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REVIEW

REINTEGRATION OF CROP-LIVESTOCK SYSTEMS IN EUROPE: AN OVERVIEW

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KEYWORDS

circular agriculture, coupled farming systems, mixed farming, specialised farming systems, GHG

HIGHLIGHTS

- ICLS combines the benefits of specialization with increased resilience of the system.
- Clear opportunities but also barriers for ICLS were observed.
- ICLS need to be embedded within future environmental legislation.
- ICLS systems with a range of intensities are needed to support a biodiverse landscape.

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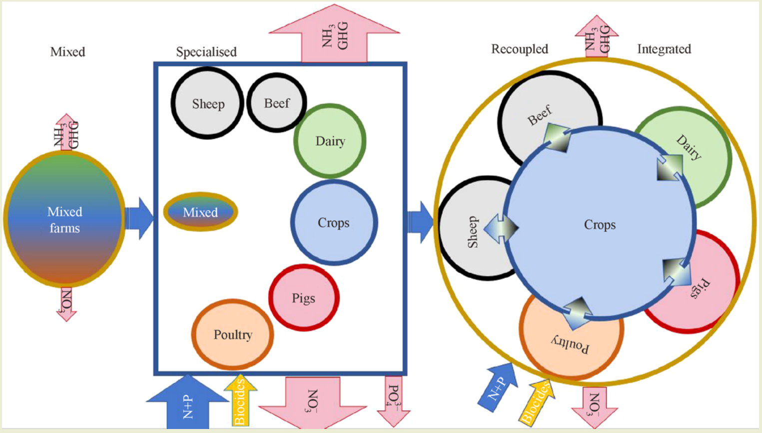
GRAPHICAL ABSTRACT



ABSTRACT

Ongoing specialization of crop and livestock systems provides socioeconomic benefits to the farmer but has led to greater externalization of environmental costs when compared to mixed farming systems. Better integration of crop and livestock systems offers great potential to rebalance the economic and environmental trade-offs in both systems. The aims of this study were to analyze changes in farm structure and review and evaluate the potential for reintegrating specialized intensive crop and livestock systems, with specific emphasis on identifying the co-benefits and barriers to reintegration. Historically, animals were essential to recycle nutrients in the farming system but this became less important with the availability of synthetic fertilisers. Although mixed farm systems can be economically attractive, benefits of scale combined with socio-economic factors have resulted in on-farm and regional specialization with negative environmental impacts. Reintegration is therefore needed to reduce nutrient surpluses at farm, regional and national levels, and to improve soil quality in intensive cropping systems. Reintegration offers practical and cost-effective options to widen crop rotations and promotes the use of organic inputs and associated benefits, reducing dependency on synthetic fertilisers, biocides and manure processing costs. Circular agriculture goes beyond manure management and requires adaptation of both food production and consumption patterns, matching local capacity to produce with food demand. Consequently, feed transport, greenhouse gas emissions, nutrient surpluses and nutrient losses to the environment can be reduced. It is concluded that reintegration of specialized farms within a region can provide benefits to farmers but may also lead to further intensification of land use. New approaches within a food system context offer alternatives for reintegration, but require strong policy incentives which show clear, tangible and lasting benefits for farmers, the environment and the wider community.

1 INTRODUCTION

Throughout agricultural history, animals have played a key role in the farming system, providing manure to fertilise cropped fields and converting residues, by-products and grazed biomass into animal products for food. Since the second agricultural revolution that started around 1850 in the United Kingdom (UK)[1], farms have specialized and expanded, a process that is still continuing. Also, regions in the European Union (EU) are still specializing and concentrating knowledge, supply chains and processing industries.

Agricultural specialization has provided many benefits of scale, including lower production costs and ease and efficiency of management, but it has also resulted in widespread environmental issues[2]. For example, in response to the EU-Nitrate Directive, northern EU countries developed bureaucratic systems that regulate animal density and the amount of manure that can be applied per ha which tackle nitrogen surpluses and excess manure applications. This has stimulated manure transport to other regions and the processing and incineration of manure, e.g., chicken manure in the Netherlands[3]. However, approaches to reduce nitrate leaching vary across the EU and measures taken in certain regions with both nitrate vulnerable and non-vulnerable zones are much less effective than, for example, the whole territory approach as applied in Denmark[4]. In many regions of Europe with high concentrations of specialized poultry and pig farms, manure is no longer a valuable resource for cropping due to the availability of low cost synthetic fertilisers, but is a cost for livestock specialists, associated with manure storage and disposal[5]. Accepting manure from other farms may even provide a small source of income for land owners in specific areas[6].

Alternatively, an integrated crop and livestock system (ICLS) at farm or regional level can substantially reduce manure management costs for livestock farmers[6] while also providing potential benefits to arable farmers including a more diverse crop rotation and greater flexibility to respond to market dynamics[7]. In an ICLS, land resources are more efficiently used and can support more animals per hectare[7] and a larger proportion of the landscape under high-value crops such as potatoes. Mixed farms or locally collaborating farms that share resources have the additional benefit of better utilization of labor throughout the year[8]. Despite these potential benefits, current EU farming systems are further specializing[9,10] with increasing farm size, irrespective of the reforms in the Common Agricultural Policy (CAP) that were introduced in 2003 and the introduced single farm payments for income stability, aimed to decouple subsidy from production and to support a greater diversity of smaller farms.

All farming systems are subject to forces driving specialization and integration of crop and livestock systems[2,11,12]. As discussed extensively in Garrett et al.[2], differentiating forces include globalization, industrial development, and corporatization of agriculture, supported by CAP policies focused on specific commodity crops, financial risk reductions and increasing profitability of specialized systems. The CAP reform of 1968, often referred to as the Mansholt Plan, aimed to rationalize and industrialize agriculture and proved successful across Europe. In the Netherlands, farmers were encouraged to participate in financially attractive land reforms and consolidation projects[13] that concentrated land near their agricultural holding. Extension services[14,15], tax incentives, rising land prices and a larger loan capacity for farmers with land stimulated investment in farm expansion and intensification of production. In recent times the influence of CAP on farm structural changes is fairly modest, and explains only 5% to 10% of observed changes in farm structure between 1989 and 2013[16].

In countries without risk reduction policies such as Australia, where farmers are exposed to strong price fluctuation, the reintroduction of ICLS has gained momentum as a risk management strategy[2]. In the EU, sustainability emerged as a major integrating force of the 1980s, resulting in approval of the EU-Nitrate Directive in 1991 to reduce nitrate leaching to ground and surface waters. In regions with high livestock densities such as the Netherlands an extensive bureaucratic system was set up to enforce farmers to reduce nutrient surpluses and export manure off-farm. Nitrate concentrations in surface waters were partially reduced[3,17], but costs of manure transport and processing for agriculture were estimated at 159 million $\mathrm{EUR \cdot yr^{-1}}$ for 2015[3]. In addition, nitrate targets have still not been fully met[18] and eutrophication problems still remain[17]. Hence reviving mixed farming systems could be a way forward, and this has gained much research attention in the past 25–30 years[11,19–24]. It is critical, however, that this research is now effectively translated into policies to enable widespread and lasting adoption of ICLS best practices.

There is a greater focus on crop-livestock integration in organic agriculture than in conventional agriculture as it aims to close feed and manure cycles at a local or regional scale. The integrating forces are embedded in the organic ideology[25,26]. Organic farms have also specialized over time, especially in north-western Europe, and are subject to the same forces as mainstream agriculture. The majority of the conventional farms converting to organic agriculture since the 1980s were specialized. This encouraged specialization in existing organic farms to remain competitive and implies that there is no real balance between animal and crop production. Legislation in countries across Europe differs, although they all meet the general standards of the European label for organic products[27].

In general, interest in mixed crop-livestock systems is increasing, with special attention for intersectoral cooperation between specialized farms to keep the economic advantages of specialization but at the same time reducing the pressure on the environment[19,28]. Within Europe, regions differ strongly in farm types and heterogeneity of farm structures[9]. Both the need for ICLS and the initiatives taken to stimulate ICLS differ greatly among countries. However, this diversity of approaches also provides opportunities for sharing best practice beyond national borders.

The aims of this paper are (1) to analyze current trends toward farm specialization in European agriculture, (2) to evaluate the opportunities and challenges of mixed, specialized and re-integrated crop-livestock systems, and (3) to review current initiatives to re-integrate livestock and cropping systems as part of a future farming system for Europe that provides sufficient, safe, healthy and nutritious food with reduced environmental costs and maximum biodiversity.

To this end, we provide in section 2 an overview of the history of mixed farming in Europe and recent trends in eastern and western European countries, followed by section 3 discussing opportunities and challenges of specialized and mixed farming systems. Section 4 gives an overview of efforts to re-integrate crops and livestock in selected areas of Europe. Section 5 provides a reflection on observed trends and discusses conditions and policy implications.

2 HISTORY AND TRENDS IN SELECTED REGIONS OF EUROPE

The first farm systems in Europe were truly mixed, with dairying being a key component in the first farms around eight millennia ago[29]. Food and fiber demand from growing cities in the Roman period (between 27 AC and 467 AD) intensified animal husbandry, changing types and sizes of animals kept throughout the Roman empire[30]. In later medieval times, animal husbandry improved[31] with regional differences in proportions of cattle, pigs and sheep[32]. On the Pleistocene sands of the Netherlands and Western Germany[33] and in wider north-western Europe[34], the so called ‘plaggen’ culture created Anthrosols concentrating nutrients on cropland where plaggen were used as bedding material for ruminants[35]. The mixed farming systems including livestock and crops were tightly balanced to the limited nutrients available[36]. In the first and second agricultural revolution, from 1750 to 1880[1], the growing demand from urban centers triggered intensification of animal husbandry. The earnings from crop and livestock products and exhausted heathlands fuelled demand for nutrient sources (e.g., guano and sodium nitrate) and later synthetic fertilisers enabling farmers to produce more food and feed on ever smaller farms[1]. After 1950 and especially after the implementation of the Common Agricultural Policy in 1962, grain prices in Europe were controlled and trade-access to European markets was limited with the exception of grain replacement crops. These imports provided cheap feed that triggered the intensification of chicken and pig husbandry near seaports in areas with small farms and limited alternatives to increase farm income[37]. Currently, intensive husbandry can be found in all areas with Anthrosols in north-western Europe, including Denmark, Brittany and Catalunya. Regions with suitable soils for crops specialized into arable farming, e.g., the great Paris basin[38] and eastern Germany. Grassland dominated areas (floodplains, peatlands or chalks) became livestock dominated. In mountainous areas with shallow soils on steep slopes or in more remote areas, extensive farming systems with agroforestry remained common. This on-farm specialization also brought regional specialization with large benefits for the servicing industry. New services developed ranging from contractors for disease control and field work to companies and cooperatives providing cheap and high-quality concentrates, specialized veterinary services, feed specialists and animal management consultants that encouraged farmers to further specialize. Dairy farmers specialized into primarily milk or meat producers, the poultry industry has specialized farms to produce chickens, laying hens (eggs) and broilers (meat), with farms servicing other farms. This process brought many economic benefits but also environmental and socioeconomic challenges[39].

This process of specialization supported by new technologies increased the efficiency of production but also resulted in the decline of the number of farms and a proportionate decline in mixed farms[40] combining crops and livestock on a single farm. In the EU-28, the EU in 2016 with 28 member states, farm type (Fig. 1) and farm size (Fig. 2) differed between eastern and western countries. Many eastern EU farms have emerged from collective farms and were exposed to the EU policies for a much shorter period than farms in western EU countries. In Eastern EU, farms are typically small (< 2 ha) and dominated by mixed farms in contrast to farms in western Europe. In western EU countries, farm size is increasing while the proportion of mixed farms declines. In 2016, all types of mixed farms accounted for 10.4% of all farms in the EU-10, including 10 original member states of the EU. However, only 2.5% are mixed crop-livestock farms (Fig. 3). Between 2005 and 2016 the number of mixed farms declined by 10.9% and 3.7% in eastern and western EU countries, with mixed crop-livestock farms declining by 1.9% in eastern EU countries and 1.8% in western EU countries[41]. Within the EU, change in farm specialization between 2005 and 2016 was largely dominated by an increase in specialist cropping farms (Figs. S1–S2). In this period, specialist cropping farms increased by 12.4% and 3.3% in eastern and western EU countries, respectively[41].

3 OPPORTUNITIES AND CHALLENGES OF SPECIALIZED AND MIXED FARMS

3.1 Benefits and challenges of specialized farming systems

The predominant production narrative[39] focuses on a strong

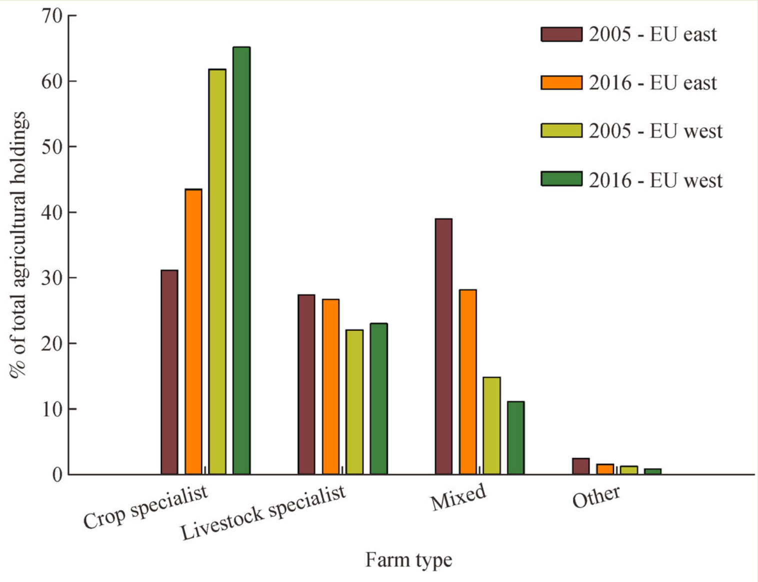


Fig. 1 Change in specialized and mixed farm types in selected western and eastern EU countries in 2005 and 2016, in western (EU west) and eastern Europe (EU east). Here, EU west comprises Belgium, Denmark, France, Germany, Greece, Italy, Ireland, Luxembourg, the Netherlands, Spain, Portugal and the UK; and EU east is composed of Austria, Bulgaria, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and Slovenia. Source from eurostate[41]. Database: ef_m_farmleg.

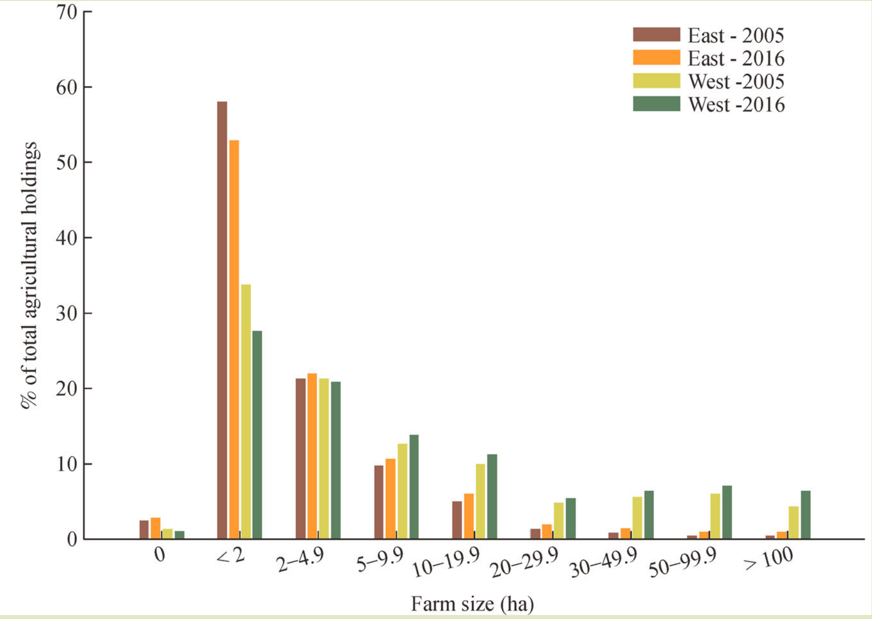


Fig. 2 Change in farm size in selected western and eastern EU countries in 2005 and 2016, in western (EU west) and eastern Europe (EU east) as in Fig. 1. Source from eurostate[41]. Database: ef_m_farmleg.

cost-price reduction for agricultural products. In Europe, farm specialization was a direct result of European policies targeting technical efficiencies, with central commodity marketing and price policies to reduce farmer risks[42]. Decisions to invest in a mixed system, or only in livestock or cropping, are driven by biophysical conditions and location of the farm but also by personal preferences and skills. Hence within the same landscape a wide diversity of farms with different levels of specialization can be found. However, trends toward increasing farm sizes and more specialized farms are still strong[37] and are expected to continue in response to European CAP policies aimed at producing for international markets[39]. Benefits of scale in larger operations include lower prices for inputs, labor and contract work and higher net prices for farm produce due to reductions in cost for transport per unit or product. A limited production scope allows farmers to focus their expertise and become more efficient. The advantages of specialization go beyond the benefits of scale and also have important social dimensions. Small and intermediate sized farms are too small to absorb financial risks associated with long-term contracts for part- or full-time workers and rely on year-round family labor, strongly limiting flexibility and social activities, especially for dairy farmers. Further, farms directly compete for land, the most limiting resource in many EU regions. Specialised and often larger farms often have more capacity to invest and can buy larger areas of land when the opportunity arises. Small farms who miss out may therefore be better off with diversification of income in the short-term, but risk that their farms become too small to compete with large specialized farms with lower production costs and cannot earn an income for the next generation[43].

Larger-scale specialized farms tend to concentrate problems in comparison to mixed farms. With more animals per production unit, risks of transmittable diseases and impacts on the local environment are greater. Although many of these issues of specialized farms can be addressed with technical measures (e.g., air filter systems, slurry acidification and manure injection to limit ammonia emissions), impacts of for example disease control measures and fires affecting a large number of animals at once are felt much more strongly in wider society. High concentrations of specialized farms in one region often exacerbate environmental issues associated with agriculture, e.g., N deposition in nearby natural areas and increased risk of transmittable animal diseases. High concentrations of aerosols and ammonia in regions with a high density of chicken, goat and pig farms are known to affect human health and increase respiratory problems, e.g., pneumonia symptoms of residents living near goat[44] and chicken[45] farms. The probability of zoonotic infection of humans also increases[46] and has caused severe problems with, for example, Q fever in the Netherlands[45].

Fig. 3 Farms within the EU-10 in 2016 by type of specialization, as % of total farms for each crop and animal category (outer ring) and when grouped into specialized crop and livestock farms and mixed farms (inner ring). Here, EU-10 comprises Belgium, Denmark, France, Greece, Germany, Luxembourg, Ireland, Italy, the Netherlands and the UK. Source from eurostate[41]. Database: ef_m_farmleg.

3.2 Benefits and challenges of mixed farming

Although specialized farms dominate in western EU countries, mixed crop-livestock farms may still offer benefits. Mixed farming systems typically use crop-ley rotations and grazing of forage crops and crop stubbles to improve soil quality[47–50]. Grazing crop stubbles reduces agrochemical inputs[47,48], manages crop weeds and pests[51–53], and increases farm productivity and resilience of productivity[54]. In less regulated systems, mixed systems are reinvented to reduce risks with new options to combine cropping and grazing, for example, in Australian 'grain and graze' systems[55,56]. Benefits of scope, combining multiple products on a single enterprise, can in theory provide substantial cost reductions of 20%–70% when compared to specialized farms[57]. However, inefficiencies in the system reducing production (compared to specialized systems) can drive farmers toward specialization[58]. Examples of such inefficiencies are related to lack of labor at specific times for optimal timing of management (seeding, pest control, detection of animals that are in-heat or have health problems) and inability of farmers to manage complexity.

Mixed systems at farm level, with both crops and livestock on one farm, are more difficult to manage, require skills in a wide range of activities and can less easily take advantage of economies of scale. An ICLS operating at regional level does not have these disadvantages and offers both the economic opportunities of specialization and the environmental benefits of crop-livestock integration, but may require third party organizations (e.g., contractors) to facilitate trade and transport of materials (e.g., manures and straw).

In a modeling study, Bos[59] compared labor income on both specialized and mixed farms situated on the fertile clay soils in Flevoland, the Netherlands. The cropping sector was characterized by different crops, cropping frequency, N application and yields. The dairy sector was characterized by milk production level per cow, grazing system and share of concentrates in the ration. Standard input-output coefficients were used based on experimental and statistical data for Flevoland. Labour income was defined as the financial returns from products sold and direct payments minus fixed and variable costs. Labour income was maximized for the two sectors separately and for the mixed system for the same total land area. The prevailing manure legislation was included in the calculations which put a maximum on manure application rates and the difference between calculated N and P in- and output per ha on farms. The crop rotations on mixed farms changed when compared to the specialized farms. Specialised dairy farms had permanent grasslands and grew their own maize for silage. On mixed farms, grass-leys and maize for silage were part of the rotation and replaced onions and allowed change of frequency of potatoes from once every four years to once every five years. The maximum labor income under mixed farming was 45% higher (730 EUR·ha^{-1}) than under specialized farming (Table 1). This was partly due to the manure legislation which was limiting dairy production while cropping was not affected. Cropping farms used manures to only half of the legal limit, as manures are associated with risks of weed proliferation and the nutrient supply to crops with manures is less controlled than with synthetic fertilisers. They estimated that if farmers used manures to the legal limit (170 kg·ha^{-1} N from animal manures) the specialized dairy farm could supply more manure and hence potentially keep more cows and produce more milk. This would reduce the difference in labor income between the specialized and mixed farming systems to 475 EUR·ha^{-1}. The difference was largely explained by higher yields per hectare of crops in the mixed system due to lower cropping frequencies of the most profitable crops, potato and sugar beet, while the area cultivated remained the same. The differences in the nutrient balances of mixed and specialized systems were small and hence environmental effects were limited.

In another study, Bos and van de Ven[8] showed that total hired labor inputs in a similar mixed system in the same region were reduced by 12% compared to the two specialized farms, due to a better utilization of available labor. These two studies show that mixing the prevailing farm configurations gave a better economic performance but with similar environmental losses. This implied that for a reduction of the environmental impacts more adaptations are required that go beyond just mixing farm systems.

Table 1 Key characteristics of specialized and mixed farming systems involving crop production and dairy production, maximizing regional labor income in Flevoland, the Netherlands based on Bos[59]

Characteristic	Specialised farms	Mixed farms
Regional labor income (EUR·ha^{-1})	1650	2380
Dairy farming component (EUR·ha^{-1})	1150	2030
Crop farming component (EUR·ha^{-1})	500	350
Grassland (%)	Permanent 40	Leys 50
Continuous maize (%)	10	12.5
Crops (%)	50	37.5
Crop rotation	Winter wheat-ware potato-onion-sugar beet	Leys (1–4 years old)-sugar beet-maize-winterwheat-ware potato
Dairy cows (LU·ha^{-1})	1.65	2.50
Milk production (kg·ha^{-1})	13,200	19,900
Nitrogen surplus (kg·ha^{-1} N)	152	140
Phosphorus surplus (kg·ha^{-1} P)	7	9

Note: The dairy:crops land use ratio is 50:50 in the region. Crop rotations include onion (*Allium cepa*), potato (*Solanum tuberosum*), sugar beet (*Beta vulgaris* subsp. *vulgaris* convar. *vulgaris* var. *altissima*), winter wheat (*Triticum aestivum*) and maize (*Zea mays*).

3.3 Concepts of crop-livestock integration beyond the farm

Collaboration between specialized neighboring farmers is quite common. In intensive farming systems this is, however, mostly restricted to exchange of feed for manure or exchange of land to high value crops, for example to grow potatoes or flower bulbs on grassland in the Netherlands[19,60]. Existing research has classified integrated systems according to their reliance on inputs, capital and labor[61], space, time, ownership and management[62], and the level of interactions between crops, livestock and animals[63]. Building on these typologies, we can define systems with the lowest level of integration as segregated, where crop and livestock units interact primarily through the market. At the other end of the integration spectrum, crops and livestock can be highly coupled through crop-pasture rotation and in situ animal grazing, which increases nutrient availability for crops and can improve soil structure, if kept at low to moderate grazing intensities[61,64].

Within local areas, specialized farms can (1) coexist and exchange products without adapting crop rotations; (2) complement each other and adapt crop rotations to produce feed for animals; or (3) generate synergy by exchanging fields that allow to produce more high value crops or widen the crop rotation[65]. The benefits of option 3 are potentially larger than of options 1 and 2 but also strongly limited by distance between collaborating farms and sociocultural barriers. Mixed farms and these three levels of ICLS can be considered as models for an agroecological transition when they enhance metabolic functions and ecosystem services[66]. Metabolic functions include closing the nutrient cycles[67,68] while limiting environmental impact[69] and providing organic fertilization to improve soil quality. Ecosystem services require enhanced biodiversity at field, farm and landscape levels[70] to favor biological regulation, soil fertility building and water filtration[71]. Until recently, research on ICLS has mainly focused at farm level and on a biotechnical approach of practices-environment relationships, with few considerations of landscape and socioeconomic dynamics[2].

Synergistic ICLS provides direct exchanges of crop and livestock products between two or more individual farmers. The coupling of collaborating farmers often occurs at the landscape level (e.g., a watershed, community, island or complementary plain and mountain areas). The logic of these systems is (1) to keep costs down by maintaining economies of scale via specialized land use and producing feed for livestock on-farm, and (2) to diversify income streams. The farms participating in synergistic-ICLS systems may be partly diversified or fully specialized[63]. A common conclusion for several existing farm system typologies[61–63] is that more integrated farms are likely to be more sustainable and resilient to external shocks (e.g., weather extremes and market condition) due to synergies in space and time between crops, pastures and animals.

Synergistic ICLS at regional level requires farmers to sacrifice part of their independence and accept the complexity of arrangements needed for their organization. Hence, mixing at both farm scale and at regional scale has trade-offs and the optimum in economic terms is situation-specific.

4 INITIATIVES TO RE-INTEGRATE CROPS AND LIVESTOCK

4.1 New roles of livestock in cropping systems

Livestock grazing on temporary pasture or forage crops and crop stubble can recycle nutrients within the system and return C and N to the soil through urine and dung concentrated in patches[72]. Excretal returns to pasture and trampling of crop residues can increase soil N content for the following crop, reducing the need for external inputs[73]. If livestock are kept outdoors in winter and fed on forage crops this also has significant advantages in reducing feed imports as well as bringing tangible benefits by reducing the need for animal bedding and housing infrastructure and improving animal welfare[74]. Ploughing dairy-grazed grass-clover leys reduces fertiliser requirements of the subsequent crops in the rotation by 170 $kg \cdot ha^{-1}$ N in the first year, declining to 30 $kg \cdot ha^{-1}$ N by the third year[75]. However, benefits, risks and costs are highly dependent on livestock type, stocking rate, duration of grazing, duration of ley or forage crop in rotation, species composition of grazed ley or forage crop, region specific climatic conditions, and soil type. For example, high stocking rates strongly increase the risk of N and P leaching to groundwater[76,77] and water bodies and of atmospheric N losses as NH_3 and N_2O[47], as well as potential soil compaction with subsequent risk of runoff. Reintroducing livestock to already degraded arable soils can either accelerate or reverse declines in soil quality, for example, affecting soil strength and bulk density, as evidenced by a range of case studies (Table S1). These studies, along with others from EU and non-EU countries (Table 2), highlight the potential benefits, risks and costs of introducing livestock into cropping systems.

In addition to increasing soil organic matter content and soil fertility, arable farmers have increasingly been adopting livestock to manage herbicide resistant weeds, for example black-grass (*Alopecurus myosuroides*), and disrupt crop pest cycles, for example cabbage stem flea beetle (*Psylloides chrysocephala*)[53]. However, careful management is required. In Brazil, a soybean-beef cattle rotation found that high grazing intensity (sward maintained to < 10 cm) increased the weed seed bank by more than threefold, whereas low grazing intensity (sward maintained to 30–40 cm) decreased the seed bank by 42%[102]. This was attributed to the taller sward outcompeting weeds. Similar findings were also reported in the UK where sheep grazing reduced some species in the soil seedbank, for example ivy-leaved speedwell (*Veronica hederifolia*) and charlock mustard (*Sinapis arvensis*), but increased other species, for example chickweed (*Stellaria media*) because grazing maintained an open canopy[51]. However, in the USA a six-year rotation of sheep grazing of cover and cash crops found no effect on the density, biomass, and species of weeds and carabid beetles[103].

ICLS research includes many aspects, yet little is known about the effects of livestock in cropping systems on GHGs, pest and disease control, and tolerance to extreme weather events, for example drought[104]. Lack of evidence is often cited as one of the social barriers to ICLS adoption.

Table 2 Number of positive, neutral and negative impacts of livestock in various cropping systems in selected case studies

Grazing system	Positive	Neutral	Negative
		Soil C	
Crop-ley	5[49,78–81]	0	0
Forage crop grazing	2[82,83]	1[84]	0
Stubble grazing	1[85]	0	2[86,87]
		Soil N	
Crop-ley	2[75,88]	3[47,80]	1[89]
Forage crop grazing	1[90]	0	2[91,92]
Stubble grazing	2[73,93]	0	0
		Soil Structure	
Crop-ley	0	1[94]	1[79]
Forage crop grazing	0	1[83]	1[95]
Stubble grazing	1[85]	1[96]	3[73,93,95]
		Yield	
Crop-ley	1[48]	1[97]	0
Forage crop grazing	1[98]	1[99]	2[90,100]
Stubble grazing	1[96]	1[95]	1[101]

Note: Summary of findings from each cited reference is given in Table S1.

4.2 Social barriers and opportunities for ICLS

Changes in agri-environment policy and environmental laws have increased opportunities for the adoption of ICLS[105]. Recent refinements to the EU's CAP for post-2020 announces a shift away from crop diversification rules toward encouraging crop rotations, allowing member states to establish individual criteria based on national and regional requirements[27]. However, while EU member states can introduce policies, financial incentives and legislation to encourage the uptake of ICLS, there are social barriers to adoption to consider. In addition, wide-scale adoption is needed if we are to see tangible improvements in ecosystem service delivery at the catchment or regional scale.

Barriers to ICLS adoption vary across farming systems. For example, high costs of labor and synthetic inputs combined with a lack of supply chain support were identified as key barriers to the adoption of ICLS[105,106]. Further, poor infrastructure, lack of qualified labor and limited financial incentives are often cited by farmers as the key barriers to ICLS adoption[2,104,107]. However, integrated systems can use the experience of specialized crop and livestock farmers to produce beneficial agreements and overcome skill gaps and labor shortages. Agreements such as manure-for-straw deals allow arable farmers to exchange bedding straw in return for nutrient-rich manures to improve soil quality without the costs or labor associated with managing livestock[108]. Similarly, agreements between shepherds and owners of arable land to use "flying flocks" allows for mobile grazing sheep herds to manage herbicide-resistant crop weeds and increase soil nutrients in crop rotations, in return for increasing the grazing season and allowing livestock access to fresh pastures with low gastrointestinal parasite burden[109]. These agreements can also be used in coupled systems such as crop-ley rotations, which face similar barriers, e.g., unclear funding sources, fluctuating demand, and lack of logistical and social (labor force) infrastructure[110]. These are highlighted in Fig. 4.

Introduction of agri-environment schemes and policies are often cited as one of the solutions to adoption barriers but in the EU their success is varied[114]. Other countries provide some successful examples with schemes that promote ICLS. In Australia the Grain and Graze program aimed to reintegrate sheep and cattle into arable systems to address livestock feed gaps, increase yields, reduce environmental impacts and increase

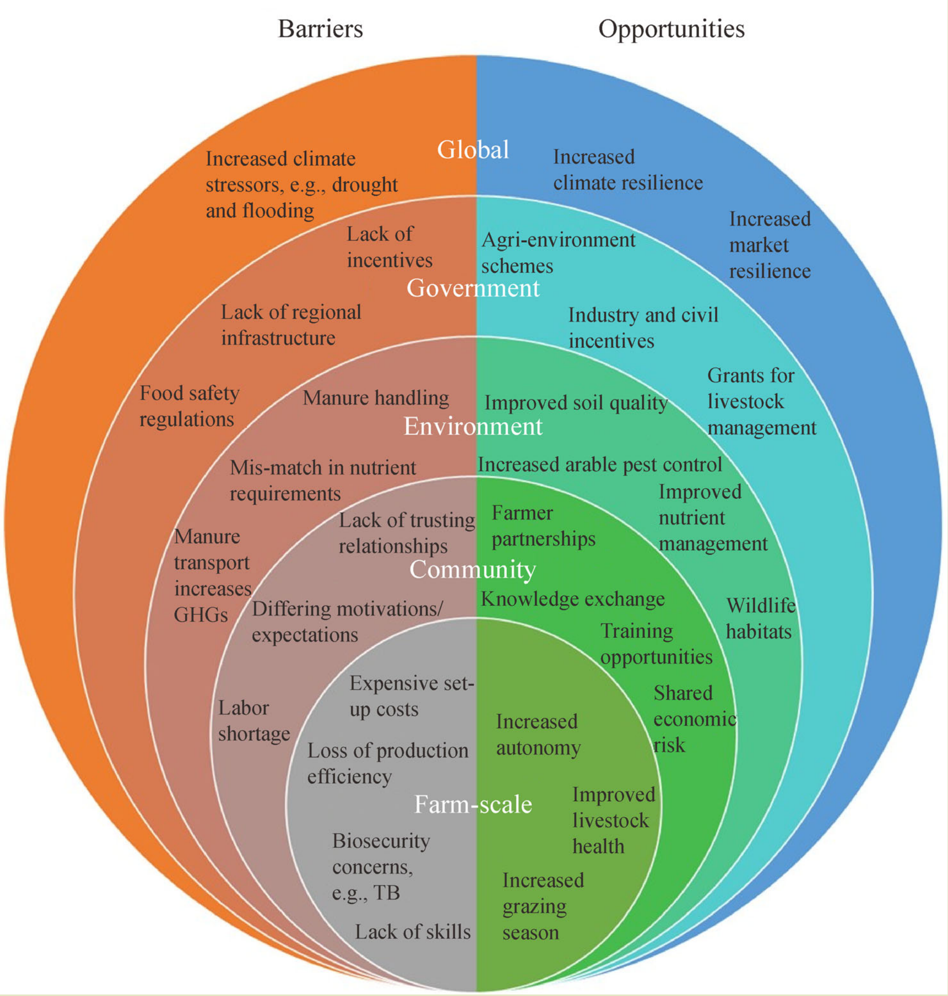


Fig. 4 Social barriers and opportunities of coupled and integrated crop-livestock systems[105,110–113].

profits[115]. However, participants of the program identified trade-offs between grain yield loss and livestock deaths by addressing feed gaps through forage crop grazing[116]. Introduction of the Low Carbon Agriculture Plan in Brazil in 2010 and the Integrated Crop-Livestock-Forestry law in 2013 provided financial credit for ICLS, aiming to increase agricultural productivity and quality, increase farmer resilience and mitigate deforestation and GHG emissions[104]. Financial credit was key to increasing farmer uptake but lack of agribusiness infrastructure, insurance, and land tenure limited ICLS adoption[104].

To overcome these barriers, farmers, researchers, policy makers and governments need to improve infrastructure and access to services, for example by financial support and education and awareness of the environmental and economic benefits of ICLS. In particular, training and financial incentives provide a key role in increasing the adoption of ICLS and allow for progression from barriers to opportunities.

Infrastructure for ICLS can be addressed by introducing centralized depots and service hubs to reduce distances traveled to access resources, for example manures, digestates and livestock feeds, and allow farmers access to standardized products at a standardized price while reducing the carbon footprint and transport costs borne by the farmer. Additionally, centralized depots would allow for the standardization of product quality, reducing the risk of spatial disparity of environmental benefits, for example from manure spreading, between integrated farms. This could also improve access to service contractors, for example shepherds during lambing season, and reduce the need for trusting partnerships between neighboring farms by using third parties. Farmers often cite the lack of pre-existing trusting relationships as a barrier to uptake but with the introduction of depots and service contractors, this establishes formal agreements for utilization[110].

4.3 Opportunities for integration of crop and livestock systems

ICLS provides benefits of the economies of scope, where multiple products are produced together with lower production costs than when produced separately[56], and can be practised in collaboration between individual farmers or via connections to a service hub. A mixed farm has the advantage that the farmer is independent, can make independent decisions and spread risk, is more resilient to weather and market shocks[56] and knows the quality of the intermediate products such as feeds and manures. ICLS with collaboration between individual farmers has the advantage that all farmers can remain specialized in their own sector with the associated specialized knowledge. All farmers can profit from the economies of scale as an important economic driver for development. They can together agree on the type of cooperation, what is included and what is not, and on the remuneration for each of them. The success of such a cooperation highly depends on farmers' attitude toward trust of other farmers and the perspectives for farmers in their alliances[28,117]. The farmer can still know the quality of the resources but in less detail. If such an alliance is too complex, the third opportunity is to establish service hubs functioning as brokers where farmers can offer their products and purchase inputs either physically or online. This saves them time and energy in organizing the detailed agreements. The hub or depot can also deliver other services such as quality control. For all types of ICLS the focus is on a higher efficiency of resources including nutrient use and reduction of inputs with the same or higher yields.

The fourth direction of development is toward more extensive systems with specific connection to local markets. This concerns generally mixed farms and is of specific interest to organic farming. Biodiversity and landscape aspects are more easily included in such systems and valued by consumers who are willing to pay relatively high prices for these products[19,25].

4.4 ICLS and circularity

Cities are major drains of nutrients in current food systems[118]. Most of the nutrients brought into the cities in Europe with food and pet feed are lost through the sewage system and end up in wastewater treatment facilities (WWTF). Currently, in some EU countries a proportion of these nutrients from WWTF is recycled back into agriculture via compost and anaerobic digestate, while in other countries waste solids are incinerated or used in post-industrial land remediation[119]. During wastewater treatment, most of the N is lost to the atmosphere, mostly as N_2, but about 3% as N_2O, a strong greenhouse gas[120]. These losses of nutrients in the food system need to be compensated to maintain soil fertility and are currently derived from mined resources or synthetic fertilisers[121]. In the Netherlands, nutrient balances for agriculture showed a 132 $\text{kg}\cdot\text{ha}^{-1}$ N and 7.8 $\text{kg}\cdot\text{ha}^{-1}$ P surplus in 2018[122], mainly due to large feed imports. Partly replacing synthetic fertilisers with manures and organic wastes can improve nutrient balances at the national scale. In western EU regions with typically large soil P stocks, P fertiliser inputs on croplands can be strongly reduced without affecting P uptake[123]. In western EU regions, feed adds more P to the system than fertiliser contributing to a surplus on the P balance for grasslands[124]. However, without P fertiliser and reduced feed imports, the current P surplus becomes a deficit and all manures need to be applied on dairy farms to compensate P offtake[125]. A reduced import of animal feed is not possible for current livestock densities on conventional farms in the Netherlands at current levels of P fertiliser use. Feed self-sufficiency is also challenging for the Dutch organic sector; the area under crops would have to be increased by 65% for the volume of livestock production in 2004. Of the total area, 27% would be in food crops, 38% in grassland and 35% in other feed crops[126].

Circular systems aim to recycle nutrients in the system and reduce surpluses and losses where possible with maximum utility of biomass[127]. Animals are fed residues and waste products and convert feed that is not edible to humans into protein rich food, and as such can use land efficiently[128] and reduce GHG emissions[129]. A reduction in animal sourced proteins is needed to reduce losses and limit GHG emissions. However, a food system with a limited consumption of animal products requires less land than a vegetarian food system[130], and animals will remain essential for a future food system. The conversion efficiency of feed into human edible products is relatively low, and the production of meat, eggs and dairy results in large losses of N in the food system. To minimize these losses the number of monogastric animals in a circular system needs to be balanced with waste streams and ruminants with areas unsuited for crops, with a range of production intensities[131].

To this end, de Boer and van Ittersum[127] formulated that animal feed should not compete with human food as a guiding principle, with arable farms on the best land and ruminants in areas unsuited to arable farming because they are too dry (rangelands), too wet (floodplains/peatlands) or too steep (hill slopes). However, compromises are required to service the needs and demands for specific animal products. Demand for grain for chicken and pig feed may be minimised when utilizing residue streams, producing food from resources that cannot yield food directly or indirectly after conversion by, e.g., insects. Although ICLS is limited to the exchange of products or land in crop and livestock systems[61–63] and does not directly consider the larger food system perspective as circular agriculture does, they do share the agricultural perspectives and are an important stepping stone to support this transition.

5 REFLECTIONS

5.1 Observed trends and current situation

Farmers in both western and eastern EU countries are specializing and increasing farm sizes as evidenced by the decreased number and proportion of mixed farms selling crop and animal products to markets. These trends were observed for both mainstream and organic farms, suggesting that the intensity of the system is not an important driver for specialization. We expect that the trends of further on-farm specialization will continue, driven by social and economic factors[58]. ICLS are better able to utilize resources efficiently and can operate at higher intensity levels with higher economic returns on capital, land and labor[7]. A coupled crop-livestock system can combine the benefits of specialization[106] while utilizing inputs in the system most effectively[7] reducing the need for mined resources and synthetic fertiliser inputs. However, possible trade-offs exist: one of the main drivers of ICLS is a more efficient use of resources reducing the costs of inputs but that may also lead to further intensification with more animals per hectare and a larger share of valuable cash crops in the landscape with associated negative environmental impacts. The potential benefits of ICLS therefore need to be balanced against the risks of further intensification with increased negative environmental impact.

5.2 Enabling conditions for integration of crop and livestock systems in future

ICLS will not develop without policy support and institutional incentives. In the Netherlands the policy on circular agriculture is such a supporting policy. It was formulated to restore the balance between food production and the capacity of the land, to reduce wastes and to enhance biodiversity and nature values[132]. This increased farmer and public awareness that the focus of food producers and consumers needs to shift from primarily economic to an integrated focus on economic and environmental aims. The different agricultural sectors are stimulated to utilize resources from other production chains, for example locally produced manures and feeds, and from the (regional) food processing industry. ICLS is eminently suited to comply with this policy.

Landscape planning aiming at a diverse environment for agriculture, biodiversity and recreation provides opportunities for ICLS at a regional scale, with a mix of farm types within one region. The EU policy on agri-environmental schemes (AES[133]) targeted these issues which were open for specialized individual farmers without requirements for ICLS. Drivers for farmers to participate were fair payments, lower dependency on just agriculture for their income and making progressive changes[114]. Although the AES so far do not focus on crop-livestock integration, they could be a starting point and provide opportunities for ICLS if directed at landscape level, adapted to productivity and context of the landscape[134] and connected to farmer motivation to participate. Other enabling conditions for ICLS at a regional level are service hubs and depots or storage facilities which link resources and products between individual farmers in different sectors, for example large manure storage facilities, with local transport and specialized application services that enable a timely application on cropland.

5.3 Policy considerations

The 2021–2027 CAP refinements highlight the need for efficient soil management as one of the nine key objectives for the future of CAP in the EU. Under the new CAP, EU member states are obligated to meet nutrient management targets to reduce N_2O and NH_3 emissions, with focus given to preserving carbon-rich soils and switching to crop rotation from crop diversification[135]. To qualify for CAP payments member states must meet conditions of statutory management requirements (e.g., the EU Nitrates Directive) and the Good Agricultural and Environmental Condition (GAEC) framework[136]. These key GAEC framework targets focus on climate change and soil quality including establishing buffer strips, using the Farm Sustainability Tool for Nutrients, improving tillage management, prohibiting bare soil at certain periods in the year, and crop rotation[136]. However, in the modernized CAP proposals for 2021–2027, no recognition is given to the role of ICLS within the EU.

We found that ICLS provides social and economic benefits supporting ecosystem services with, for example, higher soil fertility and biological regulation (weed and pest and disease control)[137]. By introducing policies to promote livestock in crop rotations, farmers and EU member states would qualify for CAP payments and sustainably achieve GAEC targets. For example, GAEC 3, which bans burning of crop stubble, could be addressed by grazing livestock on crop stubble. The largest benefits for farmers may arise from reduced manure processing costs in areas with large concentrations of animal husbandry. Mixed farms, or specialized ICLS farms at synergistic levels of integration, have a clear economic benefit and can operate at lower nutrient surplus levels with positive impacts on ecosystem services. Yet, these positive aspects can be offset by higher intensity levels with more animals per hectare and larger use of biocides on profitable crops occupying a larger share of the landscape. Therefore, legislation that promotes ICLS may not result in desired environmental outcomes[7], viz., reduced emissions to ground and surface water and the atmosphere, and should be accompanied by proper environmental policy to control emissions.

We did not find clear evidence that ICLS alone will result in reduction of emissions to the environment[7], including GHG emissions. However, it is expected that reduction of N losses from manures and limiting synthetic N fertilisers would result in reduced GHG emissions, yet overall effects may be rather limited when animal densities increase. Emissions to the environment strongly depend on the intensity of the system and efficiency of input use, less on the level of coupling of crop and livestock systems.

In the short-term, policies should encourage ICLS where possible to reduce excessive applications of manures and stimulate synergistic collaborations between arable and livestock sectors to reduce dependency on feed imports and inorganic fertilisers. This will require regional assessments of the spatial location of cropping and livestock farms, matching manure production with allocation capacity[138]. Incentives that encourage identification and implementation of innovative crop rotations that include grazed leys and forage crops, for example the Grain and Graze program as developed in Australia[115], should be prioritized. This could be achieved through environmental stewardship schemes such as the UK GS4 Countryside Stewardship scheme, which provides payments of up to 309 GBP $\cdot$ha^{-1} for the inclusion of legume and herb-rich multispecies leys in rotation for biodiversity and the reduced use of agrochemicals[139].

In the longer term, policy should encourage a healthy mix of farm types within close proximity to enhance ICLS, building on collective participatory design tools at the landscape scale[65]. Planning should also include biodiverse areas and agri-environmental schemes to control intensity levels, creating buffer zones around sensitive areas while facilitating habitats to enhance biodiversity. For the future, EU policy on nutrient recycling from urban centers and on food import and export is required to stimulate circular agriculture.

To achieve these targets, adjustments should be made to the Rural Development Policy by the European Commission to include financial incentives for ICLS systems such as those seen in Brazil. Funding institutions should prioritize business incentives for (1) purchase of specialist equipment by farmers wishing to diversify to integrated crop-livestock systems, and (2) the establishment of third-party intermediaries for managing the material flows (feed, straw and manure) between specialist farmers within a region, for example via subsidies/grants for transportation and spreading equipment.

In the long-term, alternatives for animal products and a change in diets and demand for animal proteins can also be expected as result of the introduction of so-called future foods[140], the push for healthier diets[141], and the need to reduce GHG emissions[142]. Policies that affect demand-side drivers, for example dietary choices, food waste and animal welfare could be used to promote the integration of cropping and livestock at the farm and regional scales. This change in demand and alternative protein supply may lead to a transition of farming systems with fewer animals. Animals will then primarily provide manure for fields, produce food from resources that cannot yield food directly, for example unsuitable land for crops, industrial wastes, and improve recycling of nutrients within the system. Policies for the long-term should therefore consider and facilitate structural adaptations that promote improved resource utilization at regional scales through coordinated circular solutions.

6 CONCLUSIONS

When compared to the mixed farm that was once common in Europe, specialized farms provide a wide range of benefits to farmers in a market with reasonable levels of risk protection, including large economies of scale, ease of management and opportunities to better manage farmer workloads. We found that reintegration of specialized farms in ICLS combines the benefits of specialization and reduces the dependency on mined resources and synthetic fertilisers while increasing the resilience of the system with enhanced ecosystem services and social, economic and technological advantages. Clear opportunities but also barriers were observed.

We conclude that ICLS need to be embedded within a future environmental legislation that limits emissions to the environment. ICLS for specialized farm types that are in close proximity provide synergistic benefits. However, further intensification is an important driver for ICLS adoption with clear economic benefits for farmers. In current settings with strict environmental legislation and limitations on N and P use, further intensification is constrained and policy incentives are, therefore, needed to promote ICLS to use inputs into the system more efficiently. We urge for policies that build on a long-term vision at landscape scale to encourage a regional mix of farm types and natural reserves, reducing the environmental challenges associated with strong ongoing regional specialization. An adapted mix of intensive and more extensive ICLS systems is needed to support a biodiverse landscape and cater for expected dietary changes in future with a changing role of livestock in a circular agriculture.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2020373 contains supplementary materials (Figs. S1–S2; Table S1).

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Compliance with ethics guidelines

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