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Integrating Livestock for Enhancing Sustainability of Soil, Water and Agroecosystem: Implications from a One Health Perspective

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Abstract

Livestock systems play a pivotal role in sustaining environmental health, enhancing ecosystem services, and supporting agricultural productivity. Well-managed integration of livestock into agroecosystems contributes to soil fertility through organic matter deposition, microbial stimulation, and nutrient cycling, while improving soil structure and long-term productivity. Grazing and pasture management regulate water infiltration, retention, and hydrological balance, mitigating soil erosion and enhancing water-use efficiency. Livestock also promote biodiversity by maintaining habitat heterogeneity, facilitating coexistence with wildlife, and supporting plant and microbial diversity, thereby preserving ecosystem resilience. Furthermore, livestock contribute to carbon sequestration, biomass utilization, and renewable energy generation, reducing greenhouse gas emissions and advancing circular bioeconomy strategies. Despite these recognized benefits, knowledge gaps remain regarding the optimal integration of livestock to maximize environmental services while minimizing trade-offs. Quantitative assessments of livestock-mediated impacts on soil carbon stabilization, nutrient retention, water regulation, and biodiversity under varying agroecological conditions are limited. This review synthesizes current knowledge on the mechanisms through which livestock enhance soil, water, and biodiversity sustainability, highlighting the interplay between productivity and ecological conservation. Future research directions are proposed to optimize grazing management, improve nutrient and water efficiency, evaluate biodiversity outcomes, and integrate One Health principles, with an emphasis on climate resilience and sustainable land stewardship. Understanding these interactions is essential for designing adaptive livestock systems that balance agricultural productivity with environmental sustainability, ecosystem health, and global food security

Keywords: Agroecosystem, biodiversity, livestock, soil health, water regulation

INTRODUCTION

Sustainable livestock production is recognized as a component for maintaining environmental health, ensuring food security, and promoting ecosystem resilience [1]. Livestock systems influence multiple aspects of agroecosystems, including soil fertility, water regulation, nutrient cycling, and biodiversity conservation [2]. Integration of livestock into agricultural landscapes provides opportunities to optimize these ecosystem services, transforming traditional farming practices into sustainable and multifunctional systems [3]. By returning organic matter to the soil through manure deposition, livestock enhance soil structure, nutrient availability, and microbial activity, contributing to soil fertility and long-term productivity [4].

Grazing and pasture management further regulate water infiltration, reduce erosion, and improve

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hydrological balance, mitigating the impacts of climate variability on farming systems [5]. Livestock also support biodiversity by maintaining habitat heterogeneity, promoting plant species diversity, and facilitating coexistence with wildlife [6]. Beyond environmental benefits, livestock play a pivotal role in carbon sequestration, biomass utilization, and renewable energy production, providing pathways for mitigating greenhouse gas emissions and advancing circular bioeconomy approaches in agriculture [7].

Despite these recognized contributions, knowledge gaps remain regarding the optimal integration of livestock for maximizing ecosystem benefits while minimizing environmental trade-offs [8]. Quantitative assessments of livestock-mediated impacts on soil carbon stabilization, nutrient retention, water-use efficiency, and biodiversity under diverse agroecological conditions are limited [9]. Moreover, the synergies and potential conflicts among soil, water, and biodiversity objectives in mixed farming systems require systematic evaluation [10]. This review synthesizes current knowledge on the environmental roles of livestock, highlights mechanisms through which livestock enhance soil, water, and biodiversity sustainability, and identifies areas where further research is needed to develop adaptive, climate-resilient, and One Health-oriented livestock systems.

Livestock, Soil Fertility and Structure Improvement

Organic matter enrichment

Manure and urine deposition increase soil organic carbon and nutrient availability. The organic inputs enhance humus formation, improve soil texture, and raise cation exchange capacity [11]. This enriches soil fertility, strengthens nutrient retention, and supports sustainable crop and pasture productivity through continual organic recycling and biological renewal of the soil ecosystem.

Balanced carbon-nitrogen ratio

Livestock-derived compost regulates soil carbon and nitrogen balance, promoting efficient microbial activity and nutrient turnover. A stable ratio minimizes nitrogen loss through volatilization, supports residue decomposition, and enhances soil aeration [12]. The improved equilibrium ensures steady nutrient supply and maintains long-term fertility, contributing to productive and resilient agricultural soils.

Microbial nutrient mineralization

Animal manure fosters diverse soil microbes responsible for decomposing organic matter and releasing nutrients. Microbial mineralization enhances the bioavailability of nitrogen, phosphorus, and sulfur for plants. The process sustains nutrient cycling, boosts soil vitality, and supports productive ecosystems with enhanced nutrient efficiency and improved soil biological quality [13].

Enhanced soil enzymatic activity

Livestock manure increases key soil enzymes such as urease, phosphatase, and dehydrogenase that drive nutrient transformation. Elevated enzymatic activities improve decomposition of organic substrates and accelerate nutrient release. The enhanced biochemical reactions strengthen soil health, promoting sustainable nutrient recycling and long-term productivity of farming systems [11].

Improved soil aggregation

Grazing stimulates root development of pasture plants, improving soil porosity and aggregate stability. Deeper roots enhance water infiltration, reduce compaction, and promote the incorporation of organic matter into deeper layers [11, 12]. This biological interaction fortifies soil structure and maintains sustainable conditions for productive and resilient agroecosystems.

Nutrient Cycling and Waste Utilization

Manure-driven nutrient cycling

Livestock manure contributes essential nutrients, including nitrogen, phosphorus, and potassium, back to the soil [14]. This deposition enhances microbial activity, stimulates decomposition, and improves nutrient availability for plants. Continuous nutrient cycling through manure maintains soil fertility, supports sustainable crop and pasture production, and reduces reliance on synthetic fertilizers.

Efficient nitrogen and phosphorus recycling

Livestock systems efficiently recycle nitrogen and phosphorus from feed and residues. Animal excreta return these key nutrients to the soil, minimizing losses through leaching or volatilization [15]. This recycling supports sustainable nutrient management, maintains soil fertility, and reduces environmental pollution associated with excessive synthetic fertilizer use.

Conversion of non-edible biomass

Livestock transform non-edible crop biomass, crop residues, and byproducts into high-quality protein for human consumption. This process adds value to agricultural byproducts that would otherwise decompose or be wasted, improving resource efficiency and supporting sustainable food systems [14].

Food industry byproduct utilization

Byproducts from the food industry, such as oilseed cakes, brewery waste, or pulp, can be converted into protein-rich animal feed. Livestock transform these residues into edible protein and other products, reducing industrial waste while contributing to circular economy practices within agricultural systems [15].

Crop residue recycling

Livestock feed on crop residues that are otherwise discarded, such as straw, husks, or pruning biomass. This utilization reduces waste accumulation, recycles nutrients back into the soil through manure, and supports sustainable fodder supply, enhancing both environmental and economic efficiency in farming systems [14].

Carbon Sequestration and Climate Regulation

Grassland carbon storage

Grazing animals enhance plant regrowth and root turnover, leading to greater carbon storage in soil organic matter [16]. Manure deposition adds further organic carbon inputs, while root exudates stimulate microbial carbon stabilization. Well-managed grazing promotes carbon accumulation in both biomass and soil, contributing significantly to long-term carbon sequestration and ecosystem stability [17].

Silvopastoral carbon offset

Integrating trees into livestock systems through silvopastoral management enhances carbon capture in above-ground biomass and soil [18]. Tree roots store carbon deeper in the soil profile while providing shade and microclimatic regulation. This system reduces emissions intensity per unit of production and improves overall carbon offset potential of livestock-based farming landscapes [19].

Reduced greenhouse emissions

Feed optimization and nutrient-balanced diets improve feed conversion efficiency, lowering methane and nitrous oxide emissions from enteric fermentation and manure. Enhanced digestion reduces waste production and energy losses, minimizing the total greenhouse gas output per unit of animal product. Efficient feeding systems contribute to climate-resilient and environmentally responsible livestock production [20–22].

Restoration of soil carbon

Livestock-driven organic inputs restore depleted soil carbon pools in arid and semiarid regions where vegetation is sparse. Controlled grazing and manure incorporation improve soil moisture retention and microbial carbon stabilization. These processes enhance resilience against desertification, promote soil regeneration, and strengthen long-term carbon storage under harsh climatic conditions [4, 12, 23].

Carbon-neutral management

Adoption of precision feeding, improved manure handling, renewable energy use, and integrated pasture management supports carbon-neutral livestock production. Efficient nutrient cycling and energy recovery from manure offset emissions generated during rearing. Such innovations strengthen climate mitigation strategies, promoting environmental sustainability within modern livestock enterprises [14, 24–26].

Pasture Regeneration and Grassland Health

Controlled grazing regeneration

Managed grazing allows alternating rest and grazing periods, preventing overutilization and enabling pastures to recover naturally [27]. This controlled approach maintains vegetative cover, promotes seed dispersal, and improves root vitality. As a result, grasslands remain productive, erosion-resistant, and ecologically balanced, ensuring sustainable forage availability and ecosystem restoration over time.

Moderate defoliation recovery

Grazing at moderate intensity stimulates photosynthetic activity and encourages tiller formation in grasses. Partial defoliation increases light penetration, enhancing regrowth capacity and nutrient uptake efficiency [14]. This balance between utilization and regrowth strengthens the sward structure, supporting continuous productivity without compromising long-term pasture sustainability or soil health.

Stability of grassland ecosystems

Well-managed grazing sustains the natural equilibrium between plants, soil, and herbivores. This balance stabilizes nutrient cycles, maintains vegetation diversity, and prevents land degradation. Consistent grazing pressure supports ecological succession, ensuring that grassland ecosystems remain resilient, functionally diverse, and capable of sustaining both livestock and wildlife populations [24].

Enhanced photosynthetic activity

Optimal grazing intensity maintains green leaf area, maximizing light interception and carbon fixation. Healthy photosynthetic efficiency supports biomass accumulation and nutrient recycling. Through balanced defoliation, plants maintain vigorous growth, higher chlorophyll activity, and improved carbon sequestration, enhancing overall productivity and ecological performance of the pasture system [28].

Adaptive grazing resilience

Adaptive grazing strategies align livestock movement with forage growth patterns, rainfall variability, and ecosystem capacity. This dynamic management approach enhances resource efficiency, prevents overgrazing, and maintains plant-soil integrity. By adjusting stocking rates and grazing intervals, the system improves ecological resilience and long-term sustainability of grassland ecosystems [3].

Biodiversity and Habitat Conservation

Grassland biodiversity maintenance

Managed grazing preserves species-rich grasslands by preventing dominance of a few plant species. Regular grazing maintains habitat heterogeneity, supporting a wide variety of grasses, forbs, and microorganisms [6]. This diversity ensures ecological stability, enhances forage quality, and provides resilience against pests, diseases, and environmental stresses within productive agroecosystems [29, 30].

Wildlife habitat support

Livestock systems that integrate conservation principles create spaces where native wildlife can coexist. Pasture mosaics, buffer zones, and rotational grazing protect nesting sites and food resources for birds, small mammals, and reptiles [27, 31, 32]. Such habitat coexistence promotes conservation while sustaining livestock production and ecosystem functionality.

Local biodiversity enhancement

Grazing animals influence seed dispersal and nutrient distribution, facilitating establishment of native plant species across pastures. This activity enhances floral diversity and supports associated fauna [33, 34]. Diverse plant and microbial communities improve ecosystem resilience, productivity, and the adaptive capacity of grazing landscapes under changing environmental conditions.

Pollinator habitat provision

Mixed farming systems with livestock preserve flowering plants, providing essential foraging habitats for pollinators such as bees and butterflies. Pollinator activity enhances seed set, plant reproduction, and crop yields [35, 36]. Livestock integration indirectly supports pollination services, contributing to sustainable food production and ecological health.

Ecological balance promotion

Livestock grazing maintains the equilibrium between plant growth and animal consumption, preventing overdominance or degradation. Balanced interactions among herbivores, vegetation, and soil microbes sustain nutrient cycles and ecosystem processes. This ecological balance supports long-term productivity, biodiversity conservation, and overall stability of pasture ecosystems [37, 38].

Water and Hydrological Benefits

Enhanced water infiltration

Livestock manure improves soil aggregation by increasing organic matter content, which enhances pore connectivity [39]. This improved soil structure allows rainwater to infiltrate efficiently, reducing surface runoff and promoting groundwater recharge. Better water penetration also supports root growth and nutrient absorption, maintaining soil health and long-term pasture productivity.

Soil erosion reduction

Properly managed grazing maintains vegetative cover and prevents bare soil exposure. Roots stabilize the soil matrix, while moderate grazing reduces trampling damage [40, 41]. These practices minimize wind and water erosion, protect topsoil integrity, and sustain productive pasture landscapes, ensuring both environmental and agricultural stability.

Hydrological balance improvement

Grazing systems that maintain soil structure and vegetative cover regulate water distribution across ecosystems. Improved soil porosity enhances infiltration and reduces runoff, while retention of organic matter improves moisture storage [29, 42]. These processes support consistent water availability, regulate local hydrology, and strengthen resilience against drought or flood events.

Reduced nutrient leaching

Integration of livestock with cropping systems ensures nutrients from manure and urine are absorbed by plants rather than lost to leaching [43–45]. Improved soil structure and plant cover reduce nutrient runoff into water bodies, enhancing soil fertility while protecting water quality in adjacent ecosystems.

Water-use efficiency enhancement

Forage-based livestock systems with optimal grazing intensity improve plant water utilization. Healthy pastures with dense root systems extract water efficiently, supporting biomass production with minimal water loss [46–48]. Efficient water use reduces irrigation needs, enhances pasture sustainability, and contributes to resource-efficient livestock production.

Waste-to-Energy and Renewable Resource Generation

Biogas energy production

Livestock manure can be converted into biogas through anaerobic digestion, producing renewable energy for cooking, heating, or electricity [44]. This process reduces reliance on fossil fuels, mitigates greenhouse gas emissions, and converts organic waste into a clean energy source, contributing to environmentally sustainable livestock systems.

Composting for soil enrichment

Organic waste from livestock, including manure and bedding, can be composted to produce nutrient-rich amendments [49]. Composting stabilizes organic matter, improves soil structure, enhances microbial activity, and provides essential nutrients, reducing the need for synthetic fertilizers while promoting long-term soil health and fertility.

Circular bioeconomy support

Manure-based energy systems integrate livestock waste into a circular economy model. Organic residues are recycled for energy production, nutrient recovery, and soil enhancement [49]. This approach reduces waste, lowers environmental pollution, and maximizes resource efficiency, linking livestock production to sustainable and resilient agroecosystems.

Reduced fertilizer dependency

Application of manure as organic fertilizer provides essential nutrients like nitrogen, phosphorus, and potassium, decreasing the need for chemical fertilizers [49]. This substitution lowers input costs, reduces environmental pollution from synthetic fertilizers, and sustains soil fertility, promoting ecologically sound livestock-crop integration.

Sustainable nutrient recovery

Livestock waste management enables recovery of nutrients through composting, biogas slurry, or direct soil application [49]. These practices recycle nutrients efficiently, maintaining soil productivity and closing nutrient loops. Sustainable nutrient recovery supports environmental health by preventing nutrient loss to waterways and minimizing ecological disruption.

Land Restoration and Utilization

Efficient use of marginal soils

Livestock can graze on lands unsuitable for conventional crops, converting low-quality forage into valuable protein [50]. This utilization transforms otherwise unproductive areas into productive systems, maximizes land efficiency, and reduces pressure on arable land, supporting both food security and environmental sustainability.

Degraded land restoration

Managed grazing helps restore degraded soils by improving vegetation cover, reducing erosion, and increasing organic matter through manure deposition [39]. Controlled livestock movement stimulates plant regrowth and soil microbial activity, gradually rehabilitating land and restoring ecological function for long-term productivity.

Revitalizing abandoned lands

Underutilized or abandoned lands can be transformed through integrated livestock systems. Grazing animals recycle biomass, stimulate natural vegetation, and contribute organic nutrients, gradually converting unproductive areas into productive pastures or mixed-use agricultural systems, enhancing both economic and environmental value [42].

Agroecosystem resilience enhancement

Livestock integration improves ecosystem resilience by maintaining soil structure, vegetation diversity, and nutrient cycling [51, 52]. Adaptive grazing and organic nutrient inputs buffer agroecosystems against climatic extremes, drought, or erosion, ensuring sustained productivity and ecological stability under changing environmental conditions.

Sustainable land stewardship

Livestock farming encourages responsible land management practices, including rotational grazing, soil protection, and biodiversity conservation [53–55]. These practices maintain ecosystem services, optimize resource use, and support long-term productivity while aligning agricultural activity with environmental sustainability goals.

Integrated Farming and Ecosystem Services

Ecosystem services provision

Crop-livestock integration delivers multiple ecosystem services, including soil fertility enhancement, organic waste recycling, and habitat provision [23, 56]. Manure and crop residues support nutrient cycling, while grazing regulates vegetation, maintaining ecological balance [57]. This integration strengthens ecosystem functionality, improves resource efficiency, and enhances sustainability of agricultural landscapes.

Nutrient synchronization

Linking crops and livestock optimizes nutrient flows, as animal manure provides essential nutrients for crops, and crop residues feed livestock [16, 56, 58]. This cyclical nutrient exchange reduces external fertilizer requirements, improves nutrient-use efficiency, and maintains soil fertility while supporting productive and environmentally sustainable farming systems.

Low-input sustainable agriculture

Integrated systems minimize dependence on synthetic inputs by recycling organic matter and utilizing on-farm resources [21, 59, 60]. Livestock convert crop residues into protein and manure, reducing feed and fertilizer costs. This approach supports resilient, low-input farming, lowering environmental impact and promoting long-term agroecosystem sustainability.

Balanced agroecosystem interactions

Integration fosters functional interactions among plants, animals, and soil microbes. Grazing regulates crop residue decomposition, nutrient cycling, and vegetation structure, while crops provide feed and organic matter [26, 31, 61, 62]. These balanced interactions sustain biodiversity, improve soil health, and maintain ecological stability within agricultural systems.

Complementary productivity enhancement

Crop-livestock integration increases total system output by combining complementary production streams [63–66]. Livestock convert residues into animal products, while crops benefit from organic amendments and improved soil conditions. This synergy enhances overall efficiency, maximizes land productivity, and strengthens economic and environmental sustainability.

Pest, Weed, and Fire Management

Biological pest control

Diverse grazing patterns by livestock reduce pest populations by disrupting insect life cycles and consuming pest-host plants [67]. This natural control limits the need for chemical pesticides, maintains ecological balance, and supports sustainable crop and pasture health while enhancing overall biodiversity.

Natural weed regulation

Grazing animals selectively feed on invasive or fast-growing weed species, limiting their spread and reducing competition with desirable forage [68]. Continuous but controlled grazing maintains plant community balance, improves pasture quality, and minimizes dependence on herbicides for weed management.

Wildfire risk reduction

Livestock consume dry vegetation and residual biomass, decreasing fuel loads in pastures and grasslands. Reduced accumulation of flammable material lowers wildfire frequency and intensity, protecting ecosystems, human settlements, and agricultural infrastructure while enhancing landscape resilience [68].

Invasive plant control

Managed grazing targets invasive plant species, preventing their establishment and spread. Regular defoliation, trampling, and nutrient redistribution by livestock inhibit encroachment, allowing native vegetation to thrive [67]. This management supports rangeland biodiversity and long-term ecosystem stability.

Ecological succession support

Grazing maintains a dynamic balance between early- and late-successional plant species, sustaining natural ecological succession [67]. This regulation preserves habitat heterogeneity, promotes species diversity, and ensures the long-term functional integrity of rangeland ecosystems while supporting sustainable livestock production.

CONCLUSION

Livestock play a central role in sustaining soil health, regulating water resources, and maintaining biodiversity within agroecosystems. Through nutrient recycling, organic matter deposition, and controlled grazing, livestock enhance ecosystem functionality while supporting agricultural productivity. Integration of livestock into farming systems not only strengthens ecological resilience but also contributes to climate mitigation and circular bioeconomy strategies. Despite these benefits, optimizing livestock management to balance productivity with environmental sustainability remains a key challenge, and quantitative assessments of their ecological impacts are still limited. Future research should focus on system-specific strategies that maximize soil, water, and biodiversity benefits, while addressing potential trade-offs, to design adaptive, resilient, and One Health-aligned livestock systems. In conclusion, strategically integrated livestock systems represent a vital pathway to achieving sustainable agricultural landscapes, ensuring environmental health, and supporting global food security.

Future Directions

Future research should focus on quantifying the specific contributions of livestock to soil fertility, water regulation, and biodiversity across diverse agroecological zones, providing robust, context-specific evidence. Optimizing grazing management through evaluation of stocking rates, rotation schedules, and timing is essential to enhance soil health, pasture productivity, and ecological balance. Long-term studies are needed to examine the effects of livestock manure, grazing intensity, and pasture management on soil carbon sequestration and greenhouse gas mitigation. Investigations into water-use efficiency within integrated livestock-crop systems, including infiltration, retention, and nutrient leaching, are critical under changing climate conditions. Research on livestock-mediated biodiversity should explore plant and microbial diversity dynamics, including potential synergies and trade-offs between forage production and wildlife conservation.

Further studies should evaluate the circular bioeconomy potential of livestock through manure-to-energy conversion, composting strategies, and nutrient recycling efficiency to reduce reliance on synthetic fertilizers. Climate resilience modeling, integrating predictive tools for soil, water, and biodiversity outcomes under projected climate scenarios, is recommended. Incorporating One Health perspectives to assess links between livestock-environment interactions, human health, and ecosystem integrity, including zoonotic risk mitigation, is essential. Socioeconomic research on adoption barriers, economic feasibility, and policy incentives will support practical implementation, while technology-driven monitoring using remote sensing, precision livestock management, and GIS tools can optimize environmental outcomes and guide adaptive decision-making in real time.

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