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Integrated crop-livestock systems: enhancing ecosystem services and productive potential

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1 Introduction

Diversified cropping systems serve as a cornerstone to agroecology (Altieri et al., 2015; Gaudin et al., 2015; Lemaire et al., 2014). However, agriculture has largely expanded through a limited number of crops and confined livestock production at the expense of more diverse forms of agriculture (Petersen-Rockney et al., 2021; Rasmussen et al., 2024). These trends have resulted in the homogenization of landscapes (Estrada-Carmona et al., 2022), eroding

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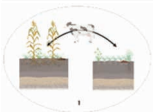
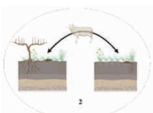
traditional ecological knowledge and biodiversity-based management of working lands (Altieri et al., 2015; Kremen and Merenlender, 2018). Animal Feeding Operations (AFO) are a product of specialization, where livestock and poultry are raised in confined feedlots without access to grazing for more than 45 days per year and where no crops, vegetation, forage, or post-harvest residues are produced (USEPA, 2015). Concentrated Animal Feeding Operations (CAFO) are large AFOs (>1000 animal units). While CAFOs account for a small percentage of AFOs, they produce the vast majority of US livestock (>75%) and poultry (>99%) (USDA-NASS, 2024). These operations produce a significant amount of manure (1.4 billion tons in the US alone), equating to approximately 8.1 million tons of nitrogen and 2.6 million tons of phosphorous (Pagliari et al., 2020).

Specialization has severely decoupled crop and livestock enterprises, disconnecting the cycling of critical natural resources between animal and crop systems both at farm and regional scales. However, sustainable manure management for fertilizing croplands is becoming more difficult as AFOs expand and available land for application declines. These trends contribute to excessive soil nutrient accumulation (Burkholder et al., 2007) and nonpoint-source pollution that threatens water supplies and aquatic ecosystems (Pagliari et al., 2020). Additionally, large-scale decoupling has incentivized the use of animal antibiotics prophylactically (Kümmerer, 2004) and to promote rapid growth (Cromwell, 2002; Gaskins et al., 2002; Liu et al., 2005) along with high quantities of other pharmaceuticals. This has resulted in the rise of antibiotic resistance (He et al., 2020; Kümmerer, 2004) and pharmaceuticals pollutants (Burkholder et al., 1997; Mallin, 2017). Specialization has therefore resulted in farms underutilizing key ecosystem services that could support both animal and crop production, creating vast nutrient imbalances, while making farms reliant on mechanical, chemical, and pharmaceutical interventions with large negative externalities (Bonaudo et al., 2014; Fenster, LaCanne et al., 2021; Garrett et al., 2020; He et al., 2020).

Reconnecting crop and livestock enterprises in Integrated Crop-Livestock Systems (ICLS) offers an opportunity to recouple ecological processes across scales, thereby reducing reliance on synthetic inputs while conserving biodiversity and assisting transformative redesigns and transitions toward more sustainable and resilient farming systems (Franzluebbers and Gastal, 2019; Franzluebbers and Hendrickson, 2024; Garrett et al., 2020; Lemaire et al., 2014). ICLS systems can take many forms (Table 1). They can emphasize crop production (e.g. cover crop and residue grazing systems, manure fertilization), producing livestock (e.g. pasture rotations, cut-carry systems), or have a more balanced focus (e.g. silvopasture systems). These systems can be combined and often work in conjunction. Prior to 1960, ICLS were the predominant form of agriculture across the world but are generally in decline across large parts of

Table 1 Table highlighting the different types of ICLS, focusing on the key features and considerations for each system. While these system types are separated, it should be noted that these system types can be combined and work in conjunction. For example, farms may combine Crop Residue Grazing, Cover Crop Forage, and Dual-Purpose Crops into one system. Table images created in BioRender. Fenster, T. (2025) https://BioRender.com/18z6x8r.

Main types of Integrated Crop-Livestock Systems (ICLS)

System Type	Key Features	Key considerations
 **1. Rotational Grazing**	Livestock rotated through croplands/ pastures in cycles. Can encourage perennial pasture adoption	Increased infrastructure and management complexity
1.1 Crop Residue Grazing (Box 3)	Graze post-harvest residues (e.g. corn stalks).	Limited to seasons with residues and grazing intensity dependent on crops; no perennial forage.
1.2 Cover Crop Grazing (Box 3)	Cover crops grazed for termination	Timing so cover crop is grazed in time for planting primary crop with implications for synchrony of nutrient cycling to sustain crop fertility.
1.3 Dual-Purpose Crop Grazing	Crops used for both grain and forage (e.g. winter wheat, canola).	Requires crop varieties suited to dual use, possibility of yield trade-offs.
 **2. Silvopasture, Agroforestry (Box 1 and 2)**	Trees/vines + pasture + livestock (e.g. cattle under timber stands or small ruminants in orchards and vineyards).	Long-term investment; potential competition for resources, food safety concerns in some specialty crops.

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Main types of Integrated Crop-Livestock Systems (ICLS)

System Type	Key Features	Key considerations
3. Resource Based Integration without grazing (Box 1 and 4)	Can happen at the farm scale or landscape scale	Collaborations and collective redesign required.
3.1 Manure Fertilization	Livestock manure applied to fields.	Main goal is to reduce synthetic fertilizer use but over-application and sustainable fertility management remains a concern.
3.2 Cut Carry	Animals stall-fed with farm-grown fodder.	Labor-intensive; requires fodder production space.

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the global North (Garrett et al., 2020). While ICLS account for less than 10% of the agricultural area and number of farms in the US and Northern, Central, and Western Europe, approximately 15–25% of farms remain integrated in Brazil and Baltic Europe (Garrett et al., 2020). In Australia and New Zealand, 40–45% of non-pastoral farms still include some form of exchange between crop and livestock production, and in Argentina and Uruguay, 40–45% of all farms are grazed ICLS (Garrett et al., 2020). Across the world, ICLS are far from anecdotal and have been moving from niche to mainstream at larger production scales (Delandmeter et al., 2024; Fenster et al., 2023; Franzluebbers and Hendrickson, 2024; Garrett et al., 2020). This includes beef cattle grazing in maize, small grains, and soybean systems in the US (Franzluebbers and Stuedemann, 2008) and Brazil (Silva et al., 2014) as well as silvopasture systems such as sheep grazing in vineyards in New Zealand, the US, and Europe (Garrett et al., 2020; Niles et al., 2017; Julie Ryschawy et al., 2021; Schoof et al., 2021).

Globally, ICLS have been shown to provide new opportunities to enhance food security (Sekaran et al., 2021) with little impact on crop yields compared to unintegrated systems, except in dual-purpose crops where yield lags may occur (Peterson et al., 2020). Integrating livestock with crop production provides an opportunity to recycle underutilized crop biomass and residues, with manure and urine depositions diversifying organic inputs to the soil, which feed more robust and diverse soil communities (Garrett et al., 2020; Lemaire et al., 2014). This can lead to enhanced soil health, allowing farms to address critical management challenges while reducing the risk of negative socio-ecological externalities (de Faccio Carvalho et al., 2021; Franzluebbers, 2024; Franzluebbers and Hendrickson, 2024). In addition, life cycle analysis (LCA) shows that ICLS systems can significantly reduce greenhouse gas (GHG) emissions and environmental impacts compared to decoupled animal and crop production systems (Ying Cai et al., 2025; H. Li et al., 2024; Paolotti et al., 2016; Weiler et al., 2014). This can be attributed to land use optimization and the reduction of inputs associated with feed production, weeding, fertilizer, and pesticide usage. These systems engage complex ecological interactions, and the resulting emergent properties can be managed to enhance land productivity and better manage risks posed by climate change, such as fire and drought (Thornton and Herrero, 2015). Emergent properties can include enhanced soil fertility and health through nutrient cycling (Tittonell et al., 2010) and reduced vulnerability to environmental stressors (Delandmeter et al., 2024; Franzluebbers and Hendrickson, 2024). Farming practices that allow animal grazing on cropland, such as those still employed by smallholders and indigenous peoples, also often maintain multifunctional landscapes that incorporate a diversity of trees, crops, and animals (Ortiz-Gonzalo et al., 2017). The complex structure of the landscapes that emerge as a result of ICLS can support a wider range of habitats and wildlife species (Estrada-Carmona et al.,

2022), which reinforces biodiversity conservation and benefits across scales. As such, and if well managed, ICLS could play a key role in fulfilling the major tenets of sustainable crop and animal production (Van Zanten et al., 2018; Van Zanten et al., 2019), while supporting the implementation of systems grounded in agroecological principles (Franzluebbers and Hendrickson, 2024). However, to harness the benefits of integration, the exchange of resources and stocking densities need to be carefully managed to maintain the delicate balance between forage and animal production at multiple scales. In grazed ICLS, overgrazing limits the ability of diverse microbial and plant communities to sustain ecosystem processes and functions (Wang et al., 2020), leading to further degradation of the system. Therefore, for farmers to avoid socio-ecological trade-offs, while maintaining the long-term sustainability of these systems, proper planning and flexibility are needed to implement the best management practices associated with Adaptive multi-paddock (AMP)/prescribed grazing (Brewer and Gaudin, 2020; NRCS, 2017a; Stanley et al., 2024).

While the existing literature strongly suggests the ICLS offers opportunities for enhancing the sustainability and resilience of farming operations, research and work are still needed to address knowledge gaps and characterize synergies or trade-offs among the ecosystem services provided by ICLS. This includes research that explores the connection between diversity, ecosystem services, and multifunctionality in ICLS, as well as identifying potential levers and indicator metrics for optimizing synergies, while minimizing trade-offs of ICLS. Also, while more in-depth research has been conducted in some cropping systems, more research is needed in different regions and cropping systems to identify optimal grazing levels and how grazing can best be combined with other management practices to maximize benefits, while minimizing trade-offs. Finally, there are multiple structural barriers to the implementation of ICLS, and policy, market, technical, and research solutions need to be developed to help overcome these barriers.

Here we examine, through a review of the literature and case studies (Boxes 1–4), the opportunities and challenges currently associated with the expansion and management of ICLS. We outline impacts of ICLS and grazing across a variety of systems on (a) biodiversity, from soils to landscapes, (b) soil ecosystem functioning, and (c) vulnerability to environmental stresses and discuss the key underlying ecological processes and potential trade-offs. The case studies represent some of the different forms and scales these systems can take. The first case study highlights smallholder mixed farming systems in Kenya, which incorporate cut-carry, agroforestry, and crop-residue grazing to enhance biodiversity by enabling the diversification of the farming landscape (Box 1). The second case study presents large-scale agroforestry systems in California where wine grape growers partner with livestock operations to integrate sheep into vineyards, thereby enhancing soil health and reducing

inputs (Box 2). The third case study highlights how cover crop forage systems can enhance the resiliency of Midwest row cropping systems by having cows graze winter or full season cover crops (Box 3). While integration of livestock and crop systems is typically thought of as occurring at the farm level, ICLS can also successfully be implemented at the landscape level (Box 4) through reconnecting neighboring specialized farms with exchanges of grain, fodder, crop by-products, and manure, or even by sharing other resources, such as workers and equipment (de Faccio Carvalho et al., 2021; Martin et al., 2016). Finally, we appraise potential socio-ecological trade-offs while considering management structures to guide optimization and propose ways to strengthen the socioeconomic drivers of agroecological transition.

2 Utilizing integrated crop-livestock systems to enhance and conserve biodiversity

Integrated crop-livestock systems can be a key part of the efforts to mitigate reductions in biodiversity by enhancing the productivity of working lands and furthering the adoption of practices that foster biodiversity and conservation. The implementation of ICLS enables the diversification of agricultural land at both field and landscape levels, thereby expanding the delivery of ecosystem services. Grazing annual cropland and incorporating grazing into perennial silvopasture systems is one element of many that increases biodiversity. Livestock grazing of cropland can enhance both planned and associated species richness and conserve biodiversity from soils to landscapes according to temporal and spatial arrangements of the integrated system. The decision to graze livestock adds a trophic level at the field scale, while also allowing the maintenance of animals within landscape matrices and co-adoption of biodiversity conservation practices with implications for resources and habitat provisions across scales (Box 1). Adding direct grazing to a system represents a radical departure from continuous annual cropping systems or even less integrated ICLS. However, grazing does not need to occur directly on cropping land to be a tool for enhancing and conserving biodiversity. Integrating livestock with crop production has a cascading effect, creating incentives to adopt more diverse crop rotations and soil conservation practices that have their own mechanisms for enhancing biodiversity and the subsequent delivery of ecosystem services.

2.1 Field level biodiversity

Within a single field, ICLS can support greater crop and livestock species diversity, thereby building more functional diversity. This increase in ecological niches supports a broader range of species than monoculture

systems (Bonaudo et al., 2014; Lemaire et al., 2014). ICLS can support higher functional diversity by incorporating plant and animal species with diverse ecological roles, such as nitrogen-fixing plants, deep-rooted grasses, and perennial forages, thereby enhancing the synergies between management practices (de Faccio Carvalho et al., 2010, 2021; Paul et al., 2020). Whether the land is directly grazed or not, ICLS systems incentivize longer soil covers and the presence of living roots coupled with rotation diversification or pasture phases in rotation. These have been shown to enhance soil ecosystem services, plant biodiversity, and productivity (Delandmeter et al., 2024; Paul et al., 2020; Sulc and Franzluebbers, 2014). When perennial forages are added (ie. cut and carry system, rotational pastures), these services can be further enhanced by the large increase in root presence. Grazing directly using best management practices generally conserves and improves plant diversity in semi-arid landscapes, which improves productivity and the buildup of a diverse soil biota (Abdalla et al., 2018; Bakoglu et al., 2009). Grazing can also be part of a vegetation management strategy that reduces or eliminates tillage and herbicide usage, which can negatively impact soil biodiversity, including beneficial decomposer, detritivore, and predator communities. (Briones and Schmidt, 2017; Fenster, Oikawa et al., 2021; Ingels, 1998). The integration of grazers or manure applied from stalls also diversifies organic matter inputs, generally increasing the biodiversity of the soil and understory plant community (Abdalla et al., 2018; Bakoglu et al., 2009; Piñeiro et al., 2010) that in turn enhances nutrient cycling at the farm level (Bender et al., 2016; Birkhofer et al., 2008). Additionally, manure deposition promotes beneficial predators by providing them with additional food sources and habitat (Birkhofer et al., 2008; Mäder et al., 2002). These mechanisms are provided directly and indirectly through the integration of grazers which facilitates niche complementarity and partitioning, as well as functional redundancy to support resource flow and self-regulation. This in turn reduces reliance on external inputs, such as pesticides and fertilizers, which may further harm species and degrade habitats while reducing input costs for farmers (Bansal et al., 2024; Bonaudo et al., 2014).

2.2 Landscape level biodiversity

At the landscape scale, ICLS have the potential to preserve or enhance landscape heterogeneity and encourage spatial and temporal variability, thereby promoting higher scale biodiversity (Bhagwat et al., 2008; Claire Kremen et al., 2012). Temporally, ICLS can encourage asynchronous practices such as diverse timing for planting, harvesting, rotational grazing, crop rotations, and feed production, all of which promote resource and habitat continuity and landscape-scale heterogeneity (de Faccio Carvalho et al.,

2021). Additionally, ICLS can lead to a more diverse spatial distribution of crops by creating incentives for native planting strips (i.e. prairie strips) and other semi-natural habitats (Costa et al., 2018; Duru et al., 2015; Estrada-Carmona et al., 2022). These semi-natural areas can be managed via grazing, allowing for the delivery of ecosystem services alongside agronomic productivity. Consequently, these semi-natural habitats support increases in insect and native bird species richness, pollinator abundance, and the abundance of bird species requiring conservation, as well as the delivery of ecosystem services, such as the reduction of water and nutrient run-offs (Claire Kremen et al., 2012; Lemaire et al., 2014; Schulte et al., 2017; Shennan, 2008; Soussana and Lemaire, 2014; Waters et al., 2017). For example, farmers have developed systems that consider the overall landscape. Marginal lands, which are usually areas with steeper slopes, are reserved for grazing, while areas less vulnerable to erosion are used for arable crops. Reserving these marginal lands for grazing reduces the input costs and potential environmental degradation associated with farming marginal landscapes. Further, these semi-natural areas increase the heterogeneity of the landscape, which promotes biodiversity and enhances the delivery of ecosystem services. When grazing is integrated across the landscape, it encourages the spatial and temporal diversity of crops, while the alternative source of feed provides rangelands with the necessary time to recover. This mitigates the negative effects that overgrazing has on biodiversity (de Faccio Carvalho et al., 2021; Stanley et al., 2024; Torma et al., 2023), while enhancing the synergies between biodiversity and the provisioning of ecosystem services, such as improved productivity and carbon sequestration (Delandmeter et al., 2024; Soussana and Lemaire, 2014).

Box 1 Mixed crop-livestock systems in Kenya: an opportunity to foster and conserve biodiversity

Smallholder mixed farming systems, which often integrate crops, livestock, and trees, form the backbone of agriculture in Africa (Thornton and Herrero, 2015). Kenya has a large diversity of agroecosystems supporting food security and livelihoods. As agriculture continues to expand into natural habitats due to demographic and economic pressures, integrated crop-livestock systems including agroforestry systems have the potential to both safeguard agrobiodiversity and increase food security (Mburu et al., 2016; Quandt, 2021) (Fig. 1).

The degree of crop-livestock integration varies across regions and agroecological contexts. In areas with low population densities and less fertile land, extensive livestock and pastoral systems prevail, with minimal cropping constrained to locally adapted species. In more fertile and humid regions, as population density increases and

Figure 1 Diversified farm in Central Kenya.

farm sizes decrease, agricultural intensification occurs (Boserup, 1965). Farms in Kenya have diversified activities and increased inputs and labor per unit of land through crop-livestock interactions (Baltenweck et al., 2003). Livestock practices evolved from free grazing to more managed patterns and stall-feeding systems. In the Central Highlands, semi-zero grazing involves a combination of stall-feeding and limited grazing, while zero-grazing fully confines livestock, relying on fodder like Napier grass and crop residues (Bebe et al., 2003).

This integration diversifies farm production and increases material transfer between farm enterprises, as well as labor requirements. Livestock manure is essential for maintaining soil fertility by recycling nutrients from crop residues and fodder (Rufino et al., 2007). These practices contribute to sustaining soil fertility and biodiversity by fostering diverse microbial and invertebrate communities (Bender et al., 2016). Further, ICLS allow for these agroforestry systems to be a refuge for species while providing ecosystem services (Bhagwat et al., 2008; Pinard et al., 2014), such as fodder trees, which can supplement traditional forage sources. It also enhances resource synchronicity, promoting both functional and response diversity, which in turn can increase farm resilience (Fig. 2).

3 Utilizing integrated crop-livestock systems to enhance soil ecosystem functioning

If well managed, recoupling crops and livestock systems can be an effective tool for ecological nutrient management with the potential to help sustain production while mitigating climate change and soil degradation (Delandmeter et al., 2024; Franzluebbers and Hendrickson, 2024; Lemaire et al., 2014). Here

Figure 2 Smallholder crop-livestock systems in Central Kenya.

we focus on how ICLS impacts the soil ecosystem and the delivery of ecosystem services through a variety of mechanisms, such as the redistribution of animal waste onto croplands, the priming of soil ecosystems for improved carbon and nutrient cycling, and the build-up and retention of carbon and nutrients to sustain highly functioning systems. These are illustrated in the irrigated US context with sheep grazing in vineyards (Box 2).

3.1 Nutrient cycling and provision

Integrating crop and livestock operations re-couples nutrient cycles across farm and landscape scales by supporting *in situ* cycling and the conservation of carbon, nitrogen, and water (Brewer et al., 2023; Chen et al., 2015; Delandmeter et al., 2024; Piñeiro et al., 2010; Silva et al., 2014). Livestock integration *in situ* can directly and indirectly influence net primary productivity of the understory vegetation, and therefore the amount of energy resources and organic matter that enters the agroecosystem (Lemaire et al., 2014). While grazing can initially decrease aboveground biomass as the animals directly consume it, certain grazing pressures can stimulate compensatory above and belowground growth, leading to higher plant biomass production if plants are allowed enough time to recover between grazing events (Bardgett and Wardle, 2003; Oesterheld and McNaughton, 1991). In particular, grazing can increase the allocation of photosynthates to the root systems, leading to higher belowground plant biomass and increased rates of root exudation (Hamilton et al., 2008). The subsequent increase in microbial biomass triggered by root exudation represents a potential mechanism for increased C storage

and sequestration (Sokol et al., 2019; Zhu et al., 2020). Inputs of labile C and plant-available forms of N through feces and urine deposition generally boost microbial growth and activity, leading to higher decomposition and nutrient cycling rates, supporting positive shifts in primary productivity and C and N inputs to the soil ecosystem (Abdalla et al., 2018; Bansal et al., 2024; Brewer et al., 2023; de Faccio Carvalho et al., 2010; Lazcano et al., 2022).

Grazing can drive changes to soil physical properties, which regulate plant available water in the soil, indirectly affecting primary productivity and soil cycling of C and N (Soussana and Lemaire, 2014). Grazing can influence multiple indicators of soil physical health such as bulk density, aggregate stability, and porosity with implications for water infiltration, water holding capacity, and percolation (Abdalla et al., 2018). In fact, some studies have found higher soil aggregation in no-till ICLS systems from the increased presence of roots (de Moraes et al., 2014) and modeling projections show that ICLS can increase water infiltration and reduce erosion, while increasing yield at the watershed level (Pérez-Gutiérrez and Kumar, 2019). However, the impact of grazing on soil physical structure is heavily dependent on stocking rates and the timing of grazing events. Excessive trampling has been shown to lead to soil compaction, increased bulk density, and the reduction of soil porosity, thereby decreasing water infiltration and increasing runoff and erosion (Flores and Tracy, 2012; NRCS, 2017b; Valani et al., 2022).

3.2 Stocking rates and tradeoff management

For ICLS that directly integrate livestock into annual or perennial cropland, proper grazing management is essential (Table 1 Systems 1–2). Livestock, if not properly managed when integrated, can cause damage to crops through trampling, grazing, or browsing (Niles et al., 2017; Julie Ryschawy et al., 2021). A certain level of disturbance is generally needed in ecosystems to promote complexity and ensure optimal ecosystem functioning (Falk et al., 2007; McKenzie and Kennedy, 2011; Newman, 2019). However, overgrazing can constitute an over disturbance, thereby eroding sustainability and resilience mechanisms. Adaptive multi-paddock (AMP)/prescribed grazing is a key practice for nutrient storage. It uses short-duration rotational grazing events at high stocking densities, moving the livestock through different fenced paddocks on the farm (NRCS, 2017a; Teague et al., 2013). This strategy allows for the control of grazing intensity (50% of the forage is consumed approx) and the provision of enough recovery time afterwards to support the regrowth of vegetation (Stanley et al., 2024; Teague et al., 2013). If not managed properly, the integration of livestock can lead to soil compaction and erosion issues (overgrazing) as well as decreases to plant diversity (overgrazing and under grazing) and plant residues (overgrazing) (Rowntree et al., 2020; Stanley et al.,

2024). Lower infiltration rates lead to increased runoff and erosion with the associated loss of topsoil and reductions in crop growth (Rocha Junior et al., 2017; Sulc and Tracy, 2007). Compaction issues can be aggravated if grazing is performed on wet soils, leading to 10-fold reductions in water infiltration rates compared to non-grazed areas as shown in a Nebraska (US) study (Sulc and Tracy, 2007). Despite concerns that grazing can increase compaction, farmers integrating livestock have effectively learned how to best manage plants and grazers across variable yearly conditions so as not to negatively affect soil physical properties. Declines in on-farm water dynamics, increased GHG emissions, and the increase in nutrient runoff decrease the resilience and resistance of cropping systems by making them more vulnerable to environmental stresses, while increasing their exposure to market volatility by making operations more dependent on external inputs. When transitioning to *in situ* ICLS, it is essential for the intensity, frequency, and duration of grazing (Delandmeter et al., 2024; Jouven et al., 2010; Stanley et al., 2024) to be a function of climate, underlying soils, and other agricultural management practices so that growers can harness the soil ecosystem benefits of ICLS.

3.3 C storage and GHG emissions

Shifts in soil physical properties and organic matter input quantity and quality with livestock could impact soils' ecosystem capacity to mitigate climate change in the medium term. While short term (<3 years) studies examining the *in situ* integration of grazers show increases in soil microbial activity without increases in C stocks (Bansal et al., 2024; Lazcano et al., 2022), longer term studies indicate that at least 4 years of continuous practice implementation can significantly enhance soil C storage (Brewer et al., 2023; Delandmeter et al., 2024; Fultz, Moore-Kucera, Zobeck, Acosta-Martínez, Wester et al., 2013; Prairie et al., 2023; Renwick et al., 2025; Silva et al., 2014). *In situ* grazing in ICLS alters carbon cycling by modifying both the quantity and quality of organic matter inputs (Brewer et al., 2023; Prairie et al., 2023). Grazing, which is a key element of ICLS, is often implemented in combination with conservation co-management practices, and can enhance soil organic carbon (SOC) stabilization through three key mechanisms: (1) redirecting carbon allocation to belowground pools with grazing-induced shifts in root photosynthate allocation (Chen et al., 2015), (2) modified microbial decomposition dynamics driven by altered plant litter C:N ratios and animal waste inputs (Piñeiro et al., 2009; Tian et al., 2010), and (3) stimulating microbial enzyme activity (Acosta-Martínez et al., 2004; Brewer and Gaudin, 2020; Fultz, Moore-Kucera, Zobeck, Acosta-Martínez, and Allen, 2013; Tian et al., 2010; Tracy and Zhang, 2008). These effects are amplified when ICLS are combined with other agroecological practices (Prairie et al., 2023) (Fig. 3). For instance, combining ICLS with no-till can enhance soil aggregation and

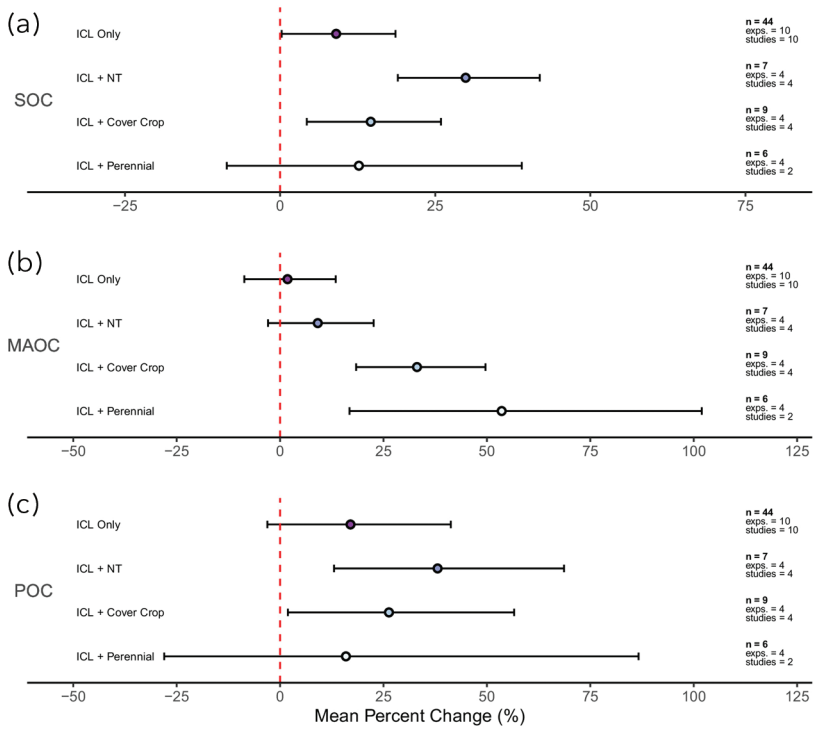

Figure 3 Potential synergistic effects between Integrated Crop – Livestock (ICL) with NT and cover crop intensification on topsoil (0 to 20 cm) carbon concentrations (g C kg soil^{-1}) in total SOC (a), MAOC (b), and POC (c). 'ICL only' compares ICL systems to annual cropping systems without livestock. 'ICL + NT' compares ICL systems that are NT to annual systems without livestock that are conventionally tilled. 'ICL + cover crop' compares ICL systems that have been intensified using cover crops to less intense systems without livestock. 'ICL + perennial' compares ICL systems that have been intensified using perennial grass to annual systems without livestock. Residue management, fertilization regime, and environmental variables were held constant. Effect sizes were considered significant if 95% CI did not overlap zero. The number of observations (n), experiments (exps), and studies analyzed for each moderator variable is displayed on the far right of the figure. Source: (Prairie et al., 2023).

structure, resulting in greater particulate organic carbon (POC) accumulation beyond no-till alone (Prairie et al., 2023). When paired with cover crops, *in situ* grazing shifts carbon allocation toward more stable mineral-associated organic carbon (MAOC) fractions, with significant effects in perennial systems (Brewer et al., 2023; Prairie et al., 2023).

The carbon sequestration potential of ICLS varies considerably depending on management and environmental factors. Regarding grazing management, adaptive multi-paddock (AMP)/prescribed grazing systems effectively enhance NPP and balance litter retention with dung inputs. Cut-carry systems reduce

soil erosion by 50% while increasing SOC (10%), crop grain yields, and revenue (300%) by integrating planted forages into the cropping system (Paul et al., 2020). Agroforestry-based ICLS can sequester carbon by enhancing NPP and storing carbon in both biomass and soil. Carbon storage capacity varies by climate, ranging from 9 Mg C ha^{-1} in arid regions to 63 Mg C ha^{-1} in temperate zones, with tropical smallholder systems sequestering 1.5–3.5 Mg C ha^{-1} yearly (Montagnini and Nair, 2004). Beyond direct sequestration, agroforestry-based ICLS can indirectly enhance carbon sequestration by protecting natural forests (largest sink of terrestrial C) and indirectly improve SOC by providing natural synergies with soil conservation practices. For example, prescribed grazing in agroforestry systems can increase SOC and be used as a tool to reduce tillage while providing incentives to plant cover crops and perennial forages. Agroforestry systems that integrate perennial crops exhibit strong potential to function as carbon sinks, whereas agroforestry systems that integrate intensively managed annual crops exhibit carbon dynamics more comparable to conventional agricultural systems (Montagnini and Nair, 2004). Overall, the carbon sequestration potential of agroforestry-based ICLS depends on the land use it is replacing. If replacing natural forests, the potential is low, but if replacing degraded cropland or rangelands, the potential for enhanced carbon sequestration could be substantial (Montagnini and Nair, 2004).

The timeline for measurable GHG mitigation reflects the complex interplay of biological, chemical, and physical processes. Higher retention of C and N could translate to lower soil GHG emissions, but outcomes remain uncertain. While manure depositions can increase soil C inputs, high amounts of labile C and N can trigger increases in microbial respiration, nitrification, and denitrification rates, enhancing the efflux of CO_2 and N_2O from the soil (Lazcano et al., 2022; Oertel et al., 2016). Furthermore, methanogenic bacteria in animal manure could trigger the release of CH_4, resulting from the anaerobic decomposition of labile C compounds (Yanjiang Cai et al., 2017). Under high grazing intensity, the release of CH_4 and N_2O could be further increased due to trampling and compaction (Ambus et al., 2018; Smith et al., 2003). Lazcano et al. (2022), observed that short-duration high-intensity sheep grazing in a vineyard in a Mediterranean climate resulted in increased fluxes of N_2O right after the grazing events; nonetheless, these fluxes were sporadic and, when added up through the seasons, did not contribute to higher cumulative annual emissions as compared to non-grazed soil.

At the larger systems scale, various life cycle analyses have shown the climate change mitigation potential of this practice, with ICLS having 55% lower GHG emissions than conventional non-integrated systems in Brazilian Cerrado crop-livestock-forest systems (Costa et al., 2018). Analysis of 114 farms in China's Northern region showed that integration of livestock and crop production reduced greenhouse gas emissions by 8% compared to

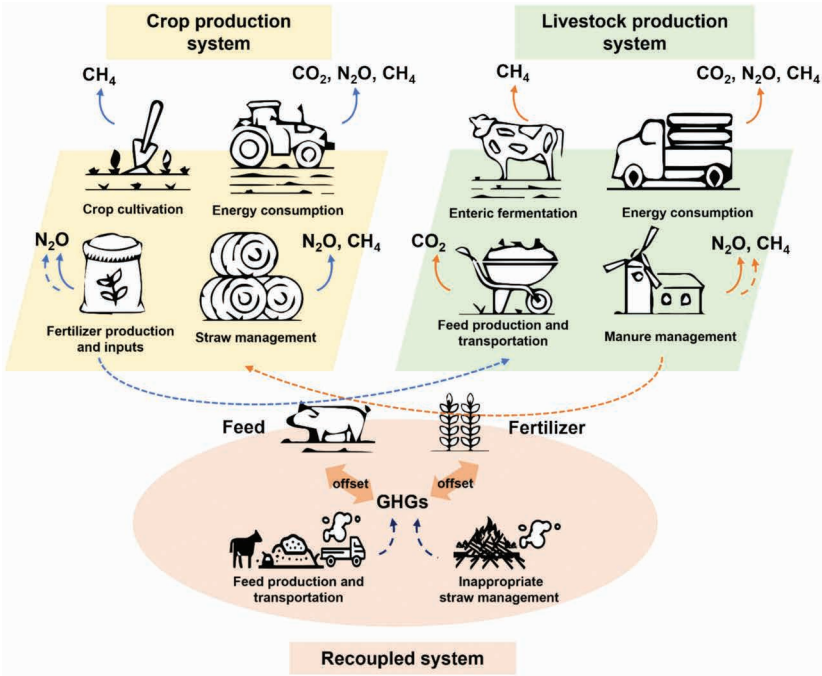

Figure 4 The system boundaries of the current decoupled and hypothetical recoupled agricultural systems. Source: (Ying Cai et al., 2025).

non-integrated farms (J. Li et al., 2024), with projections estimating a 40% emissions reduction when scaled across provinces (Ying Cai et al., 2025). The lifecycle assessment (LCA) outcomes from this study depended on system boundaries. This LCA encompassed both crop and livestock production systems (Fig. 4). This complex mechanistic model estimated greenhouse gas (GHG) emissions from conventional decoupled systems to those of the newly proposed ICLS where manure replaced synthetic nitrogen to meet crop nitrogen demand-considering livestock carrying capacity, and environmental safeguards to prevent overapplication. Additionally, the system incorporated previously underutilized crop residues as livestock feed, thereby avoiding the cultivation and transportation emissions associated with conventional feed production. By closing these resource loops, the study demonstrated how crop residues and manure could be transformed into circular assets, maximizing their recovery and reuse efficiency within the agricultural system. Recoupling crops and livestock in these systems could allow for the offset of significant GHG emissions associated with feed production and transportation, fertilizer use, and inappropriate straw/manure management.

Box 2 Soil ecosystems of integrated sheep vineyard systems in California

In the last 15 years, sheep grazing in vineyards has expanded extensively across California's Northern and Central coasts (Avila, 2023; Mobley, 2024). This practice has also begun to be adopted by Central Valley vineyards in high yield production systems (Boyd, 2024; Rieger, 2023). While in some cases the vineyards may own their own sheep herd, the general model consists of vineyards partnering with existing livestock operations as service providers. Expansion has been aided by the fact that the wine grapes are fermented and therefore do not have the same food safety restrictions as other specialty crops more directly consumed, such as nuts crops (Mazaroli and Carlisle, 2023).

Figure 5 Sheep grazing in a non-organic, high-yield vineyard around Lodi, CA. The high trellising system used in this vineyard allows grazing sheep all year long, allowing it to eliminate herbicides, mowing, and tillage. In this image, the sheep are grazing at ~75% veraison, approximately a month before harvest. Notice the shading provided to the sheep by the vines in the high trellising system. Photo Credit: Tommy Fenster.

Key Benefits: Soil health and input reduction

Producers are motivated to integrate sheep into their vineyards due to potential soil health benefits and reductions in input usage and tractor passes associated with mowing, herbicide applications, and tillage, all of which reduce the costs of production (Mazaroli and Carlisle, 2023; Julie Ryschawy et al., 2021). Recent research and agroecological innovation efforts

have established a network of commercial vineyards across Northern and Central California (n=49). This has facilitated research, knowledge transfer, and co-learning. Further, it has provided a better understanding of the timing requirements to make grazing integration successful, as well as the extent of the legacy effects of grazing and co-management practices.

Preliminary data demonstrate that vineyards employing grazing can eliminate 2–5 tractor passes per season by replacing mowing, herbicide applications, and tillage. This reduction in inputs and tractor passes is enhanced when sheep can graze all year long (Fig 5.) Grazing is also a keystone management practice for enhancing soil C and N dynamics, microbial biomass, and the diversity of the understory plant community (Fenster et al., 2023). The data suggests that sheep grazing can be a **low-risk, high-reward** practice for vineyards (Fig. 6).

1. **Carbon and Nitrogen cycling (Fig. 6)**
    - Grazing significantly increases **organic N** and **plant available N** (Fenster et al., 2023). This indicates that grazing enhances N cycling *without* inducing short-term N immobilization, as evidenced by stable C:N ratios in both water-extractable and bulk soil fractions.
    - The number of years under grazing is positively and significantly correlated with soil C and N (total N and plant available N) accumulation, and these increases were found in both organic and conventional systems.

2. **Microbial activity (Fig. 6)**
    - Microbial biomass and carbon mineralization – critical drivers of nutrient cycling – also increase under grazing, further supporting soil fertility.

3. **No detriment to soil physical properties or crop performance (Fig. 6)**

Contrary to concerns, grazing did **not** lead to:

- **Soil compaction** (no increase in bulk density or soil compaction measurements).
- **Reduced water infiltration**, which is critical in drought-prone California.
- **Changes in pH or salinity**, which could otherwise disrupt vine health. Critically, grape yield and quality remained unaffected.

Potential limitations and unanswered questions

While the benefits are compelling, potential trade-offs exist:

1. **Timing and intensity**: Overgrazing or poorly timed grazing (e.g. post budbreak in low-trellis systems) could damage vines or compact wet soils, though current protocols mitigate these risks.
2. **Scalability**: High-trellis systems (Fig. 5) facilitate year-round grazing, while also enhancing the climate resilience of vineyards by restructuring the canopy, which reduces

water usage and maintains fruit quality during heat waves (Yu et al., 2022). Further, the high trellising ensures that the vines provide shade for the sheep (Fig. 5), which reduces heat stress (Marcone et al., 2021), thereby enhancing animal health and welfare (Knight et al., 2023; Silanikove, 2000), and potentially improving weight gain, milk production, and reproduction (Lemaire et al., 2014; Masters et al., 2023). Preliminary reports suggest that vineyards can transition to high wire systems in approximately 1.5 years and that new plantings are cheaper. Future research should explore how higher trellis systems, grazing, rootstock and scion selection, and other agroecological practices can be synergized to enhance soil ecosystem functioning and livestock health, thereby improving farm resiliency.

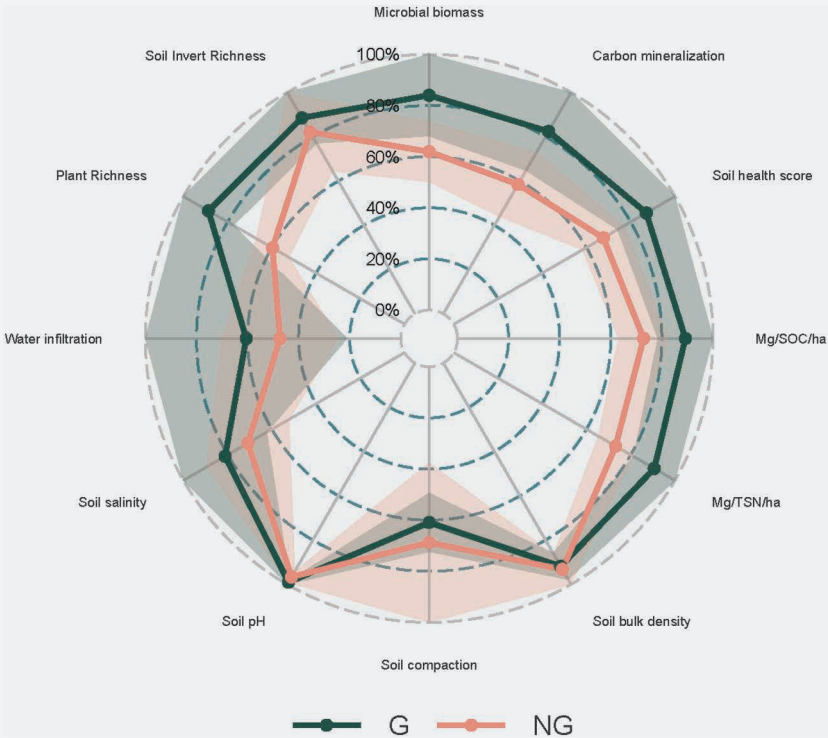

Figure 6 Soil health metrics from a series of long-term trial hubs on commercial vineyards across Northern and Central California (n=49) (Fenster et al., 2023). The spider plot presents a comparison of non-grazed (NG) and grazed (G) vineyards that integrated sheep. Covariates, such as soil texture, latitude/longitude, and grazing intensity are not included in this visualization. The means were normalized and scaled. The shaded areas represent the 95% confidence intervals. Soil health score refers to the Haney Soil Health Score.

4 Utilizing integrated crop-livestock systems to boost resilience

The potential of ICLS to enhance resilience could be a major asset as farmers confront global climate change. With climate change, farmers are already experiencing heatwaves, droughts, wildfires, and rainfall events that are more frequent as well as of greater intensity and duration (Shukla et al., 2019). These environmental stresses, coupled with geopolitical turmoil, could increase and threaten farm productivity, and increase price volatility, as well as the availability and costs of external inputs (Shukla et al., 2019). When grazers are integrated into cropping systems without exceeding the carrying capacity of the system, ICLS can increase species diversity, which enhances land productivity and production stability while also diversifying revenue streams and synergies between operations to increase socio-ecological resilience (Box 3).

4.1 Decreasing vulnerabilities or risks to stressors

Many of the mechanisms underlying the stability of production in ICLS reduce vulnerability to biotic and abiotic stressors by shifting the state of the ecosystem when grazing and planning for grazing (i.e. cover crop plantings). The ecological resilience and resistance exhibited by an agroecosystem are dependent on the functioning of its regulating ecosystem services related to soil, water, and nutrient conservation, pest suppression, and vulnerability to extreme events. Integration of grazers adds a trophic level (herbivores) and species diversity to the cropping system, while also promoting increased biodiversity of the agroecosystem through cascading effects on other organisms. Research strongly suggests that greater ecosystem diversity enhances the ability of the ecosystem to be more resilient to and resist environmental stresses due to synergies across the various trophic levels (Di Falco and Chavas, 2008; Gaudin et al., 2015; Isbell et al., 2015; Lin, 2011). As such, integrating grazers into cropping systems at the optimal intensity, frequency, and duration (Stanley et al., 2024) can lead to enhanced resilience (Bonaudo et al., 2014; Lemaire et al., 2016)

The soil's capacity to regulate water and nutrient cycling, while provisioning key ecosystem services, is anchored in sustaining and building soil organic matter (Weil and Brady, 2016). Optimized grazing has been shown to increase soil organic matter (SOM) (Delandmeter et al., 2024; A. J. Franzluebbers and Hendrickson, 2024) with the potential to enhance the soil and ecosystem's ability to rebound from disturbances like fires, floods, and drought (A. J. Franzluebbers, 2010), while reducing vulnerability to extreme weather events (Delandmeter et al., 2024; A. J. Franzluebbers and Hendrickson, 2024; Peterson et al., 2020). Diversified rotations and particularly cover crops are critical to ICLS as they increase available forages in crop rotations or between the rows of perennial

cropping systems. This, in turn, enhances the biodiversity, resilience, and resistance of the agricultural landscape (de Faccio Carvalho et al., 2021; Wittwer et al., 2017). Resilience building occurs as cover cropping reduces the erosion of soil and compaction, controls weeds, supports pollinators and other beneficial insects, fixes nitrogen, reduces nitrogen leaching, and sequesters carbon, while improving soil structure and water cycling (Pinto et al., 2017; Reicosky et al., 2021; Wauters et al., 2021). Utilizing ICLS with other agroecological practices such as cover cropping and no till offers the opportunity to enhance the synergies between these practices and further improve the delivery of resistance and resilience building mechanisms (de Faccio Carvalho et al., 2021; Fenster, LaCanne et al., 2021), including enhanced agronomic productivity (Delandmeter et al., 2024). ICLS also provide opportunities for farmers to reduce vegetation fuel loads on and around their farms, enhancing their resistance to the risk posed by wildfires (Nader et al., 2007; Siegel et al., 2022; Starns et al., 2019; Taylor, 2006), while increasing the amount of forage available for livestock herds, which is often limited during hot and dry spells (Russelle et al., 2007).

Rising temperatures associated with climate change pose a direct threat to the health and well-being of livestock (Lemes et al., 2021). Livestock face significant challenges from heat stress, which negatively impacts health, productivity, and profitability across the industry, with annual losses in the US dairy sector reaching approximately US$1.5 billion (Key et al., 2014). The temperature–humidity index (THI), which accounts for both heat and humidity, serves as a critical indicator, with values surpassing 72 triggering stress responses in animals (Aguilar et al., 2010), conditions that may persist for over a third of the year in warmer regions (Castillo et al., 2020). Symptoms include elevated breathing rates, decreased appetite, and lower fertility, as livestock divert energy from growth to cooling themselves (Poudel and Castillo, 2024). Silvopastoral and agroforestry systems offer an opportunity to enhance the resiliency of livestock operations and counteract these negative effects by offering shade, moderating microclimates, and reducing solar exposure (Marcone et al., 2021; Poudel and Castillo, 2024). Shaded areas under tree canopies maintain lower THI levels during peak heat, improving animal welfare, with livestock in these systems resting more and exhibiting less stress-related actions (Poudel et al., 2022). Beyond welfare benefits, silvopastures enhance productivity by supporting better weight gain, reproductive success (Lemes et al., 2021; Poudel et al., 2022), forage diversity, and overall pasture productivity (Dubeux Junior et al., 2017; Gomes da Silva et al., 2021; Pent and Fike, 2019), while mitigating issues like fescue toxicosis (Poudel and Castillo, 2024). The integrated agroecological approach provided by silvopasture and agroforestry systems aligns land management with economic and animal health objectives, presenting a viable solution for enhancing the resilience of livestock operations by mitigating the effects of heat stress.

4.2 Enhancing production and economic stability

By enhancing productivity with lower external input levels, these systems can increase resistance and resilience to economic shocks, such as increases in external input costs and market forces decreasing the return for farms' crops (Bell et al., 2014; Bonaudo et al., 2014; de Albuquerque Nunes et al., 2021). Research carried out in Brazil to elucidate the long-term effects of a range of grazing intensities (none, low, medium, high) on the stability of soybean-pasture ICLS found that the overall productivity of the system increased with each level of grazing intensification (Delandmeter et al., 2024). This was driven by the higher stocking rates associated with higher intensity grazing and the associated improvement in live weight gains and income diversification (Delandmeter et al., 2024).

Growers utilizing ICLS can reduce their vulnerability to price shocks by practicing semi-integration and leasing some of their land out to crop producers (providing them with price-independent crop income), and by internalizing the supply chain of feeds when grain and oilseed prices rise (R. D. Garrett et al., 2017; Mercio et al., 2021). Cover crops generally cannot be utilized for human consumption, nor can growers receive direct payments for these crops (de Faccio Carvalho et al., 2021; Wittwer et al., 2017). Meeting the large demand from livestock managers for forage with cover crops in ICLS allows for multiple food source options while sustainably increasing profit from cover crops and human consumption of animal products (Russelle et al., 2007; Sulc and Franzluebbers, 2014). In France, cattle-cash crop farms demonstrate enhanced economic resilience since they can sell meat or cash crops on different markets, thereby making these ICLS less sensitive to respective market fluctuations (J. Ryschawy et al., 2012). A diversified production base that relies less on external inputs allows operations to weather short-term shocks and make management decisions based on persistent long-term trends (Russelle et al., 2007). Despite requiring more complex management plans, some growers view ICLS as less labor intensive because animals perform fertilizing and crop terminating activities without the machinery, training, and cost of labor (Julie Ryschawy et al., 2021). This provides opportunities in regions with high labor costs and/or labor shortages that require farmers to adapt to and mitigate yearly variations. As such, ICLS helps agroecosystems realign their resource use with local ecological and social constraints to enhance or preserve profitability (Bonaudo et al., 2014).

A key problem for the resilience of specialized industrial agriculture remains the compartmentalization of the food system at several scales, forcing producers to choose between being farmers or being ranchers. The two systems that for generations contributed to rural resilience were severed on individual farms, leading to the decline of rural communities (Lobao and Stofferahn, 2008). While agricultural output per farm increased, there was a

decline in the number of farm operators (A. J. Franzluebbers and Hendrickson, 2024). This led to processing, aggregation, and regionalism in production that further increased efficiency but lowered stability and resiliency, while displacing economic power from the hands of the farmers and their communities (de Faccio Carvalho et al., 2021; Lyson and Welsh, 2005). While ICLS cannot on its own fully address the issues industrial agricultural systems pose to rural communities, it can play a significant role in helping producers improve their operations' productivity, economic stability, and resilience.

Box 3 Integrated crop-livestock systems across the US to build resilience

ICLS enhance the resiliency and resistance of farm operations when grazing is used as a tool to reduce or eliminate spatio-temporal bare soil events and synthetic inputs, while increasing plant diversity and living roots on the ground (Fenster, LaCanne et al., 2021; LaCanne and Lundgren, 2018). The management of livestock is crucial to enhancing farm resiliency and tailored to the farm by allowing high densities of animals to graze for short durations followed by ample rest for the plant community to resurge. The 1000 Farms Initiative is studying the diversity of farming operations across multiple socio-ecological contexts in the US and Canada. The study is focused on quantifying the potential of diversification to enhance the resiliency of farms via an increase in the delivery of ecosystem services.

In 2022–24, data on soils, water, biodiversity, nutrition, productivity, and social and economic well-being of the farmers were collected on 837 croplands and orchards in 35+ food systems and 5+ livestock systems in 30 states and 2 Canadian provinces. ICLS were surprisingly more frequent than hypothesized (Lundgren et al., 2026). Overall, ICLS were found on 24% of the farms sampled to date and more frequently observed on organic (30.11% of farms) versus non-organic (21.87%) farms. Regionally, farms west of the Mississippi River (29.54% of farms) were twice as likely to practice ICLS than farms east of the Mississippi River (13.70% of farms). Smaller farms (<10 acres; 17.19%) were about half as likely to integrate animals as large farms (>100 ac; 30.28%). One possible reason that organic certified operations were more likely to integrate animals is that these management systems rely on natural inputs from animals in lieu of synthetic products to increase the productivity of their lands. Larger acreages tend to produce lower profits per acre than smaller operations, and the data suggest that animal integration may be one way that farmers increase the profitability and resilience of these larger, western farms. Also, food safety and zoning regulations are more likely to prohibit animal integration into smaller acre fruit and vegetable crops that are closely integrated to urban centers.

Row crop farms (wheat, corn, soybeans, etc) that integrated livestock with multiple agroecological practices to form agroecological systems had 46% more total carbon (to a depth of 60 cm), greater abundance

Figure 7 Cows grazing a winter cover crop in the Midwest.

and diversity of organisms on the farm (non-crop plant species richness [+1700%], total bacterial biomass [+60.20%], total fungal biomass [+194.19%], foliar invertebrate species richness [+63.66%], and bird species richness [+268.66%]), and reduced input usage, while being as profitable and having equivalent yields as their fully conventional counterparts (Lundgren et al., 2026). The increased biodiversity of these operations and the greater diversity of income streams combined with a reduced reliance on external inputs suggest that ICLS may thus increase farm resilience and resistance while solving larger problems facing society, such as GHG mitigation and biodiversity loss (Lundgren et al., 2026) (Fig. 7).

An example of this approach includes integrating cows into Midwest row cropping systems by having them graze winter cover crops or full season cover crops. Fluctuating prices paid for commodity crops, increases in extreme weather events (i.e. droughts and flooding), and spikes in fertilizer prices due to global events led farmers to seek ways to improve the ecological and economic resiliency of their operations. Some of the first steps farmers in this area took were to incorporate no-till/reduced tillage and cover cropping into their operations. To help manage cover crops without the use of synthetic inputs, a number of producers in 1000 Farms began to integrate cattle and other livestock into their croplands. They explained that it felt like a missed opportunity to not take advantage of the plant biomass supplied by the cover crops to increase the agronomic productivity of the land. Additionally, the integration of livestock into

their operations diversified their income streams while reducing and in some cases eliminating the inputs associated with terminating the cover crops. Integration of livestock, therefore, allows farmers to implement agroecological intensification and improve the resilience of their operations while maintaining and even enhancing productivity (Lundgren et al., 2026).

5 From niche to mainstream: key opportunities to expand integrated crop-livestock systems

Management complexities, uncertainties, and globalized markets associated with policy disincentives toward ICLS currently contribute to a low level of integrated operations (R. D. Garrett et al., 2017). Navigating the transition to ICLS is daunting for farmers who are not accustomed to managing more complex systems, although they can have diverse motivations for implementing ICLS (Meunier et al., 2024). Farmers often describe perceived challenges (e.g. decreased yields, climate and weather variability, high initial investment costs, long time horizons for returns, farming norms that favor specialization) as barriers to ICLS adoption. ICLS are perceived as being less profitable than specialized systems, with the decline in profitability associated with greater labor requirements and higher materials costs (Cortner et al., 2019). Even though many of these challenges can be mitigated by emergent ecosystem properties and synergies between crop and livestock production, Hayden et al. (2018) identified three main socio-economic structural challenges that farmers face when implementing ICLS at the field and landscape scales: norms in *financing and insurance industries,* inadequate *farm and county infrastructure,* and *long time horizons for returns*. These challenges are the result of structural policies that favor continuous cropping in specialized production systems, and therefore require structurally informed solutions that are beyond the capabilities of any individual farmer (Hinrichs, 2003). Growers implementing ICLS without institutional support may face difficulties financing their transitions, making it hard to invest in essential infrastructure, and even more difficult to tolerate a delay in the profitability of production. This has the effect of making ICLS more attractive to larger, better resourced farms which can mitigate some of these short-term losses via economies of scale (Pannel et al., 2014). While external structural changes increase the profitability of large specialized systems and generally explain much of the shift away from ICLS (Garrett et al., 2020), the decision to adopt ICLS often involves internal motivation factors besides maximizing farm income (Gil et al., 2016; Meunier et al., 2024).

5.1 Reducing the economic uncertainties of transitions

Reducing economic risk of integration without increasing production costs is key to enabling adoption (Pannell et al., 2014; Varner et al., 2011) in a structural landscape with inadequate/ineffective incentives or even disincentives for the adoption of ICLS (Garrett et al., 2017). In countries with highly industrialized agricultural systems that have policies in support of current farming norms (e.g. the subsidies offered to specialized export-oriented commodities), financing and insurance industries are more likely to provide support to farmers who can promise annual profits (Hayden et al., 2018). When farmers face difficulties in funding investments for ICLS implementation, the potential for medium- to long-term horizons for returns is especially intimidating to risk-averse farmers (Hayden et al., 2018). Due to upfront costs, cattle-cash crop farmers implementing ICLS in Brazil expect negative cash flows in the first two years of the transition, but in the long term, their operations experience increased profitability (dos Reis et al., 2020).

Current regulations, credit mechanisms, and supply chains incentivize single commodity agricultural production systems, making financing and marketing of ICLS products more challenging (Cortner et al., 2019; Gil et al., 2016). In countries with policies that allocate funds to financially incentivize ICLS adoption, growers often experience difficulties and have little assistance navigating the bureaucracy necessary to acquire those funds. It can also be difficult for farmers to achieve economic efficiency when attempting regional integration due to the difficulties of coordinating and transporting feed, manure, and animals (Asai et al., 2014, 2018). For certain ICLS agricultural products, green marketing such as labels and/or direct-to-consumer sales can help mitigate these issues. Direct-to-consumer markets also strengthen consumer trust in the quality of agricultural products and promote risk sharing between consumers and producers (Martin et al., 2016). Risk sharing plays a role in the financial and labor advantages of ICLS adoption. Consumers in direct-to-consumer markets are more likely to financially support producers when facing production losses from climate shocks and stresses, even volunteering to help replant crops and distribute new topsoil in some cases (Furman et al., 2014). However, in remote agricultural regions, where local supply chains are lacking, the lack of consumer demand for diversified products can limit ICLS adoption (Cortner et al., 2019; R. Garrett et al., 2020).

5.2 Enabling local cooperation to address operational and management challenges

The reluctance to transition to ICLS also stems from the lack of data and technical extension resources to support implementation. This prevents

farmers from utilizing best management practices and learning from other practitioners. This includes a lack of extension advisors trained to consider ICLS as part of a farm management program (Moojen et al., 2023). When advisors are trained to consider ICLS, they are valuable partners in successfully expanding the integration of ICLS (Moojen et al., 2023). The lack of institutional support and the collaborative nature of ICLS will often prompt farmers to seek out or build communities of practice. These communities offer support from peers to implement and manage ICLS, helping them access niche direct-to-consumer markets and incentive programs to support transitioning farmers (Hayden et al., 2018). Farmers highly value social learning across their operations, and participants in collective learning environments are often more likely to test and adopt systems re-designs (Kroma, 2006).

Cooperation and knowledge sharing can therefore help overcome social barriers to ICLS implementation. With landscape-scale ICLS, crop and livestock producers need to collaborate, resulting in shared decision-making and management. For instance, California has seen a rapid increase in custom grazing operations partnering with vineyards and other perennial cropping systems to graze the understory plant community as part of their winter grazing operations before grazing rangelands and other semi-natural areas in the spring/summer as part of their fire fuel load mitigation grazing (Box 2). In California, this relationship was developed through farm communities as grazing operations sought forage and ways to supplement their income streams, while vineyards sought to build soil health and reduce their reliance on chemical inputs and mechanical interventions. Non-profits working to develop regional fiber systems (i.e. Fibershed) were also instrumental in rebuilding markets for animal products. Community networks helped connect graziers and vineyards, and as neighboring vineyards saw the benefits of integrating sheep, the practice expanded.

Success requires trust and an alignment of goals between the two parties and good communication to ensure that the grazing plan aligns with the crop management goals. Additionally, good communication ensures that animals graze on the cropping systems under ideal conditions and that there is necessary storage available for feed and manure (Ryschawy et al., 2022). Frequent meetings and communication among participants and a third party have been shown to be critical to developing and maintaining effective relationships between livestock and crop producers (Asai et al., 2018; Cofré-Bravo et al., 2019). This ensures that partnerships between livestock and crop producers to establish ICLS across farms have the necessary contracts, as well as billing and transportation arrangements (Ryschawy et al., 2022). For example, coordination between neighboring vineyards can lower the cost of grazing for each individual operation by allowing the graziers to more easily move animals. When such collaboration occurs beyond the farm level, technical

knowledge sharing and logistical aspects such as distance or infrastructure are key to making this practice viable (Ryschawy et al., 2022). Cooperation can limit upfront costs via the sharing of materials, while providing more flexibility as to where and when to move animals to graze. Further ICLS collaborations enable farmers to develop collective practices to reduce environmental pollution such as nitrogen losses (Box 4).

Box 4 Cooperation and landscape scale ICLS in Southwestern France

In Southwestern France, efforts have focused on expanding crop-livestock integration beyond the farm level through collaborative arrangements between specialized crop farms and livestock farms, e.g. through grain-manure exchanges (Ryschawy et al., 2017). This is seen as a relevant option to address limiting factors related to the loss of skills and labor organization at the farm level. However, this integration within farmer groups is challenging because it requires collective redesign to address organizational issues.

Crop farmers are concentrated in the valleys, where they tend to specialize and simplify their cropping systems, growing mostly cereal cash crops (wheat and corn for seeds with a high market value), with some oilseed and mixed vegetable crops intermixed. Grasslands have been decreasing except in smaller and/or steep parcels. Crop-livestock and specialized livestock farmers are in the Piedmont region or the mountains and raise beef cattle. While in the past it was common for livestock to graze in crop fields over the winter, both systems are disconnected today. Crop farmers are dependent on synthetic fertilizers whereas livestock farmers are dependent on concentrated feed inputs, especially for proteins.

To encourage collaborations beyond the farm level, researchers from INRAe and local advisers worked in collaboration with a network located in Southwestern France (Ariège), involving three separate groups of neighboring farmers (10–15), including one group of organic farmers. These groups aimed to develop a landscape-level ICLS. Crop farmers were interested in diversifying their rotations and being supplied with cattle manure, while livestock farmers were interested in local, non-GMO feed for their animals. These groups engaged in a co-design process for five years to increase resource use efficiency, while mitigating GHG emissions and increasing soil carbon sequestration, soil fertility, and nutrient cycling.

These collective collaborations allowed the cropping and livestock farmers to design an optimal system that would work for both parties. This included the addition of cereal–legume mixtures into feeding systems, diversifying crop rotations of arable farms, haying available temporary grassland, and establishing manure transfers from livestock operations to crop farmers. A multicriteria evaluation of this landscape level ICLS highlighted an increased overall gross margin and decreased collective nitrogen balance. However, farmer

Figure 8 Landscape scale ICLS in France. Credit: Francesco Accatino.

workload increased due to the regular meetings required to meet the greater logistical complexity of this system and address social issues such as knowledge development.

Throughout the process, bonding ties among farmers emerged through group discussions and convivial moments, which helped establish trust between the participants, leading to contractual arrangements. Explicitly considering trade-offs between individual farms' gross margins and group-level indicators encouraged discussions about equity and an equal sharing of benefits, highlighted by guaranteed price floors and ceilings. Legal barriers limited the scope of these partnerships, particularly current legislation in France that bans direct selling of crops between farmers without an official contract. Additional policy support that could incentivize this type of ICLS in France is (1) Targeted policies such as collective payments which incentivize longer-term whole-farm outcomes and collective action, and (2) The development of green and local market chains that make use of agricultural by-products, such as wool (Fig. 8).

6 Conclusion and prospects

When well-managed, ICLS systems can enhance soil health and function, including improvements in water cycling and the retention of C and N. ICLS increase land use efficiency and allow for manure and urine to be recycled on-site, thereby reducing the environmental impacts of these systems compared to conventional decoupled systems. These improvements to soil health and function, including soil C sequestration, can take time and require

long-term commitment from the farmers and ranchers. Furthermore, the net benefits of ICLS are strongly dependent on interactions with other farming practices. This spans beyond the inclusion of grazing or pastures, including diversification at multiple scales, as well as biophysical conditions that drive C storage and soil ecosystem functioning in different environments. While ICLS can increase complexity and labor requirements, there are instances where the implementation of ICLS results in direct benefits to profitability through reduced labor and input costs.

Barriers to implementation such as the potential for increased labor demands, increased management intensity, and the lack of training, dedicated advising, and government support programs all threaten to slow down the needed developments in management and technology that are critical to driving widespread adoption. Additionally, many producers may still choose to rely on purchasing crop insurance rather than enhancing their farm's resiliency via increased diversity (Franzluebbers and Hendrickson, 2024). This is highlighted by the fact that the amount of farmland utilizing crop insurance in the US has grown from 40 Mha in 1989 to 120 Mha in 2016 (Farrin et al., 2016), with insurance subsidies rising from US$1 billion in 2000 to more than US$6 billion in 2020 (Franzluebbers and Hendrickson, 2024). Additionally, other structural barriers such as high land costs and the lack of markets incentivize farmers to remain committed to commodity crops. Therefore, innovative approaches are needed to promote the adoption of ICLS. Policy changes such as providing discounted crop insurance for farmers utilizing practices that enhance the biological resilience of their systems can help overcome these structural barriers. In France, collective bonus payment systems, where a group of farmers are compensated for better managing the landscape for biodiversity, have been effective in incentivizing farmers to participate, as well as expanding the amount of land enrolled in such programs (Kuhfuss et al., 2016). There is also promise in including integrated crop-livestock grazing as part of sustainable certification systems, as demonstrated by Napa Green and Regenerative Organic Certification. Another approach is to target younger farmers and other groups of farmers who have demonstrated an increased interest in ICLS and are more likely to invest in the increased management intensity of ICLS instead of larger-scale expansion (Franzluebbers and Hendrickson, 2024). While farmers may demonstrate preferences for either livestock or crop production (Garrett et al., 2017), these farmers may be open to collaboration, which can reduce management requirements (Ryschawy et al., 2019), while enhancing regional resilience to extreme weather events resulting from climate change.

There are a multitude of context-specific management issues that still need to be addressed. As part of addressing systemic issues to enable more widespread adoption of ICLS, farmers should have greater access to local guidance on how to best implement crop rotations, cover cropping, and crop

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residues to maximize the benefits and minimize the trade-offs of integrating crop and livestock systems (Franzluebbers and Hendrickson, 2024; Moojen et al., 2023). To carry out the research that is needed to enable the sustainable adoption and growth of ICLS, collaborations between researchers, producers, the industry, and government are required. Research needs to be participatory, interdisciplinary, and context-specific while challenging the current model of industrialization. This requires systems-level research that accounts for these interactions, requiring collaborations between practitioners and biophysical and social scientists to address both the agronomic and socio-political barriers to crop-livestock integration. This includes acquiring more knowledge of:

1 The connection between diversity, ecosystem services, and multifunctionality in cropping systems that integrate grazers.
2 If there are synergies or trade-offs among the ecosystem services provided by ICLS.
3 Identify potential levers for optimizing the synergies, while minimizing the trade-offs.

7 Highlighting the key indicator metrics for quantifying the potential benefits, synergies and trade-offs of integrated crop-livestock systems

While controlled research plot trials are necessary to understand the mechanistic processes driving potential benefits and trade-offs of ICLS, research on working commercial operations is needed to see if these findings translate to real-world scenarios on working farms integrating practices at scale (Novick et al., 2022). Additionally, while controlled research trials generally follow similar management practices year to year, there is a high likelihood for some level of year-to-year variability in management on commercial operations (Novick et al., 2024; Novick et al., 2022). Further, since the benefits of ICLS can take years to manifest, it can be difficult to secure the necessary funding for multiyear trials (>5 years). Therefore, on-farm research can be designed to provide a space for time substitution to model the long-term biological, physical, and chemical effects of ICLS. Finally, on-farm research catalyzes researchers to partner with the farmers so that hypotheses can be driven by farmer observations, making the research more relevant and useful for producers. In a best-case scenario, experiments will be designed to combine ICLS research plot trials with research on working commercial operations integrating grazers at scale to elucidate how increased mechanistic understandings translate to working commercial operations.

Despite potential barriers, an increasing number of farmers and livestock operators are working to build operating capacity and reintroduce livestock

into these systems as a tool for decreasing inputs and lowering negative externalities of both crop and livestock production (Brewer and Gaudin, 2020; Moojen et al., 2024; Mulville, 2011; Niles et al., 2017). Successful integrated production models have mitigated challenges by harnessing the benefits of ecological intensification and the financial and labor advantages of synergistic production while building cooperation and community of practice (Hayden et al., 2018), providing models for others to build on.

8 Where to look for further information

While not an extensive list, the following articles provide a good overview of integrated crop-livestock systems (also found in the references):

1. Bonaudo, T., et al. (2014). Agroecological principles for the redesign of integrated crop–livestock systems. *European Journal of Agronomy: The Journal of the European Society for Agronomy*, *57*, 43–51. https://doi.org/10.1016/j.eja.2013.09.010.
2. Franzluebbers, A. J. and Hendrickson, J. R. (2024). Should we consider integrated crop–livestock systems for ecosystem services, carbon sequestration, and agricultural resilience to climate change? *Agronomy Journal*, *116*(2), 415–432. https://doi.org/10.1002/agj2.21520.
3. Garrett, R. D., et al. (2017). Social and ecological analysis of commercial integrated crop livestock systems: current knowledge and remaining uncertainty. *Agricultural Systems*, *155*, 136–146. https://doi.org/10.1016/j.agsy.2017.05.003.
4. Garrett, R., et al. (2020). Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. *Ecology and Society*, *25*(1). https://doi.org/10.5751/ES-11412–250124.
5. Lemaire, G., et al. (2014). Integrated crop–livestock systems: strategies to achieve synergy between agricultural production and environmental quality. *Agriculture, Ecosystems & Environment*, *190*, 4–8. https://doi.org/10.1016/j.agee.2013.08.009.
6. Sulc, R. M. and Franzluebbers, A. J. (2014). Exploring integrated crop–livestock systems in different ecoregions of the United States. *European Journal of Agronomy: The Journal of the European Society for Agronomy*, *57*, 21–30. https://doi.org/10.1016/j.eja.2013.10.007.

Current research on integrated crop-livestock systems as well as extension resources that can be found through the following labs and organizations:

1. ICLS | Integrated Crop-Livestock Systems (https://sites.bu.edu/croplivestock/).

2. Gaudin Agroecology Lab at University of California Davis (https://gaudin.ucdavis.edu/).
3. Ecdysis Foundation (https://www.ecdysis.bio/).
4. Lazcano Soil Biodiversity and Health Lab at University of California Davis (https://lazcano.faculty.ucdavis.edu/).
5. The Center for Integrated Agricultural Systems (https://cias.wisc.edu/).
6. Community Alliance with Family Farmers – Integrated Crop & Livestock Systems (https://caff.org/ecologicalfarming/integrated-crop-livestock-systems/).
7. USDA Sustainable Agriculture Research and Education – Integrated Crop and Livestock Systems (https://www.sare.org/sare-category/production-systems/integrated-crop-and-livestock-systems/).
8. Food and Agriculture Organization of the United Nations – What are integrated crop-livestock systems? (https://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/scpi-home/managing-ecosystems/integrated-crop-livestock-systems/icls-what/en/).
9. Organic Farming Research Foundation – Crop Livestock Integration (https://ofrf.org/crop-livestock-integration/).
10. Rodale Institute – Crop Livestock Integration (https://rodaleinstitute.org/science/crop-livestock-integration/).
11. Center for Regenerative Agriculture and Resilient Systems at California State University Chico (https://www.csuchico.edu/regenerativeagriculture/).

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