (iv) not addressing the whole system during decision-making; (v) producers' immediatism present barriers to long-term achievements; (vi) some producers believe livestock reduces crop production, so they do not consider trying ICLS; and (vii) not having contact with ICLS sources of knowledge. To illustrate, BR5 said:

> The challenge is the mindset, is to change, thinking about the system, and believing in science, believing in research in the results. This is fundamental, and you have to have the humility to change your system to see that there are ways to do it better.
>
> [Transitioning towards ICLS] it's quite lonely. [For example] I was building a fence on another area, [I] look around, there isn't a fence [just crops no livestock], nobody has a fence, what was around was demolished (…) But that's it, it's going against it. Everyone's running one way, and you're running the other. —BR5

Studying ICLS adoption, Gil et al. (2016) found that, on average, adopters are more educated and have better access to technical assistance and sector information than specialized producers. One specific point related to the "lack of awareness and how to manage these systems properly" was the "thinking that livestock reduces crop yield," which is still a concern for many crop producers despite extensive literature demonstrating that livestock integration improves long-term system stability and profits without compromising crop yields when properly managed (de Moraes et al. 2014; de Albuquerque Nunes et al. 2021). Overall, a lack of awareness and training to deal with more complex systems can be an important barrier to spreading ICLS.

### 3.4.2 Inside the gate

Besides mindset, producers identified barriers inside "the farm gate," meaning into producers' control. Inside the gate, the barriers were operational (e.g., higher workload due to livestock requirements, bad pasture management, higher cost with fencing and access to water for livestock in crop areas) and related to human capital (e.g., conflicts of interest between partners, communication that is not assertive, lack of employees properly trained and aware of ICLS objectives). US5 pointed out short-term contracts for leasing the land as a barrier:

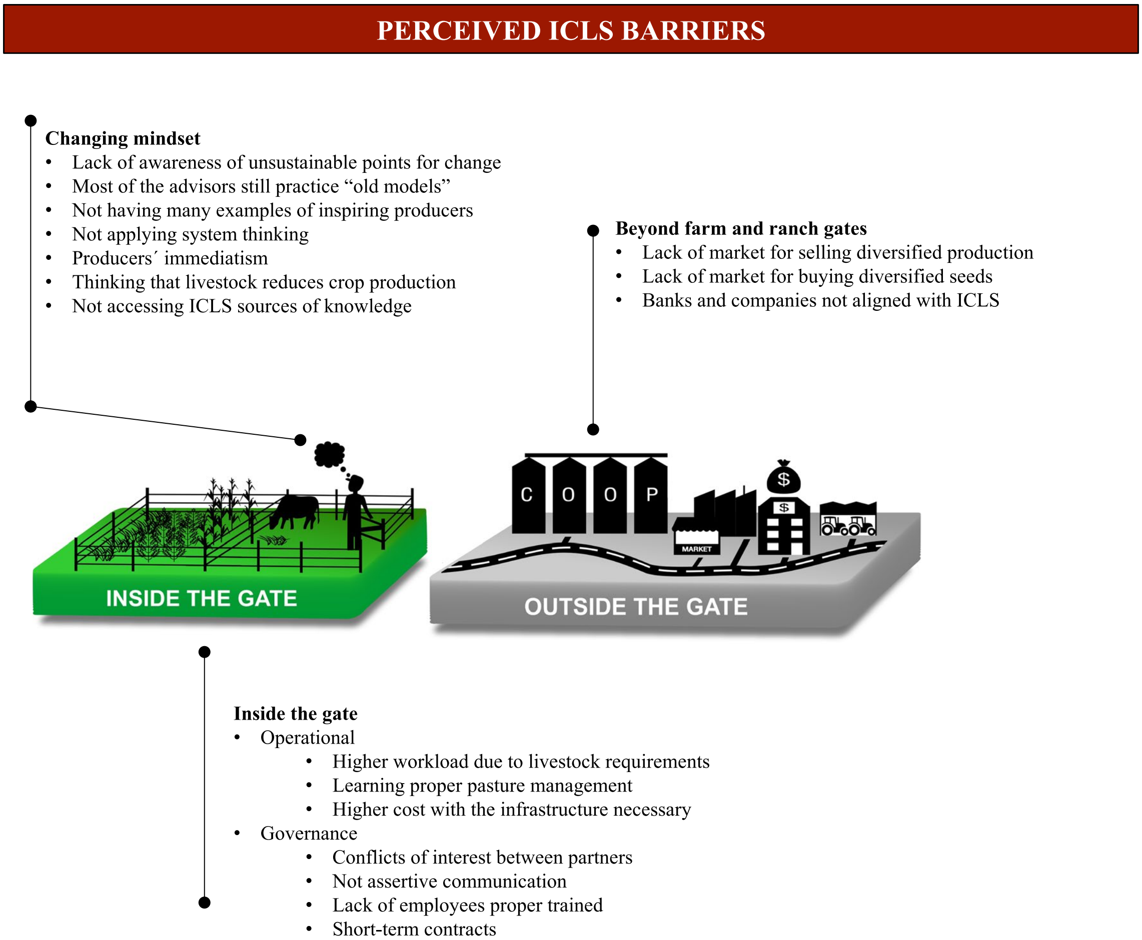


**Fig. 5** Producers' perceptions of integrated crop-livestock systems (ICLS) barriers.

> We need, in my opinion, to make this work in longer-term contracts (…) because soil health really needs livestock. That's where you truly will build it [soil fertility]. But somehow, there's got to be an incentive that I could put water out there and fence. So, I need a ten-year contract; at least you know, 20 would be better. —US5

The inherent complexity of ICLS brings a higher level of operational management, where each farming enterprise (i.e., crop × livestock enterprise) requires particular skills, knowledge, and attention to be operated effectively (Bell and Moore 2012). The authors also mentioned the challenge of allocating resources between enterprises and investing in fences for livestock to be introduced in cropping-only areas. Besides infrastructure, including livestock in crop farms also requires a workload throughout the life cycle of the animal, which contrasts with a more concentrated workload in exclusively crop-focused agroecosystems. In US, economic analysis showed that ICLS require greater capital and labor inputs than the dominant cash-only grain system (Poffenbarger et al. 2017). In the partnership aspect, producers brought up deep concerns about the lack of custom contracts between crop and livestock producers that are critical for proper ICLS management. Sulc and Tracy (2007) also addressed the importance of establishing collaborative and mutually beneficial relationships among producers, despite the scale of integration (i.e., at the same land base or in spatially separated areas—territorial level). An example of partnership at the territorial level is found in Maine-US, where potato growers set up cooperative arrangements with livestock producers to utilize their fields for fertilization with cow manure and forage production for dairy production. Other example includes sheep grazing in vineyards, walnut orchards, peach orchard, and olive orchard worldwide (Schoof et al. 2021; Ryschawy et al. 2021; Farias et al. 2022).

### 3.4.3 Beyond farm and ranch gates: structural barriers

Beyond farm and ranch gates, perceived structural barriers were related to market availability for selling diversified production and for buying diversified cover crop seed. The lack of marketing opportunities for diversified production was also described by Cortner et al. (2019) in their study. Seven producers pointed out that most financing agencies and companies (as fertilizers and machinery sellers) focus on the economic aspect of their products regardless of how it impacts the system. According to one producer, the companies (like grain traders) do not prioritize social and environmental impacts since they focus on buying the product. BR3 exemplified that in his region, a barrier is that:

> There's a lot of pressure from the cooperative grain system to produce grain in the winter. But our business is winter livestock (i.e., having pastures instead of crops), and people beat it a lot. —BR3

Garrett et al. (2020) proposed a redesign of research programs, credit systems, and insurance programs to focus more on whole-farm outcomes in the long term to cope with the structural barriers such as the lack of awareness and the ability of companies and banks to compromise to clearly support ICLS producers. The authors also suggested the need to brand ICLS as sustainable agriculture through new labels, which would help to develop well-aligned market options. The stakeholders could then directly benefit from greater ICLS adoption.

### 3.5 Turning points in producer farm trajectory toward sustainability

We identified as "turning points" all the programs, human influence, and system disturbances that producers mentioned as factors that influenced changes towards sustainability practices in their trajectories (Fig. 6).

### 3.6 Programs and initiatives

As programs or initiatives, in each study region, different examples applied from the array of turning point catalysts: training, tours to see peers, field days, seminars, mentorships, advising programs, and visits to long-term research. These initiatives varied in being provided by universities, research centers, conservation offices, and private and public advising companies. US3 advocates that "For me, what made us successful is mentorship," and he attributes that to the fact that during the mentorship, trust was established:

> I just had to get to the point where I believed what they were telling me was true (…) when I saw them doing [cover crop adoption], I knew they were right. So, I just quit questioning it. And I just took it at face value. They are right. And [I] applied at home, and it worked. —US3

Initiatives such as demonstration sites and field days are recognized to influence the adoption of sustainable practices as they allow producers to visualize and learn from experts and peers (Singh et al. 2018; Sutherland and Marchand 2021). Demonstration areas not only help those who are interested in implementing new practices but also help sustain producers' adoption (Singh et al. 2018). Sustaining ICLS adoption was highlighted in our interviewees by the need for periodic reinforcement of convictions. On a more extensive scale, the Grain and Graze ICLS project in Australia was an example of a blending of strategies (i.e., demonstration and trial sites, training courses, publications, tools, and manuals) that helped more than 3000 producers to adopt ICLS-recommended practices (Hacker et al. 2009). Another remarkable program is the PISA project in Brazil that has the ICLS as a major conceptual pillar and has reached more than 1800 smallholders since 2009 (de Faccio Carvalho et al. 2022). The authors describe that a great part of the PISA project success—assessed by SAFA (FAO 2014)—was related to the establishment of a consistent and trusted producer-advisor relationship. Drawing from these examples, to scale up ICLS adoption, programs, and initiatives should (i) promote co-learning spaces, opportunities to learn from mistakes, and guidance on redesigning the production system and (ii) foster a trusting relationship between producers, researchers, and advisors. Enabling co-learning spaces via initiatives or projects involves researchers and advisors performing a variety of roles for supporting producers during transitions (Price et al. 2009; Dockès et al. 2019). Trust can be built through interactions over time, based on perceptions of competence and commitment of those involved (King et al. 2019).

#### 3.6.1 Human influence

When addressing human influence as a turning point, producers mentioned the influence of peers, ICLS advisors, and researchers. To illustrate the adoption of no-till as mentioned earlier, US1 said:

> In 1993, I had a good friend in the northern part of the state, he was no-tiller, and he said — you need to go in no-till in order to save time and moisture. That made sense to me. — US1

For ICLS adoption, BR5 mentioned an event led by a researcher:

> So, from that talk (of a researcher), I saw that it really was possible [to adopt ICLS], that science was proving that it was possible, that many good things in the system could happen. And that motivated me! That was the initial move for a new livestock moment on

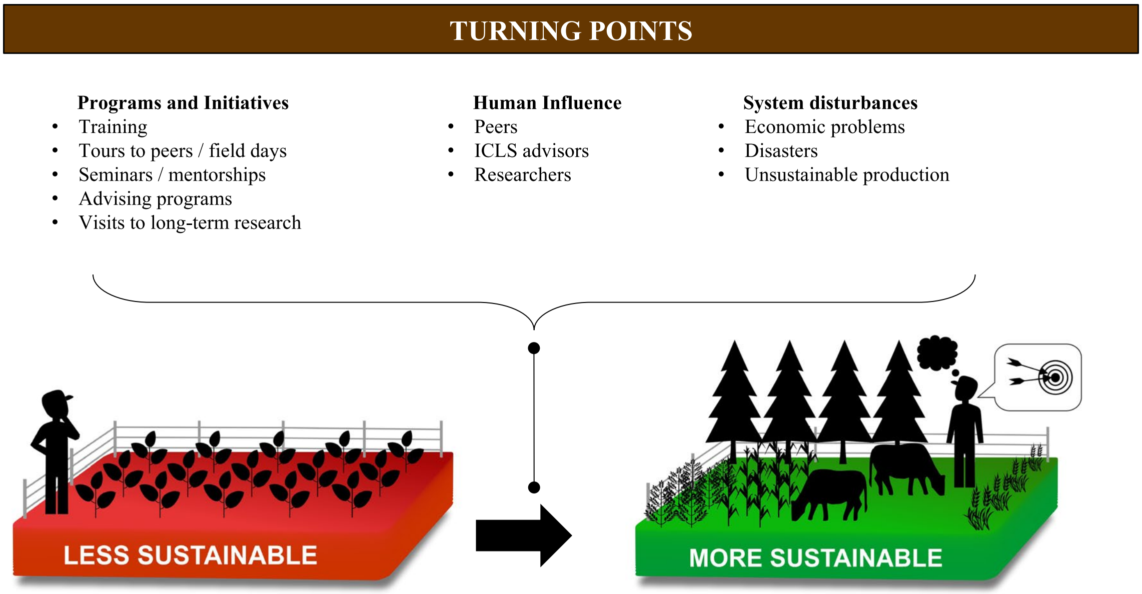


**Fig. 6** Producers' perceptions of turning points towards more sustainable agroecosystems.

> my property. That meeting was very important; there were concrete research data that showed the direction that the integration of crop-livestock farming could take. — BR5

The influences and the way of interaction ranged from informal peer visits to more formal workshops carried out by researchers and advisors. Producers learn directly from other producers in multiple ways, from conversations to visual observation of farming practices (Sutherland and Marchand 2021). However, Cofré-Bravo et al. (2019), studying on-farm agricultural innovation through different support networks, found that it is important to have a balance between closed (e.g., peers and family members to start using proven technologies and practices) and open (e.g., connection with researchers and advisors, for accessing alternative technologies and practices from off-farm sources) networks but there is no single recipe to the best configuration. In addition to fostering physical and human capital, enabling social capital from different actors also becomes essential to provide knowledge and emotional support for the turning points in a farm trajectory toward ICLS.

### 3.6.2 System disturbances

Finally, producers described a third main turning point as system disturbances, such as economic problems, disasters (e.g., dairy crises), and unsustainable production (e.g., productivity not increasing and crop failures). One clear example mentioned by BR3 was both an unsustainable scenario together with the beginning of an extension program led by a researcher:

> [we needed to change] or we have to leave the property (…) because there was no income, we had no way to continue like that, live like that. With this knowledge arriving, we didn't even know who (the researcher) was; we were smallholders who were always working, taking care of chores. —BR3

Another example of a turning point towards no-till was related to the context of unsustainability:

> It was soil erosion. In light soils, as soon as a drop of water fell, it went down with the soil at the bottom [i.e., no organic matter to hold water]. We saw that it couldn't last in time; it was not sustainable. — FR2

The unfavorable contexts were catalyst factors to profound changes or "turning points" in the farm trajectories studied. Van Dam et al. (2010), in a study concentrating on transitioning to organic production, advocate that there is a "decisive unit" from a set of biographical events with a strong emotional charge that generates cognitive dissonance and psychological discomfort in significant transitions. Changes toward ICLS may have similarities to these processes studied in transitions to organic, as cognitive work must be done to restore consonance after initiating a new system. Dissatisfaction and frustration with unsustainable productivity and economic results during unfavorable climatic years or economic contexts also motivated changes, according to our sample. So, because of the systemic nature of the current agricultural challenges, regarding high input dependence and the decoupling of biogeochemical cycles, small incremental adjustments may not be enough to effectively result in long-term changes (Fedele et al. 2019). Given these contextual parameters, consideration of the full redesign of agroecosystems is needed transformational changes (Romera et al. 2020), as experienced by most of our interviewees. The first steps (i.e., short-term) in a transformational change may be visiting other producers to get inspired and implement testing areas, gain experience, learn from mistakes, and test without compromising cash flow. Also, the redesign needs to depart from a diagnosis of capabilities and limitations of the operation, ranging from soil aspects up to the human resources willingness, to have a design that fits all that in the long term (Liebig et al. 2017; Moojen et al. 2022a).

### 3.7 Emerging themes in ICLS development

During the semi-structured interviews, two themes emerged around working with families and diversifying income. These important topics in agriculture are concerns that can be related closely to ICLS (Sanderson et al. 2013; Dogliotti et al. 2014; Bell et al. 2021). The family theme was related to pride in the legacy of past generations, ways of working together with the next generation, and the challenges of succession for the operation overall. The idea of "pride of the legacy" is in line with Ingram et al. (2013), who state that "overarching life-long motivation farm continuity" relies on decisions driven by a blend of past experiences, traditions, and future desires. Inwood and Sharp (2012) evaluated trajectories from family farms once the next generation decides to stay and identified several patterns of adaptation producers use to grow the farm. One adaptation is horizontal growth (i.e., renting or buying extra land), and another is vertical growth (i.e., intensifying and/or entrepreneurial stacking). In our study, some producers used income diversification as vertical growth. For example, four producers mentioned starting direct sales to add value to their production.

Other methods of income diversification included adding new business activities such as honey production, agritourism, dairy processing on-farm, and hunting operations. Tourism and recreation constitute potential benefits of ICLS because ICLS add landscape preservation, environmental value, and local origin, which helps in adding value (Moraine et al. 2014). Also, agritourism can help not only in the economic dimension of sustainability but also in the social dimension by providing job opportunities to family members and learning opportunities to visitors about agriculture and the rural world (Ammirato et al. 2020). Long-held beliefs can hinder the adoption of new practices; however, bringing new family members into an operation may foster exploration of additional income opportunities and provide new expertise to the human capital (Sassenrath et al. 2010). Despite all the benefits, producers also reflected on how working as a family can also present great challenges. It can be difficult to align expectations and share plans over different life moments for each generation. Overall, these examples of family dynamics from our sample are all connected to the idea of growing a sustainable business and can be inspiring for their peers.

## 4 Conclusion

This study aimed to address barriers to ICLS adoption by analyzing producers' perceptions of ICLS, identifying trajectories and turning points that made them interested in ICLS as a way to improve sustainability. Even though the perceptions differ by regional case in our analysis, a clear pattern of commonality exists in conscious and proactive actions among the cases studied. Perhaps the most telling and promising evidence from this analysis comes in the form that, despite the many barriers and despite the complexity of overcoming most of those barriers, turning points and transitions within producers' experiences *can* happen. And they *do* happen across time and space in ways that illustrate common phenomena not tied to only a specific agroecosystem type. The common thread that ties seemingly disparate and disconnected cases together is the challenge of integrating the system components into a design that matches the resources and goals of each individual system. The challenge of adapting the transitions to local situations is even more complex to ICLS than to specialized systems as they rely on the multi-dimensional features of sustainability and have different time and spatial scales and often occur as interdependent contingencies. To reduce the barriers regarding the operational level, extension teams are key—private and public—and need to work in close contact with researchers and stakeholders to assist producers in dealing with a more sophisticated level of management (e.g., on decisions about resource allocation) that ICLS require.

The transitions—started or catalyzed by "turning points"—become evident across global contexts and production settings, illustrating the need for scaled opportunities among regions—or even communities of producers within regions—to share experience, knowledge, and management strategies. These opportunities must not only be centered on producers but must embrace a broader innovation ecosystem, including stakeholders, to cope with the structural barriers, such as lack of awareness and commitment to deal with ICLS barriers outside the gate. The importance of turning points among producer experiences suggests the need for further and more in-depth research on this topic, as well as the need for additional programming to support pathways to yield those turning points. Overall, these results can help research and extension projects mainstreaming ICLS. Besides, they can help to develop outreach systems that inspire and encourage producers to embark on the ICLS journey.

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**Data availability** All data generated or analyzed during this study are included in this published article.

**Code availability** Not applicable.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** The participants of the study were informed about the conditions and the purpose of this research study and gave informed oral consent to participate in the research. The data was anonymized after the end of the interviews.

**Consent to publication** The authors affirm that the producers who participated in the survey provided oral consent for publication of anonymized data.

**Conflict of interest** The authors declare no competing interests.



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