Crop-livestock integration: Implications for food security, resource efficiency and greenhouse gas mitigation

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BACKGROUND

The global population, currently estimated at approximately 7 billion, is projected to exceed 9 billion by 2050. The demand for food production is expected to increase by 35% to 56% between 2010 and 2050.[1] The United Nations embarks on the Sustainable Development Goals (SDGs), and indicates that food shortage is a global challenge in achieving the SDGs with necessitating significant growth in both crop and livestock production. Various resources are required to be channeled into agriculture to address ongoing agricultural food production, particularly the increasing input of energy, water, nitrogen fertilizer and agricultural land. In addition, the agricultural sector is the leading contributor to the land use change, which lead to the biodiversity losses and the great increase of greenhouse gas (GHG) emission. The question is how to keep ensuring food production without too much increase in resources use and GHG emissions in future.

THE CONCEPT OF CROP-LIVESTOCK INTEGRATION

Crop-livestock integration represents a systematic agricultural practice that amalgamates crop production and livestock farming into a cohesive model, thereby fostering a more diversified, sustainable, and efficient agricultural food system (Figure 1). This approach capitalizes on the natural synergies between crops and livestock to enhance productivity, optimize resource utilization, and promote nutrient cycling that is beneficial to both food production and environment. The traditional crop-livestock integration refers to the waste manure generated by the breeding industry into farm fertilizer, which is used for crop cultivation. By employing practices such as manure recycling, residue feeding, and the reduction of straw burning, farms not only increase agricultural diversity but also achieve operational profits that can exceed double those of low-diversity farms. The future crop-livestock integration is more emphasis on re-cycling based on the large-scale breeding and planting, which emphasize agricultural cropping and animal husbandry waste resource recycling and efficiently used. Specifically, by-products, including crop residues, animal manure, biogas slurry, and dead animals, are transformed into organic fertilizers, feed raw materials, biomass materials/energy through biotechnology, to achieve efficient utilization of resources. A case study conducted in the Greater Mekong Subregion illustrates the advantages of crop-livestock integration in addressing global challenges, including food security, resource efficiency, and the reduction of greenhouse gas emissions.[2] New technologies from smart agriculture can be combined with crop-livestock systems. This includes leveraging the Internet of Things to monitor crop and livestock growth conditions, environmental parameters, and provide farmers with data-driven insights for effective farm management strategies. Furthermore, technologies such as drones and remote sensors, combined with deep learning, can be employed for weed management and animal health monitoring within integrated systems.

IMPLICATIONS FOR FOOD SECURITY, RESOURCE EFFICIENCY AND GREENHOUSE GAS MITIGATION

Food security is increasingly compromised by global population, climate change and weather variability, necessitating urgent intervention. Economic growth and rising incomes are also driving a dietary shift from staple foods to increased consumption of meat, eggs, dairy, and aquatic products, further straining food resources. The soil degradation and erosion, and overgrazing, which disrupted nutrient cycles, often exacerbate the natural resources and the sustainability of the production system. Integrated crop-livestock systems enhance the development of high-quality artificial pastures and restructures livestock production to boost the supply of beef, mutton and dairy products, and reduce the reliance on feed grains in livestock farming. Farm manure improve soil physical properties by reducing bulk density and

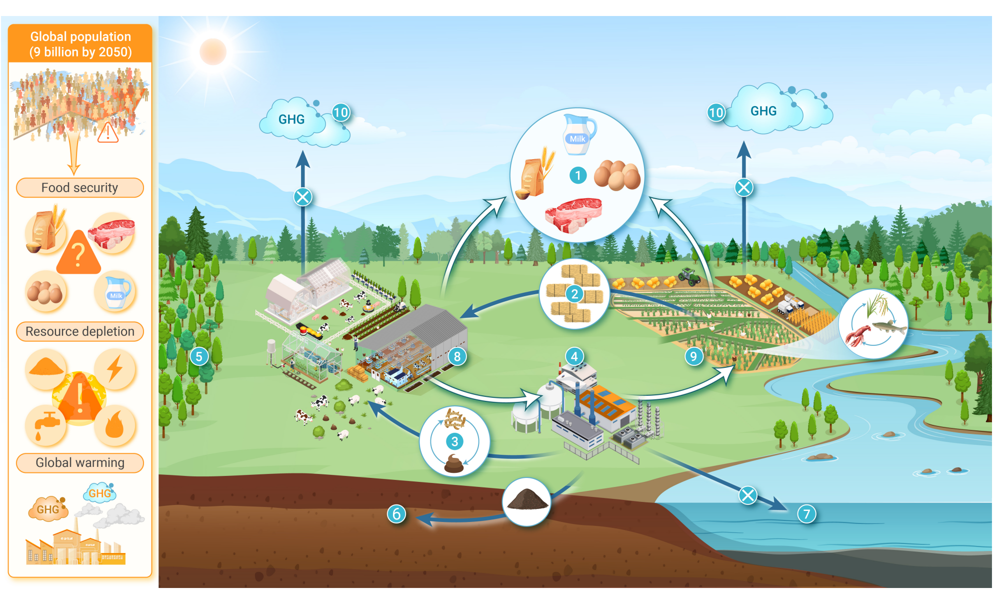

Figure 1. Overview of crop-livestock integration for food security, resource efficiency and greenhouse gas mitigation ① Enhancement of food security through providing adequate foods, such as grain, meat, eggs and processed products. ② Crop by-products for livestock feed to reduce dependency on synthetic inputs and external markets. ③ by-products as feed source for insects or animals through generating new micro-ecosystems. ④ Anaerobic fermentation of by-products and livestock manure to generate biogas. ⑤ Conservation of natural resources with sustainability for constant food supply. ⑥ Continuous improvement of soil health and water quality for ecological environment. ⑦ Reducing nitrogen and phosphorus pollutions in groundwater and aquatic ecosystems. ⑧ Increasing soil organic carbon sequestration and improves the soil quality, which will benefit for the crop production. ⑨ Livestock manure as a valuable source of organic matter through decreasing the reliance on synthetic nitrogen fertilizers. ⑩ Crop-livestock-forestry systems as strategic interventions for mitigating greenhouse gas (GHG) emissions.

increasing macroporosity, and shows the function of increasing total forage yield by 36%.[3] Farms with high levels of integration exhibit greater resilience of agricultural production to climatic variability and disease, because of their higher ecosystem biodiversity enhances their resistance and adaptability to extreme environmental changes. In addition, integrated crop-livestock systems provide farmers with a broader range of income sources and mitigate economic risks. For example, crop by-products, such as straw and cover crops, are utilized as livestock feed to reduce dependency on synthetic inputs and external markets, thereby promoting overall production and stability. Evidence suggests that the crop-livestock integration model significantly increases per capita income for participating farmers. Importantly, it also improves the food quality and nutritional value, and provides diverse foods for household dietary.

The growing scarcity of freshwater, cultivated land and the nutrient are needed for sustainable food supply, particularly in the context of feeding an estimated global population of 9 billion by 2050. As agricultural production continues to expand, neglecting the conservation of natural resources and the sustainability of production systems can lead to detrimental outcomes, including soil degradation, erosion, and disrupted nutrient cycles. These challenges contribute to an increased reliance on external inputs. The crop-livestock integration model enhances resource efficiency by allowing both crop production and livestock farming to locate on the adjacent land, minimizing transportation cost and promoting efficient use of the resources. This integrated approach maximizes sustainable use of resources though following prospects: (1) by-products from crop production on the farm can be partially utilized as animal feed, including grains and crop residues, thereby creating a closed-loop system that minimizes waste; (2) livestock manure serves as a valuable source of organic matter through decreasing the reliance on synthetic N fertilizers, and improves overall soil health; (3) anaerobic fermented of by-products generates biomass energy, which provides alternative non-fossil energy source; (4) by-products serves as feed source for insects or animals through generating new micro-ecosystems, such as rice-fish/shrimp/crab and chicken-forest; (5) continuous improvement of soil health and water ecological environment, promoting the circulation of carbon and nitrogen elements more efficient and virtuous. In addition, agroforestry practices, that recognized as environmentally sustainable land-use technologies, have the potential to substantially mitigate the loss of hydrological functions and reduce non-point source pollution in groundwater and aquatic ecosystems. The crop-livestock integration model promotes resource efficiency by enabling crops and livestock to coexist, utilizing by-products for feed and energy, improving soil health, and fostering new ecosystems.

Global warming represents one of the most significant threats to humanity, driven primarily by the increase in GHG emissions. The agricultural, land-use, and forestry sectors account for nearly one-third of total GHG emissions, predominantly due to livestock and fisheries, crop production, land use for food and feed, and supply chain. Mitigating methane and nitrous oxide emissions in agricultural food production is a critical strategy for reducing overall GHG emissions. China's national "14th Five-Year Plan" and the 2035 Vision Goals, established in 2021, emphasize the importance of green finance in achieving sustainable development. Crop-livestock integration within small-scale farming is projected to reduce GHG emissions by 28.1% to 41.3%, illustrating the potential of this approach to diminish the carbon footprint of agriculture.[4] By reducing reliance on synthetic fertilizers, crop-livestock integrated systems lower the energy consumption and carbon footprint linked to production and transportation processes of synthetic fertilizers. Substituting mineral fertilizers with organic alternatives can also significantly increase soil organic carbon sequestration rates by 925 kg C ha^{-1} yr^{-1}, while also reducing global warming potential by 116 kg CO_2 eq ha^{-1}.[5] Moreover, crop-livestock integration contributes to a net increase in soil organic matter overall by optimizing the use of crop residues and animal manure. Crop-livestock integration reduces pressure on arable land, which minimizes carbon emissions associated with land-use changes. Crop-livestock integration also effectively lowers transportation-related CO_2 emissions by organically combining crop cultivation and livestock farming on the same farm, thereby minimizing the distance and frequency of feed transport and utilizing crop by-products as livestock feed. This integrated model fosters environmentally friendly and sustainable agricultural practices. Furthermore, integrated systems, particularly those incorporating agroforestry components, exhibit a negative net carbon balance, indicating significant carbon sequestration potential. This underscores the viability of crop-livestock-forestry systems as strategic interventions for mitigating GHG emissions and promoting the sustainability of forage-based agriculture. By adopting these integrated systems, farms can not only address the mitigation of GHG emissions but also alleviate the adverse effects of climate change, contributing to a more resilient and sustainable agricultural sector.

SUMMARY

The integration of crop and livestock farming represents a potent strategy for enhancing food security, optimizing resource efficiency and maximizing the productive capacity of the land through decreasing the risk of overexploitation and degradation of land resources. This circular approach not only diminishes reliance on external resources but also significantly reduces the carbon footprint associated with agricultural production. It is essential for establishing resilient agricultural systems and for sustainable development and environmental stewardship. To fully realize the potential of crop-livestock integration, ongoing scientific research is necessary to identify best practices tailored to diverse environmental conditions. Furthermore, policymakers must offer adequate support and incentives to encourage farmers to adopt this sustainable agricultural model. By implementing such integrated systems, a synergistic advancement of global food security and ecological conservation can be achieved, fostering a more balanced and sustainable future for agricultural production.

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AUTHOR CONTRIBUTIONS

M.W., D.W. and X.X. write the contents and edited the manuscript and the figure; X.X., Z.B., R.W., X. Z., and Y.-Z. G. edited the figure and figure note; Z.T. and Y.Y. were responsible for manuscript. All authors contributed to the article and approved the submitted version.

DECLARATION OF INTERESTS

Y.Y. and Y.-Z. G. are the Editorial Board members of The Innovation Life. They were blinded from reviewing or making final decisions on the manuscript. The article was subject to the journal's standard procedures, with peer review handled independently of these Editorial Board members and their research groups. The other authors declare that they have no conflicts of interest.