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Synergistic strategies in integrated crop-livestock farming systems

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Abstract

Integrated crop-livestock farming systems (ICLS) are systems where plant and animal production are integrated on the same farm, creating mutually reinforcing benefits. Such systems recycle resources (animal dung as fertilizer and crop wastes as feed) and enhance fertility, water retention and nutrient use efficiency. This article provides a deep insight into ICLS, integrating current research and practical experience and illustrating the potential for synergistic solutions. We look at the main contributions to this field, its historical development and its conceptual basis. Key solutions include nitrogen cycling and manure management, innovative grazing systems, multi-purpose crop rotations, integration of agroforestry, water stewardship and integrated pest control with animals. Case studies reveal a diversity of techniques across geographies and scales, demonstrating economic and environmental advantages (higher agricultural yield, improved sustainability) and trade-offs (complexity, manpower requirements). Increased yields, diversified income sources, ecosystem services (carbon sequestration, habitat for wildlife) may be weighed against challenges of knowledge intensity and potential hazards (e.g. nutrient discharge if uncontrolled). We provide recommendations on implementation and policy measures (subsidies, training, market support) to promote the adoption of ICLS, via the use of comparison tables and systems diagrams. Finally, we emphasize research gaps and future endeavors include long-term field experiments, modelling greenhouse gas budgets and socio-economic analysis. Evidence shows that well-managed integrated farming may sustainably increase production while avoiding environmental consequences and is therefore an essential strategy to construct resilient global agriculture.

Keywords: Integrated crop-livestock systems, Nutrient recycling, sustainable agriculture

Introduction

Pressures on global agriculture are building. A larger population requires more food and animal products, while climate change and resource limitations put output at risk. In this sense, integrated crop-livestock systems (ICLS) have been indicated as a technique to synergistically achieve numerous aims. In these systems, crops and animals are integrated on the same ground ^[1]. Crops (cereal, forage and cover plants) offer nutrition and grazing for animals. Animals contribute manure and work to support crop production. This cyclic integration is different from specialized farming where crops and animals are produced separately. The ICLS are designed to connect farms in order to optimize efficiency of resource usage e.g., recycling nutrients from manure and crop wastes and to diversify the farm outputs ^[2]. Mixed farming was the global standard historically, with most milk and most of the world's meat coming from systems that blend crops with animals. Today, mixed farms still cover a substantial part of the agricultural area. For instance, nearly 50 percent of the world's land used for livestock (more than 2.5 billion hectares) is shared with cropland and these mixed systems provide over half of global meat and most of the world's milk (about 90 percent) ^[3]. These systems are promising for sustainability: they can sustain or even increase production, reduce dependence on external inputs, reduce soil erosion, increase nutrient cycling and support rural lives ^[4].

However, complex tactics are needed to develop successful integrated systems. Crops and animals interact in intricate ways that impact water and nutrient cycles, insect dynamics, soil health and economics.

Farmers must treat these interactions with care to achieve the full advantages. The state of the art in synergistic tactics in ICLS is reviewed [5]. We start with a brief overview of the conceptual framework and main results in the literature. We next review the historical development of integrated farming and mention leading scholars who have made their mark on the area. Then we cover the practical ways that produce synergy, from on-farm nutrient management to grazing systems, integrated pest control, crop rotations, agroforestry and water conservation. The interrelation of these elements is shown via comparative studies and graphical representations [6, 7].

Integrated crop-livestock farming is based on the ideas of ecology and agroecology. The basic concept is closed-loop nutrient cycling: animal excreta (manure and urine) go back to the fields as organic fertilizer, improving the soils, while crop wastes (straw, husks, cover crops) and fodder feed the animals. This reciprocal recycling keeps trash to a minimum and synthetic inputs to a minimum [8]. ICLS is characterized in a landmark review as “resource-saving practices that aim to achieve high sustained production while minimizing negative effects”. In reality this entails coordinating planting and grazing calendars, matching nutrient flows and balancing labour and capital amongst firms [9]. The advantages of integration have been defined in agronomic, economic, ecological and social aspects. Mixed systems are agronomically beneficial, maintaining soil fertility and productivity: legumes fix atmospheric nitrogen for subsequent crops, while manure increases organic matter [10]. Diversification is typically productive and profitable in economic terms since it yields numerous goods per unit area (grain, forage, milk, meat) and cuts input costs (e.g. less bought feed and fertilizer). Finally, on the social side, diverse farms provide consistent, year-round employment and income, assist buffer against market or climatic shocks and may decrease rural outmigration by making farming more robust [11].

This synergy is neither specialized or varied systems. In a diversified system there is coexistence between agricultural and animal companies; nonetheless, they run fairly independently of each other (for risk spreading, not dependency). Conversely, the most integrated systems purposefully connect crops and livestock, feeding crop leftovers to animals whose manure then fertilizes crops, thereby optimizing recycling on the farm. The difference is key: integrated systems are about recycling resources and mutual assistance, diversified systems are about risk management, not nutrient loops [12]. ICLS were nested within wider frameworks of sustainable intensification and nature-based solutions. Mixed farms are intrinsically a source of several ecosystem services beyond only food provision-soil protection, carbon sequestration, water control and habitat for wildlife [13]. Recent investigations in Europe have shown that the integration of livestock in cropping (or vice versa) often maintains crop and livestock yields at levels comparable to specialized systems and frequently greater over the longer term due to increased soil health [14]. Forage crops or perennials, for example, may improve later grain harvests and supply feed, leading to production improvements. In addition, environmental analyses show that mixed farms tend to generate fewer negative externalities per unit of output; for example, integrated systems avoid greenhouse gas (GHG) emissions from synthetic fertilizer production by using on-farm manure and reduce off-farm emissions by producing livestock feed on-site [15]. The research shows that effective ICLS are characterised by recycling of nutrients, complementary resource utilization and variety (of species, products and income). They are often classed along a range of low-intensity (e.g. mixed smallholder farms with broad grazing) to high-intensity (e.g. restricted livestock with intense fodder crops) integrations. There are several frameworks (ecological, economic, social) to analyse these systems, but all of them are on the alignment of crop and animal management in place and time [16].

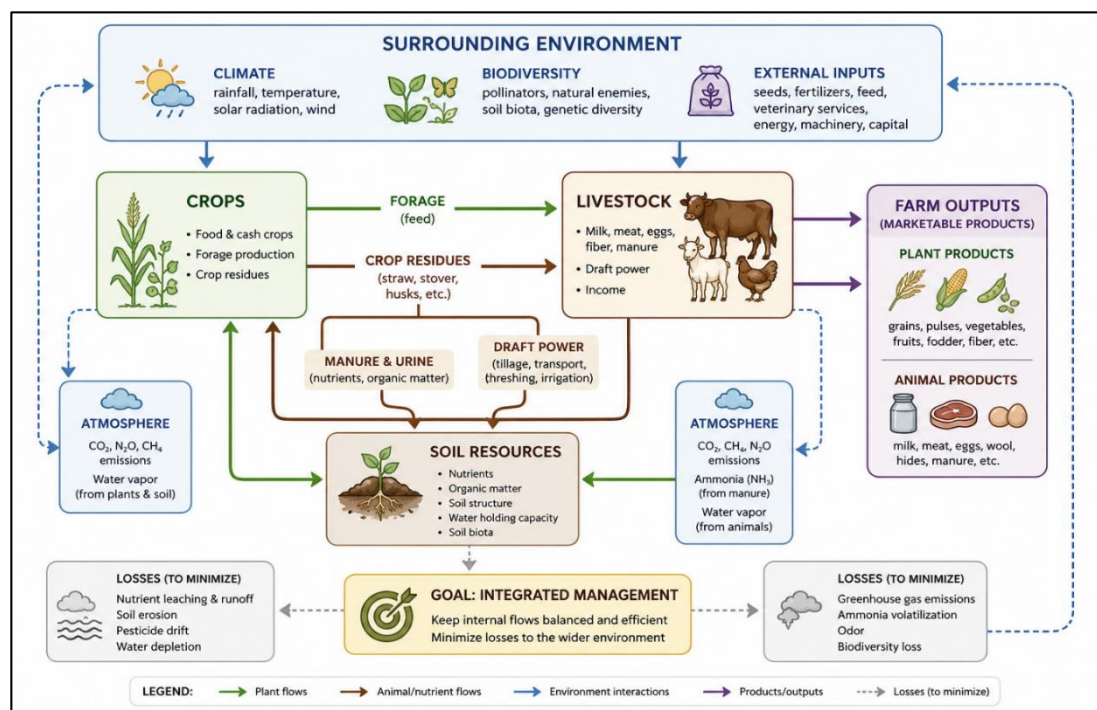


Fig 1: Diagrammatical representation of synergies between livestock and crops

The mixed crop-livestock farming system is as ancient as agriculture itself. Across the globe, farmers in ancient times cultivated crops and raised animals together, from rice-fish-duck systems in Asia to cattle-cereal cycles in Europe and cattle-maize in the Americas ^[17]. Formal ICLS study began in the late 20th century when agricultural intensification separated crops and animals. Important milestones include research by Wageningen scientists in the early 1990's (e.g. Van Keulen and Schiere) that modelled sustainability of mixed systems. At the same time, international centres (FAO, IFAD, CGIAR) organised discussions (e.g. Sete Lagoas Consensus, 2010) to give priority to integrated farming in development ^[18].

The subject has been made by great men. Rattan Lal, a world-renowned soil scientist at Ohio State University, USA, has been advocating re-linking cattle, crops and trees. In a 2020 study he authored, he noticed that the mid-20th-century model of farming had separated animal and agricultural production, resulting to nutrient pollution and greenhouse gasses ^[19]. Practices such as ley farming (cycling crops with fodder meadows) and alley cropping with animals may restore soil organic matter and reduce emissions, Lal says. In the early 2000s, Henry van Keulen

(Wageningen University, The Netherlands) and Jan Schiere (previously ILRI/Netherlands) created quantitative criteria for sustainable mixed farming, by analysis of resource allocation and efficiency. Maria M. Herrero (ILRI, Kenya) and former ILRI scientist Paul Thornton have conducted worldwide studies of the roles of mixed systems in food security and climate change, including the highly cited Science publication "Smart investments in sustainable food production: revisiting mixed crop-livestock systems" (2010) ^[20]. Michael Blümmel (CIAT/Philippines) and Shalander Tarawali (ILRI/CIMMYT) started work on dual-purpose crops and livestock feeding in smallholder systems, with a focus on fodder legumes and crop leftovers. Other key specialists include farm-level economists Antonio Bernués (Spain), Carina Antonio (Brazil) and Kirsten Rummukainen (Sweden) and extension scientists such as Neil Schulte (USA) who works on cover crops and grazing. These and many others-including extension educators and farmer advocates-added to the vast knowledge base on ICLS. Together their study illustrates how merging animal and grain operations might make the growing need for protein more sustainable ^[21, 22, 23].

Table 1: Compares some common strategies and their typical outcomes, illustrating how different approaches realize these synergies in practice ^[24, 25, 26, 27, 28]

Strategy/System Type	Crop Production	Livestock Production	Soil & Nutrients
Monoculture cropping (no livestock)	High input-dependent yields	No on-farm livestock	Soil often depletes over time (reliant on fertilizer)
Pure livestock grazing (no cropping)	-	Dependent on pastures	Pasture soil may decline without legumes
Crop rotation with synthetic fertilization	Moderate-high yields	Occasional grazing on stubble	Some soil improvement if legumes included
Crop + intensive grazing rotation	High overall output	Additional meat/milk on residues	Soil organic matter maintained by manure
Cover crops with managed grazing	Additional biomass	Livestock gain extra forage	Enhanced N-fixation and organic matter
Crop-livestock spatial integration (mosaic)	Continual cropping	Animals graze separate fields	Local nutrient recycling via manure application
No-till cropping with cattle trampling	Maintains yields over time	Cattle mobility on fields	Improved soil structure (natural aeration)
Pasture cropping (sowing grain into pasture)	Grain from permanent sward	Extended grazing seasons	Builds soil carbon; reduces bare soil erosion
Rice-fish-duck integration	Paddy rice yields	Fish and poultry production	Mutual nutrient use (waste of one feeds another)
Organic diversified system	Diverse crops (legumes, veg)	Pastured cattle/ruminants	Closed nutrient loop via compost and rotation
Intercropping (multi-species crops + grazing)	Multiple cash/forage crops	Seasonal grazing on intercrops	Dense rooting improves nutrient uptake

Practical Synergistic Strategies

This section describes key management strategies that enable crops and livestock to support each other. Each strategy is framed around the *synergies* it creates.

Nutrient Cycling

The key to integrated systems is efficient cycling of nutrients. The main carrier is manure: animal dung (solid and liquid) provides the nitrogen (N), phosphorus (P), potassium (K) and organic matter needed for crops. If administered correctly, it closes the fertility loop. For instance, when they excrete, cattle on fields slowly release nutrients for the next crop. Studies have shown that approximately 70% of the nitrogen and phosphorus consumed by animals in normal grazing systems is returned to the pasture via manure and urine ^[29]. Organic inputs improve soil structure and biological activity, increase cation exchange capacity and moisture retention. Soil

organic carbon builds over time. One analysis found that on mixed farms, consistent manure application may increase soil carbon stocks by 26% compared with no-manure fields and adding legume forages increases carbon by an additional 0.1 t/ha-year ^[30]. Farmers should time manure inputs with crop demands to optimize cycling ("system fertilization") In Brazil, for example, researchers discovered that nitrogen applied to forage crops left more N accessible to the next maize phase, decreasing nutrient immobilization and increasing yields. If this is not synchronized, N may be trapped into high C:N residues ^[31]. Therefore, the integrated fertilization plans take into account all rotation periods. Composting or digesting the manure may help boost nutrient availability. Compost bins or anaerobic digesters turn raw trash into stable fertilizer, making nutrients simpler to manage and lowering pathogens. Direct cycling from grazier to field is typical for smallholders. Animals are moved onto harvested agricultural leftovers or cover crops, then returned

to pens where manure is collected and deposited on fields [32]. The cover crops themselves are part of nutrient cycling, as are agricultural wastes. Grazing animals provide slurries to grains put after them. Forage crops contribute nutrients from rotting plant roots. Rotations that include nitrogen-fixing legumes (such as clover or cowpea) may provide

nitrogen naturally. Mixed pastures (ie. legumes, grasses, herbs) are particularly good in scavenging leftover soil nutrients and feeding microorganisms. It has also been suggested to use biochar as a co-application with manure to stabilize carbon and retard N leaching [33].

Table 2: Compares nutrient flows under different system types [34, 35, 36, 37, 38]

System Type	Nitrogen Inputs	Recycling Practices	Nutrient Outcomes
Conventional cash crops only	High synthetic fertilizer; imported feed on livestock farms	Minimal (crop residues often burned or removed)	Low retention; leaching and N ₂ O emissions
Crop rotation with legumes	Moderate fertilizer plus biological N fixation by legumes	Legume residues left in soil; cattle graze cover crops	Good N supply to next crops; reduced fertilizer
Pasture-based livestock	Low fertilizer (fertilized pasture); supplemental feeds imported	Animal excreta (dung/urine) returned to same pasture	~70% of feed N recycled in pasture
Crop + managed grazing rotation	Fertilizer on cash crop; pasture utilizes feed/forage feeds	Manure spread on crop fields; periodic grazing on stubble	Efficient loop: manure to crops, crops to animals
Integrated crop-livestock mixed	N from manure + some fertilizer; internal feeds	Balanced grazing + manure application; cover crops + compost	Very high internal recycling; minimal losses
Intensive feedlot (confinement)	Imported feed; excess N in manure storage	Partial manure recycling (often exported to distant fields)	Excess P/N leads to pollution; local surpluses
Organic mixed farming	Inputs: compost, organic amendments	Manure and green manures; rotational grazing on crop residues	Closed-loop fertility; sustainable soil building

Grazing Management

Synergies are only possible with good grazing management. Rotational grazing, in which grassland is divided into many paddocks and animals are moved often, enables plants to recover, maximizes forage usage and minimizes overgrazing. Integrated farms may coordinate grazing rotations with cropping cycles. For instance, after the grain harvest, cattle may graze stubble fields or cover crops in late autumn, decreasing waste and nourishing soil with their trampling and droppings [39]. Winter grazing on cereal or forage crops extends the availability of feed during the whole grazing season. In certain other circumstances, cover crop termination by animals is practiced: e.g., grazing a rye cover crop in spring gives fodder and the defoliated biomass settles as mulch for planting. Mixed species grazing (cattle, sheep, goats together) may enhance the results further [40]. Different animals like different flora. Goats will cut brush and weeds, sheep like grasses, cattle bulk out on rich fodder. This may lower weed pressure and improve grassland biodiversity. Plus limited stock numbers prevent compaction [41]. Animals grazing beneath tree canopies in orchards or vineyards may help remove undergrowth and provide organic matter to the soil and at the same time avoid soil crusting that can be caused by heavy equipment [42]. Studies have shown that livestock integration decreases soil compaction and tractor fuel usage, since animals naturally aerate and graze fields rather than artificial tillage. Grazing also has an effect on nitrogen and water cycles. The soil crust is broken by animal hooves and water may penetrate the soil more easily. Their dung deposition is spatially structured farmers commonly conduct “targeted grazing” to concentrate manure in areas that require fertility (e.g. trailing animals or changing fences) [43]. Water management and grazing are interlinked: in certain agro-ecosystems cattle are cycled on irrigated paddies or damp sloping fields to graze on aquatic plants, transforming thus water and crop leftovers into biomass and manure. In general, adaptable grazing systems that respond to seasons, fodder supply and animal demand, maximising feed conversion, while keeping nutrients circulating on farm, exemplify synergy [44].

Integrated Pest Management (IPM)

Integrated systems control pests and illnesses organically. Biological controls work well if animals are around. For example, free-range poultry (chickens, ducks, guinea fowl) will consume bug pests and weed seeds in orchards and fields. Experiments have shown that orchard hens may greatly reduce insect damage and the demand for pesticides. Pigs or goats in orchards will similarly consume fallen fruit and certain pests. Grazing cattle may even upset pest habitats (trampling insect cocoons on grassland, disturbing weed cycles) [43]. Livestock contribute to on-farm biodiversity: predators such as birds and beneficial insects have a wider range of habitat and food (e.g. insects in dung, small animals in less-disturbed regions), boosting biological pest management. Crop-livestock rotation is a technique in itself: planting a pasture or a non-host crop between grain crops helps stop cycles of pests or pathogens. Rotation of cereals with grass-legume leys may control several stem or soil-borne diseases of cereals [40]. Cover crops planted for grazing also have the ability to reduce pests; brassica or mustard coverings may naturally biofumigate soils. Monocultures, however, may frequently enable pests to run rampant. So integration is helpful to IPM it provides consistent habitat and food webs for beneficial species, while various rotations and animal grazing help to disrupt insect life cycles [45]. There is a caveat regarding biosecurity: the introduction of livestock may also bring new pests or illnesses to crops (e.g. hooved animals possibly spreading weed seeds or viruses). This danger may be reduced by careful scheduling (grazing before planting, not during sensitive crop stages) and cleanliness (cleaning animals/waterers between fields). In all, the IPM advantages of crop and animal integration reduced chemical usage, increased natural control, weed reduction-are a significant element of the synergy story [46].

Crop Rotations

The use of crop rotation in integrated systems is more than just yearly sequences. Forage and feed crops are mixed with legumes, grains, oilseeds and grasses: A good rotation may include maize for grain followed by a forage legume (clover

or cowpea) that is grazed by livestock, then winter cereals or rapeseed and a cover crop in autumn that feeds sheep. Each component has a dual role, providing food for people and feed or soil amendments for animals ^[47]. These rotations are good for soil N: legumes fix N early in the rotation which is beneficial for the later cereals and the presence of grasses and Brassica crops may enhance soil structure.

One famous approach is ley farming, where arable crops are rotated with temporary meadows (leys) for cattle. For example, a farm may cultivate wheat for two years, then have a two year grass-legume pasture that is grazed by cows, before going back to wheat. The pasture years provide animal products, restore fertility and suppress weeds ^[48]. Another technique is pasture cropping, which involves sowing annual crops such as wheat or soy directly onto a perennial pasture. This enables dual grazing and grain harvest from the same ground, as pioneered in Australia. Cover crops are also important: planting such species as rye, oats or vetch after harvest offers winter fodder for animals and protects soil from erosion. These coverings, when grazed or ploughed in, provide nutrients and organic matter for the next cash crop ^[49]. In ICLS, the many rotations have numerous aims with each component, increasing synergy. They stabilize yields (nutrients, moisture retention), reduce pests and feed cattle without the need for separate feed fields. These measures involve forethought (e.g., fence, scheduling), but their combined advantages to soil and production are well proven ^[50].

Manure Management

Proper management of manure and organic waste is the key to synergy and environmental preservation. Manure may be kept, composted or applied fresh but in all circumstances it recycles nutrients. Composting manure stabilizes nutrients, eliminates pathogens and makes a soil amendment that may be applied on fields as fertilizer. Fresh manure may be spread on fields by means of troughs or by rotating animals on strips of feed as mentioned before.

A key method is matching manure application to crop requirement and season ^[51]. For example, if solid manure is applied to fallow or cover-cropped land, by planting time the nitrogen will have crystallized and less fertilizer will be needed. Liquid manure (slurry) has to be handled carefully to minimize nutrient run-off. Covering slurry lagoons and injecting it into soil rather than disseminating may help reduce ammonia volatilization. In integrated dairies, farmers frequently slurry-test and distribute manure to the agricultural areas that fed the animals, completing the loop” ^[52]. Nutrient budgeting (accounting for all inputs and outputs) is best practice. Farmers may monitor the amount of N and P animals excrete to ensure fields get what crops will absorb and prevent excess leaching into waterways. In Europe, strict nitrate rules have even promoted recycling by making the on-farm use of manure more valuable than the expensive long-distance delivery. Integrating these systems typically improves profitability and ecological performance: for instance, farms that compost and recycle manure generally save expenses for synthetic fertilizer and produce soil organic matter quicker, thereby enhancing future yields ^[53]. To conclude, manure management in ICLS is not a waste issue but a resource strategy. The integrated farms see animal excrement as “farm fertilizer” and manage it prudently to maintain high fertility and limit pollution, which is the core synergy of crop-livestock integration ^[54, 55].

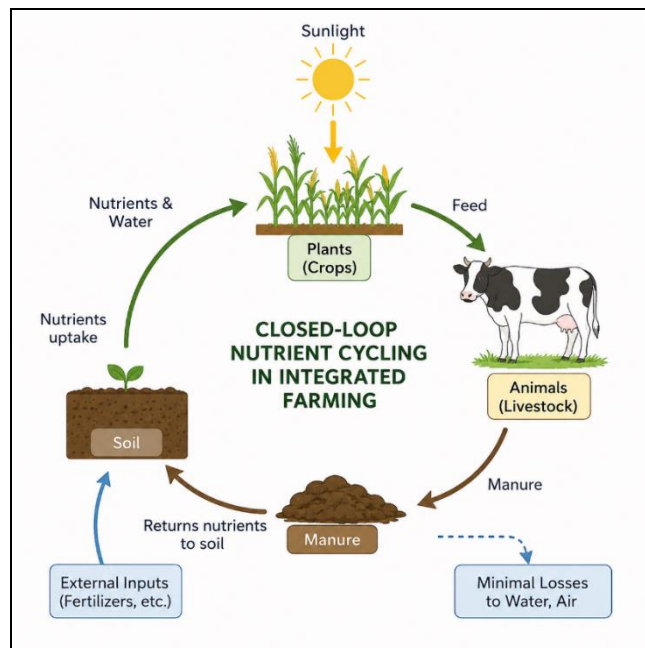


Fig 2: Closed loop nutrient cycling in IFS

Agroforestry

Agroforestry combining trees with crops or animals generates more synergies. For example, silvopasture blends grassland with dispersed trees (fruit, wood or nitrogen-fixing species). Trees shade and increase animal welfare and pasture microclimate. Leaf litter and deep roots recycle nutrients and water from the subsoil. Fodder from trees (such as leaves or pods) is an additional source of food for animals, particularly during the dry season ^[56]. Alley cropping plants rows of trees or bushes (typically legumes) between strips of crops. Trees may be trimmed for mulch and feed. Tree roots bring up nutrients and moisture, reduce leaching and cushion extremes in climate ^[57]. Trees may be regularly chopped (coppiced) to provide wood fuel or pasture without destroying the live root. This provides periodic animal feed along with long-term carbon storage. The experimental farms have shown great usefulness. For example, adding cattle in poplar or willow riparian buffer strips helps preserve streams and also provide wood and better grazing (cattle were cooler) ^[62, 58]. Another example is contour shrub fodder systems (e.g. Willows or *Leucaena* hedgerows): animals grazing these hedges recycle nutrients on slopes and decrease erosion. The economy benefits from many streams of products (fruits, nuts, wood, animals) and diversification against crop failure ^[59]. Management is more involved (time of pruning, careful spacing), but agroforestry makes for higher resilience. Trees trap carbon, enhance biodiversity habitat and may provide high value outputs. Dryland silvopastures act as windbreaks and retain soil moisture. Fruit trees may be planted in flooded regions along canals with integrated fisheries and duck flocks. There is also a big social advantage, in that trees may be collateral for smallholders, or firewood for communities, connecting income and nourishment ^[60, 61].

Water Management

Complementarities also contribute to efficient water utilization in ICLS. Deep-rooted forage plants in rotations tap into subsurface moisture to help following shallow-rooted crops in next season. Runoff is slowed enough by land-management practices such as contour hedge rows or

cover crops to enable infiltration from surface soil ^[63]. One advantage: Livestock may be utilized to manage cover crops or rice stubble, which would have to be irrigated to regenerate, saving water. A second technique is integrated irrigation: in certain systems, surplus water from rice paddies (drained for off-season) is utilized to irrigate fodder crops or ponds for aquaculture, fertilizing fields in the process ^[64, 65]. Livestock water troughs catch runoff nutrients. It is of special importance to have green manuring and permanent grazing land, so that there is less barren soil, less loss of water by evaporation and the moisture remains in the crops. Rotational grazing and other water-saving measures, also increase drought resistance ^[66]. The application of manure enhances the water holding capacity of the soil by maintaining a healthy plant cover and organic matter and so reduces the requirement for irrigation. Livestock may also take advantage of excess feed during unexpected rain events, which can avoid nutrient runoff. Lastly, water infrastructure in integrated farms may be multi-functional ^[67]. For example, artificial wetlands can be used to treat dairy effluent and to irrigate fodder, or fodder banks can be planted along rivers to utilize nutrient rich water for growth. These approaches show that the integration of agricultural and animal water demands may improve the overall water production and quality ^[68].

Economic and Social Aspects

Economically, integration provides for diversification of revenue and diffusion of risk. Farmers do not only make money from a single commodity price. They make money from grain and animal goods and frequently wood or other crops. In one site, the Mississippi cover-crop grazing research showed that introducing cattle to a no-till soybean system resulted in around \$200/acre more in net returns ^[69]. Labor utilization also changes: integration usually demands more regular agricultural labor, giving year-round employment. This is socially beneficial in rural regions by decreasing seasonal idleness and out-migration. Family labor may be shifted between crops and animals to even out workloads. On the other hand it increases the complexity since farmers have to make judgments regarding grazing patterns, feed allotment and market timing ^[70]. It is also important for smallholders who are not used to managing numerous operations to have help and training on extensions. Community and cultural considerations matter as well. Mixed farming is already the norm in many ancient communities. Rice farmers in Asia, for example, regularly raise ducks on their paddies, while Sahelian millet farmers typically allow cattle to graze on their fields after harvest. Such indigenous knowledge may be revitalised to boost acceptance ^[71]. However, socioeconomic limitations such as land tenure and access to financing may limit farmer integration. Economies of scale are also relevant: smallholders may not have access to markets for numerous goods whereas big mechanized farms may find it difficult to incorporate free-ranging animals ^[72, 73]. The social synergy of integration is in general terms resilience and rural development. Where markets exist for both crops and cattle, integrated farms may increase family income and nutrition. Furthermore, community-level cooperation (for grazing rights, shared extension) typically develops to sustain these systems. Understanding these dynamics is essential to move ICLS beyond just technical approaches ^[74].

Benefits and Trade-offs

Benefits

There is evidence of a number of advantages of well-managed integrated systems. Productivity per area is frequently greater when land is worked more intensely and constantly for longer duration of time, giving both crops and animal products ^[75]. Manure and nitrogen-fixing elements sustain or improve soil fertility, resulting in more consistent yields across time and space. Perennial pastures and cover crops may increase water usage efficiency by reducing evaporation and runoff ^[76]. There is often increased biodiversity at field and landscape level since a combination of plants and habitats supports more species and beneficial insects. Elsewhere, too, soil and trees are more effective at sequestering carbon, so helping to slow climate change. From the economic point of view, integrated farms are able to provide higher profits ^[77]. Spreading the risk by diversifying items (grains + milk + meat + other) softens losses if one market price drops. Input costs are less when manure substitutes for purchased fertilizer and when feed is farm-grown rather than purchased. Several case studies have shown increases in net farm revenue when animals are introduced to a cropping system or vice versa. Socially, integrated systems strengthen smallholder and family farms by optimizing the utilization of family labour throughout the year, decreasing vulnerability and frequently enhancing nutrition (access to fresh milk, eggs or meat) ^[78].

Trade-offs

But integration comes with trade-offs and problems. Complexities are a big worry. You need to know about animal husbandry, agricultural agronomy and logistics (e.g. fencing, scheduling) to run many businesses. Labor needs may increase and although year-round labour may increase employment, it also implies fewer idle seasons for farmers and labourers ^[79]. Infrastructure may be fencing for rotational grazing, storage of manure, drinking places for cattle in fields or separate homes for various species. Poor management may lead to production penalties, for example extensive grazing at the wrong time might lower next crop yields or badly composted manure can transmit viruses ^[80]. There are economic trade-offs between integrated and specialized scenarios: a specialized farm may have extremely high yields of a product (e.g. irrigated corn or high-yield cows) that a small-scale integrated farm cannot reach. Thus the integrated systems may not be optimized for a single product production but for a complete output and resilience ^[81]. Market access is also an issue, since farmers need customers for all their goods (crops and animals), or they need to add value on-farm (cheese-making, meat processing) to gain advantages. Another thing to consider is land usage. In certain circumstances, allocating land to forage or pasture lowers the nearby farming area. Policy contexts may aggravate or ease trade-offs ^[82]. For example, subsidy regimes that encourage monoculture may punish integration, while assistance for manure management may lessen burden. Finally, there is a learning curve. Farmers moving into integration frequently need training, demonstration plots and time to adapt ^[83, 84].

Conclusion

The integration of agricultural and animal production in farming systems is an efficient way to achieve sustainable agriculture. By deliberately integrating crops, livestock and

land management, farmers may create synergies that boost productivity, rejuvenate soils and reduce their environmental impact. Our study indicates that there are several ways to encourage good integration, such as nitrogen cycling, adaptive grazing, agroforestry, different rotations and social-economic design. ICLS, if done consistently and efficiently, has the potential to raise total farm outputs, to stabilize farm incomes and to provide environmental services such as carbon sequestration and biodiversity enhancement. However, integration is not a one-size-fits-all approach. It requires skill, coordination and occasionally building new infrastructure. There are trade offs and the outcomes are based on the peculiarities of the place. It is also important that policymakers and advisors see integrated farming as one option in a portfolio of options and that support be customized to the area, kind of farm and cultural milieu. There are ways to lower the barriers and maximize the advantages of integration through incentives, education and research. Looking forward, ICLS is well-placed to make a significant contribution to future food requirements in an ecologically friendly way. They are in line with the worldwide goals of climate-smart agriculture as well as with regenerative agriculture. Therefore, it would be very important to continue studying and to talk across industries and to learn from farmers' experience. When efficiently developed and managed, integrated systems may deliver on the promise of synergy: food for the people, better rural economies and the resource basis for future generations.

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