

Impact of controlled rabbit grazing on soil structure, aggregate stability, and nutrient cycling in agroecosystems

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Abstract. Controlled grazing is widely recognized as a key management practice influencing soil physical structure, nutrient dynamics, and ecosystem functioning. While most research has focused on large herbivores such as cattle and sheep, the specific role of rabbits remains underexplored. This paper synthesizes existing knowledge on grazing impacts, soil aggregation processes, microbial interactions, and nutrient cycling to infer the effects of controlled rabbit grazing. Soil aggregate stability, a central indicator of soil health, is strongly influenced by organic matter inputs, root systems, microbial activity, and soil porosity - all factors sensitive to grazing intensity and timing. Evidence suggests that uncontrolled or high-density rabbit grazing can reduce aggregate stability through vegetation loss, soil disturbance, and compaction, whereas controlled grazing regimes may preserve or even enhance soil structure. Additionally, rabbits influence soil processes through excreta deposition and microsite creation, contributing to nitrogen and phosphorus cycling and localized microbial heterogeneity. The interaction between rabbit gut microbiota and soil microbiomes further highlights a potential soil-plant-animal feedback system, although direct empirical evidence remains limited. Overall, controlled rabbit grazing can be integrated into sustainable agroecosystems if carefully managed, but significant research gaps remain regarding its quantitative effects on soil aggregation and biogeochemical cycles.

Key Words: agroecosystems, grazing management, nitrogen cycle, nutrient cycling, phosphorus cycle, rabbit grazing, soil aggregate stability, soil health, soil microbiome, soil structure.

Introduction. Soil structure, particularly the formation and stability of aggregates, plays a fundamental role in determining soil health, productivity, and resilience. Aggregates regulate key processes such as water infiltration, aeration, carbon sequestration, and resistance to erosion. Their stability depends on a complex interplay of physical, chemical, and biological factors, including organic matter content, root dynamics, microbial activity, and soil texture. Grazing is one of the most important land-use practices affecting these factors, yet its impact varies widely depending on herbivore type, grazing intensity, and management strategy.

Most existing studies on grazing effects have focused on large herbivores such as cattle and sheep, often overlooking smaller herbivores like rabbits or treating them as a minor component of overall grazing pressure. However, rabbits can significantly influence soil systems through selective feeding, burrowing, trampling, and excreta deposition. These activities position rabbits as ecosystem engineers capable of modifying soil structure, nutrient distribution, and microbial communities at multiple spatial scales.

At the same time, increasing attention is being given to integrated agroecological systems, where interactions between soil, plants, and animal microbiomes are recognized as key drivers of sustainability. In such systems, rabbits may play a dual role: as grazers

influencing soil physical properties and as biological agents contributing to nutrient cycling and microbial connectivity between compartments.

The main objective of this paper is to synthesize current knowledge and infer the potential impacts of controlled rabbit grazing on soil structure and aggregate stability, while also examining its role in nitrogen and phosphorus cycling and its interaction with soil microbiomes in integrated agroecosystems.

Impact of controlled rabbit grazing on soil structure and aggregate stability. A comprehensive body of work has examined how grazing shapes soil physical structure, including the distribution and stability of aggregates, but very few studies isolate rabbits. Most experiments use sheep, cattle or mixed herbivore assemblages and treat rabbits as one component of overall grazing pressure. Nevertheless, the mechanisms through which controlled rabbit grazing would influence soil aggregates can be inferred from general grazing research, from work that explicitly quantifies rabbit effects on soil health, and from studies on rabbits as soil-disturbing “ecosystem engineers”.

Soil aggregates are the basic structural units of soil and their stability, especially under wetting, is a key indicator of soil health, erosion resistance, porosity and carbon sequestration. Aggregate stability is governed by organic matter, roots and fungal hyphae, glomalin-related soil proteins, clay and silt content, and soil porosity, all of which are sensitive to grazing intensity and timing (Liu et al 2021; Dong et al 2022; Fan et al 2023; Yang et al 2025). Heavy continuous grazing typically reduces soil organic carbon, increases bulk density and shifts aggregate size distributions toward smaller, less stable units, whereas light to moderate grazing, especially in systems with good vegetation cover and organic inputs, can maintain or even improve macroaggregate formation and stability (Wang et al 2020; Zhang et al 2022; Fan et al 2023).

A global meta-analysis of livestock grazing effects on soils shows that heavy grazing, relative to ungrazed controls, significantly increases bulk density and penetration resistance while decreasing soil organic carbon, moisture and microbial biomass, particularly in the upper 10 cm (Lai & Kumar 2020). Moderate grazing still increases compaction and reduces carbon and nitrogen, but to a lesser extent, whereas light grazing can increase surface soil organic carbon (Lai & Kumar 2020). These changes have direct implications for aggregate stability because compaction and organic matter loss tend to reduce the proportion and water stability of macroaggregates. Region-specific studies confirm this pattern. In northern Xinjiang grasslands, grazing outside protective fences reduces silt and clay content, increases sand, drastically lowers the proportion of > 2 mm aggregates and reduces mean weight diameter, demonstrating weakened aggregation and soil carbon storage capacity (Fan et al 2023). In a *Stipa breviflora* desert steppe, long-term heavy grazing reduces large aggregates and overall stability, while appropriate light grazing maintains high aggregate stability; stability is positively correlated with macroaggregate content and negatively with microaggregate content, and is mediated by pH, bulk density and organic carbon (Zhang et al 2022). Similar results were obtained for alpine meadows grazed by yak: light grazing promotes macroaggregate formation (> 1 mm), improves stability and enhances organic carbon fixation in the largest and finest size classes, whereas moderate and heavy grazing shift mass toward microaggregates and accelerate organic carbon decomposition (Wang et al 2020).

Controlled or restricted grazing regimes modify this picture by limiting the duration, intensity and season of trampling. In desert steppes, a comparison of free grazing with grazing exclusion and seasonal grazing shows that exclusion markedly increases clay, silt and organic carbon and improves aggregate stability, but seasonal grazing also increases clay, silt and macroaggregates in the topsoil, suggesting that carefully timed, reduced grazing can enhance aggregate formation without the full negative effects of continuous use (Yang et al 2025). Boosted regression tree analysis in that study identifies soil porosity as the dominant driver of aggregate stability, with a higher explanatory power than other factors, highlighting trampling-induced changes in pore space as a primary mechanism through which grazing

management affects aggregation (Yang et al 2025). In a typical Inner Mongolian grassland, long-term grazing exclusion increases the fraction of water-stable fine and coarse aggregates, with maximum stability after about two decades, while a five-year rotational grazing experiment with varying intensities shows that rotational grazing has limited effect on overall aggregate stability, though light to moderate rotational grazing can enhance fine-aggregate stability relative to no grazing (Liu et al 2021; Dong et al 2022). The authors conclude that rotational, rather than prohibitionist, strategies may better reconcile soil aggregate stability with productive use (Dong et al 2022).

When herbivore type and site productivity are explicitly considered, rabbits emerge as contributors to soil degradation, though generally less so than large livestock. A large-scale structural equation modelling study across eastern Australia used dung and tracks of cattle, sheep, goats, kangaroos and rabbits as indicators of grazing intensity and found that grazing reduced indices of soil stability, nutrient cycling and water infiltration, particularly at low-productivity sites (Eldridge et al 2017). Most of the negative effects were attributed to cattle and, to a lesser degree, sheep, goats and rabbits; kangaroos had few detectable impacts (Eldridge et al 2017). While this work does not provide aggregate size distributions, its stability index integrates surface sealing, crusting and other structural attributes closely linked to aggregate breakdown. It indicates that unregulated rabbit populations, in combination with livestock, can significantly degrade soil structural integrity in water-limited systems.

Rabbits also act as ecosystem engineers through digging and foraging pits, creating microsites that differ from undisturbed surface soil and deeper subsoil. In an Australian arid woodland, comparison of echidna and rabbit pits with surface and subsurface soils along a grazing-disturbance gradient shows that microsite identity drives bacterial community composition and enzymatic activity more than the grazing gradient itself (Eldridge et al 2016). Echidna pits support higher relative abundance of Proteobacteria, lower Acidobacteria and higher mean enzyme activities, reflecting enhanced nutrient cycling and likely improved aggregation, whereas rabbit pits are more similar to subsoil or surface soils and have the least positive functional effects (Eldridge et al 2016). This suggests that rabbit disturbance alone does not strongly enhance soil structure or microbial functions and may even contribute to fragmentation of the surface, creating erosion-prone patches where aggregates are more vulnerable to raindrop impact and slaking.

Evidence from integrated crop-livestock systems indicates that well-managed grazing, when stocking rates and timing are controlled, need not damage soil aggregate stability even over long periods. In a no-till soybean-beef system grazed by steers for 13 years at different sward heights, soil aggregation was dominated by large macroaggregates (> 2 mm) and was not significantly affected by grazing intensity; macroaggregates remained about 97% of soil mass and their high stability buffered soil organic matter fractions from trampling effects, though heavy fraction carbon and nitrogen stocks were slightly higher under no grazing (Soares et al 2022). In irrigated corn-soybean rotations, 16 years of cattle grazing of corn residues had no measurable effect on bulk density, wet aggregate stability or particulate organic matter, and only modest, sub-threshold increases in penetration resistance under spring grazing; crop yields were unaffected (Rakkar et al 2017). These systems differ from rabbit pastures in hoof size, weight and seasonal use, but they demonstrate that careful control of timing, duration and residual biomass can maintain aggregate stability under grazing.

Mechanistically, grazing affects aggregate structure through three main pathways: mechanical trampling, modification of plant cover and litter inputs, and changes in below-ground biota. Trampling increases bulk density and reduces macroporosity, particularly when soils are moist, which diminishes the capacity of roots and hyphae to form and stabilize macroaggregates (Greenwood & McKenzie 2001; Lai & Kumar 2020). At the same time, grazing alters above-ground biomass and species composition, which in turn affect root distribution, exudates and litter quality. Where grazing is light to moderate and vegetation

remains vigorous, increased root turnover and organic inputs can compensate for trampling and support stable macroaggregates enriched in organic carbon (Wang et al 2020; Zhang et al 2022). When grazing is heavy or continuous, loss of protective cover, root biomass and organic matter destabilizes large aggregates, increasing the proportion of small, water-unstable units, reducing mean weight diameter and enhancing erosion risk (Wang et al 2020; Zhang et al 2022; Fan et al 2023). Long-term grazing exclusion studies show that organic carbon and nitrogen accumulate preferentially in macroaggregates over decades, and that glomalin-related soil proteins and nutrient stoichiometry are key indirect drivers of improved stability under prohibition regimes (Liu et al 2021). Restricted or seasonal grazing can preserve some of these benefits while keeping the system productive (Dong et al 2022; Yang et al 2025).

Direct, quantitative research on how controlled rabbit grazing affects aggregate size distributions and stability metrics is lacking. Existing rabbit-focused experiments in temperate grasslands have concentrated on microbial diversity, enzyme activities, root traits and nitrogen cycling under different combinations of rabbit and invertebrate grazing, liming and fertilization, generally finding that liming and nutrient additions exert stronger long-term below-ground effects than rabbit grazing per se (Macdonald et al 2015; Heyburn et al 2017). Nevertheless, by analogy with other herbivores and supported by evidence that rabbits contribute to reduced soil stability in multi-herbivore landscapes (Eldridge et al 2016, 2017), several cautious inferences can be drawn. First, uncontrolled or high-density rabbit grazing, especially on low-productivity, sparsely vegetated sites, is likely to decrease aggregate stability through loss of plant cover, organic inputs and increased trampling, echoing heavy grazing effects seen with livestock. Second, genuinely controlled rabbit grazing, with moderate stocking, rest periods, attention to soil moisture and maintenance of high ground cover, should minimize compaction, preserve soil porosity and allow root- and fungal-mediated aggregation to dominate, thereby maintaining or only slightly modifying aggregate stability. Third, because rabbits create foraging pits and latrines, they may increase spatial heterogeneity in soil structure, producing micro-zones of degradation and localized enrichment that could, depending on intensity and context, either enhance landscape-scale resilience or exacerbate patchy erosion.

From a management perspective, the literature suggests that any system using rabbits as grazing agents should treat aggregate stability and related indicators (bulk density, porosity, mean weight diameter) as critical monitoring variables. Light to moderate, rotational or seasonal grazing, adapted to local productivity and soil moisture conditions, is most likely to protect or improve soil structure, while chronic overgrazing - even by relatively small herbivores - will undermine aggregate stability, particularly in fragile, coarse-textured or arid soils (Greenwood & McKenzie 2001; Eldridge et al 2017; Lai & Kumar 2020; Wang et al 2020; Dong et al 2022; Zhang et al 2022; Zhang et al 2022; Fan et al 2023; Yang et al 2025). The absence of rabbit-specific aggregation data represents a clear research gap and an opportunity for future experiments that combine controlled rabbit stocking gradients with detailed measurements of aggregate size distributions, wet and dry stability, and associated carbon and nutrient pools. Table 1 synthesizes the main patterns relevant for understanding potential impacts of controlled rabbit grazing on soil structure and aggregate stability.

Table 1

Grazing management, herbivore type and soil aggregate stability (Consensus 2025)

| <i>Aspect</i> | <i>Main findings relevant to soil aggregates</i> | <i>Citations</i> |
|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Grazing intensity (general) | Heavy grazing increases compaction, reduces SOC and aggregate stability; light-moderate can maintain or improve structure, depending on context. | Greenwood & McKenzie (2001); Lai & Kumar (2020); Wang et al (2020) Zhang et al (2022); Fan et al (2023); |
| Rotational and restricted grazing | Long-term exclusion increases stability; rotational or seasonal grazing has limited negative impact and can enhance fine-aggregate stability when carefully managed. Soil porosity is a primary driver. | Dong et al (2022); Yang et al (2025) |
| Grazing prohibition timeframes | Decadal exclusion shifts nutrients and glomalin-related proteins into macroaggregates, increasing stability and carbon-nitrogen accumulation. | Liu et al (2021) |
| Herbivore type including rabbits | Grazing by livestock and rabbits reduces soil stability, especially at low productivity; rabbits contribute but impacts are smaller than cattle. | Eldridge et al (2017) |
| Rabbits as soil engineers | Rabbit foraging pits alter microsite microbial communities but have weaker positive functional effects on soil than native digging mammals, indicating limited structural benefits and possible degradation. | Eldridge et al (2016) |
| Well-managed grazed systems | In integrated crop-livestock and residue-grazing systems, controlled grazing can leave macroaggregate dominance and wet stability largely unchanged over more than a decade. | Rakkar et al (2017); Soares et al (2022) |

The rabbit gut-soil microbiome connection in integrated agro-ecological systems.

The interaction between rabbit gut microbiomes and soil microbiota in integrated agro-ecological systems has not yet been studied directly. However, existing work on rabbit gut communities, soil microbiomes, integrated crop-livestock systems and cross-compartment “soil-plant-gut” links allows a coherent, rabbit-focused synthesis.

Rabbit gut microbiota is adapted to a fiber-rich herbivorous diet and is dominated, in healthy wild animals, by Ruminococcaceae and other fiber-degrading taxa whose enzymes (cellulases, xylanases) enable efficient exploitation of high-fiber resources (Funosas et al 2021). High Ruminococcaceae and overall diversity are associated with a broader functional profile and may even correlate with longer individual life expectancy, whereas low-diversity microbiomes dominated by Enterobacteriaceae are associated with a more amylolytic, starch-oriented metabolism (Funosas et al 2021). Environmental factors appear more important than host genetics in structuring wild rabbit microbiomes: geographic differences in community composition are observed in the field but disappear in captivity, which indicates strong environmental imprinting through diet, habitat and local microbial exposure (Funosas et al 2021). This is crucial for agro-ecological systems, because it implies that soil, vegetation and management conditions can indirectly shape rabbit gut communities.

Soil microbiomes are key drivers of soil fertility, crop productivity and stress resilience. Their functions depend strongly on soil structure, especially aggregation and pore connectivity, which regulate the flow of water, oxygen and nutrients and thereby determine microbial habitats and activity (Hartmann & Six 2022). Agricultural practices that compact

soil, reduce organic matter or simplify vegetation can disrupt this structure, leading to erosion, reduced fertility and altered greenhouse-gas fluxes, while integrated soil fertility management and reduced-input systems promote microbial diversity and more stable ecosystem functions (Hartmann & Six 2022). Across agroecosystems, diverse soil microbiomes underpin nutrient cycling and pathogen suppression and are therefore central to sustainable, “climate-smart” production (Hartmann & Six 2022).

Conceptual and comparative work now explicitly connects soil, plant and gut microbiomes. A soil-plant-gut axis has been proposed in which certain microorganisms or functional groups can move from soil to plants and then into animal or human guts, with potential reciprocal feedbacks between these compartments (Ma et al 2025). Reviews comparing soil and mammalian gut microbiota emphasize shared mechanisms of disease suppression, the analogous roles of organic amendments in soils and diet in shaping gut microbiota, and the potential to manage both within a One Health framework (Bonanomi et al 2021). Broader “holobiome” and “Soils2Guts” narratives frame soil, plant, animal and human microbiomes as parts of a single, interconnected system in which microbial diversity and ecosystem health are common goals for agriculture and public health (Hepping et al 2025; García et al 2025). These perspectives highlight microbial biodiversity, reduced chemical disturbance and organic inputs as levers that simultaneously support soil functions and gut-mediated health outcomes.

In integrated crop-livestock systems, the most concrete evidence on gut-soil interactions comes from ruminants rather than rabbits. In organic crop-livestock integrations with grazing sheep and goats, animals graze cover crops and deposit manure directly onto fields. Fecal and soil microbiomes can be profiled concurrently to assess cross-compartment dynamics (Cheong et al 2025). In these systems, grazing and manure deposition increase the prevalence of generic *Escherichia coli* in soils but do not measurably alter overall soil microbial diversity or composition, and there is little detectable interaction between post-grazing fecal communities and grazed soils at the community scale (Cheong et al 2025). Alpha and beta diversity patterns are influenced more by animal species and region than by grazing treatment, suggesting that gut and soil microbiomes can remain partly decoupled, at least over the time scales studied (Cheong et al 2025). Nevertheless, such systems clearly create a bidirectional flux of microbes and nutrients between gut and soil, even if the net effect on bulk community composition is subtle.

Rabbits can act as ecosystem engineers of soil microbiota through their foraging and burrowing activities. In arid woodlands, comparison of microbial communities in rabbit foraging pits, echidna pits, surface soil and subsoil shows that microsite identity is a major driver of bacterial composition and enzyme activity (Eldridge et al 2016). Rabbit pits tend to resemble surrounding surface or subsoil communities, whereas echidna pits have higher relative abundance of Proteobacteria, lower Acidobacteria and correspondingly higher enzyme activities, implying more positive effects on soil function (Eldridge et al 2016). Thus, rabbit disturbance has detectable but relatively limited functional benefits compared to native soil-foraging mammals, and high rabbit densities may not improve soil microbiome-mediated functions to the same extent (Eldridge et al 2016). Even so, rabbit activity clearly structures microbial habitats at fine scales, creating feedbacks between animal behavior, soil microbiota and ecosystem processes.

When these strands are combined, a plausible picture emerges for integrated agro-ecological systems that include rabbits. First, soil management determines soil structure and microbiome composition, which in turn influence plant communities, plant nutrient content and plant-associated microbiota (Hartmann & Six 2022; Ma et al 2025). Rabbits feeding on these plants are exposed to this plant-linked microbial reservoir as well as to soil-derived microorganisms on plant surfaces or in ingested soil particles. Given the demonstrated environmental sensitivity of rabbit gut communities and the importance of fiber-degrading taxa for performance (Funosas et al 2021), forages grown on microbially diverse, well-structured soils are likely to support gut microbiomes richer in Ruminococcaceae

and related fermenters, improve short-chain-fatty-acid production and enhance intestinal barrier functions, although this has not yet been tested directly in rabbits. Second, through feces and soil disturbance, rabbits return organic matter and gut-derived microbes to the soil. While evidence from small ruminants suggests that bulk soil communities may be resilient and not easily shifted by grazing inputs over short periods (Cheong et al 2025), rabbit pits and latrines can create localized patches with distinct microclimates and resource availability that select for particular microbial assemblages (Eldridge et al 2016). Over longer time scales and at landscape level, such patchiness can influence nutrient cycling, vegetation patterns and the spatial structure of soil microbiomes.

Within a One Health or holobiome framework, integrated rabbit-crop systems can be viewed as nested feedback loops in which soil management, vegetation, rabbit gut microbiota and soil microbiota co-influence each other (Bonanomi et al 2021; García et al 2025; Ma et al 2025; Hepping et al 2025). Practices that preserve soil structure, minimize biocide use and maintain high microbial diversity are likely to benefit both soil functions and rabbit gut health, even though species-specific data are lacking. Conversely, intensive tillage, heavy herbicide or antibiotic use and high rabbit densities with limited plant diversity could degrade both soil and gut microbiomes, undermining system resilience (Eldridge et al 2016; Bonanomi et al 2021; Hartmann & Six 2022; García et al 2025). The main research gaps are clear: there is no longitudinal work following microbial taxa or functions along a soil-plant-rabbit gut-soil loop, and almost all quantitative interaction data come from other livestock. Future agro-ecological studies would need to combine soil, plant and rabbit gut sequencing with functional assays of nutrient cycling, intestinal health and productivity to fully characterize this interaction (Table 2).

Table 2

Rabbit gut–soil microbiome interactions in integrated systems (Consensus 2025)

| <i>Aspect</i> | <i>Summary of current knowledge</i> | <i>Citations</i> |
|-------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Rabbit gut microbiome structure and drivers | Dominance of fiber-degrading Ruminococcaceae linked to efficient use of high-fiber diets; environmental context more important than host genetics in shaping community composition. | Funosas et al (2021); Combes et al (2025) |
| Soil microbiome functions and management | Soil structure and microbiome diversity underpin fertility, productivity and resilience; integrated, low-disturbance management sustains these functions. | Hartmann & Six (2022) |
| Conceptual soil-plant-gut and holobiome links | Microbes and functions can connect soil, plants and animal/human guts; microbiome used as boundary concept linking agriculture and health within One Health or “Soils2Guts” frameworks. | Bonanomi et al (2021); García et al (2025); Ma et al (2025); Hepping et al (2025); |
| Evidence from integrated crop-livestock systems | Grazing ruminants and fecal deposition modestly affect soil pathogens and <i>E. coli</i> prevalence but do not strongly change bulk soil diversity; animal species and region are stronger drivers. | Cheong et al (2025) |
| Rabbits as soil microbial engineers | Rabbit foraging pits alter local soil microbial composition and function, but with weaker positive effects than native soil-foraging mammals. | Eldridge et al (2016) |

The role of rabbit excreta in nitrogen and phosphorus cycling in agricultural soils.

Rabbit excreta, comprising feces and urine, represent a concentrated organic source of nitrogen (N) and phosphorus (P) that can significantly influence biogeochemical cycles in agricultural soils. Recent work that treats rabbit manure as a fertilizer, together with broader research on manure-mediated nutrient cycling, allows a detailed assessment of how rabbit excreta contribute to N and P inputs, transformations, losses and plant uptake.

Composition, inputs and immediate soil effects. Rabbit manure contains a large fraction of the ingested organic matter and nitrogen that is not retained by the animal. During fattening, about 30% of dietary organic matter and 65% of dietary nitrogen are excreted in manure, indicating that rabbit production systems export substantial nutrient loads to soils when excreta are recycled as fertilizer (Dinuccio et al 2019). In pot and field experiments, application of rabbit manure or rabbit-based fertilizers consistently increases soil total nitrogen, total phosphorus and organic carbon compared with mineral fertilization alone or unfertilized controls (Petrescu & Petrescu-Mag 2018; Ikrarwati et al 2021; Zhang et al 2023; Khalafalla et al 2024; Wysokinski & Kożuchowska 2024). These inputs raise soil pH in acidic substrates, increase electrical conductivity and cation exchange capacity, and enhance the pool of plant-available P and exchangeable K, reflecting both direct nutrient addition and improved sorption-desorption dynamics (Ikrarwati et al 2021; Zhang et al 2023; Khalafalla et al 2024; Azeez et al 2025).

Liquid organic fertilizers derived from rabbit urine and feces, sometimes enriched with plant materials, also raise soil pH and available P, while total N and C can decline due to rapid mineralization and intense plant uptake under improved growth conditions (Azeez et al 2025). In vegetable systems, rabbit manure fertilizer matches or surpasses chemical fertilizers in sustaining yields in a second cropping season, while simultaneously increasing soil total N, total P and organic C (Zhang et al 2023). Such responses indicate that rabbit excreta act not only as nutrient carriers but also as modifiers of the soil chemical environment in which N and P transformations occur.

Nitrogen cycling: mineralization, retention and losses. Within the nitrogen cycle, rabbit excreta contribute organic N that must be mineralized to ammonium and then nitrified to nitrate to become plant-available, while also supplying soluble N in urine. Manure application in general increases soil total N, microbial N and N-acquiring enzyme activities, accelerating N cycling and improving soil fertility (Liu et al 2020). Rabbit manure behaves similarly: in maize and black cumin systems, rabbit manure alone or in combination with mineral N substantially increases crop N uptake and nitrogen use efficiency, demonstrating effective transformation of excreted N into plant biomass (Khalafalla et al 2024; Wysokinski & Kożuchowska 2024). For silage maize, increasing rabbit manure rates up to 60 t ha⁻¹, especially when combined with moderate mineral N, progressively raises N content and uptake, with the most beneficial combination for yield and crude protein being high manure plus intermediate mineral N (Wysokinski & Kożuchowska 2024).

At the same time, rabbit manure is a potential source of reactive N losses. Under laboratory-simulated storage and land application, rabbit manure loses on average about one-third of its total N as ammonia (NH₃) and a smaller but significant fraction as nitrous oxide (N₂O), a potent greenhouse gas (Dinuccio et al 2019). Specifically, cumulative N losses during storage and subsequent application average about 32.4% of excreted total N as NH₃ and 2.2% as N₂O, with more than half of excreted organic matter respired as CO₂ (Dinuccio et al 2019). Incorporating manure into soil effectively reduces NH₃ volatilization but tends to increase N₂O emissions compared with surface application, illustrating the classic trade-off between local air quality and climate forcing (Dinuccio et al 2019). These findings, although focused on gaseous fluxes, directly affect the N balance available for soil biogeochemical cycling and crop uptake.

In cropped soils, rabbit-derived fertilizers can modify inorganic N pools. In *Brassica* systems, rabbit manure raises total N but significantly lowers soil nitrate (NO_3^- -N) compared with mineral fertilization, suggesting tighter coupling between mineralization, microbial immobilization and plant uptake when organic N dominates (Zhang et al 2023). More broadly, reviews of nutrient cycling in pastures show that animal excreta are central to N redistribution, with manure and urine returning a large share of grazed N to soil, subject to losses by leaching, runoff and volatilization if not synchronized with plant demand (Schröder et al 2016; do Nascimento et al 2024). Rabbit excreta in grazing or free-range systems therefore function as localized N hotspots that can either enhance plant growth and microbial activity or become sources of nitrate leaching and gaseous losses, depending on soil conditions and management.

Phosphorus cycling: availability, fractionation and microbial mediation. Rabbit manure also plays a significant role in phosphorus cycling by adding both inorganic and organic P and by stimulating the biological processes that govern P availability. In multiple crops and soil types, rabbit manure or rabbit-containing fertilizer blends increase soil total P and plant-available P compared with unfertilized or purely mineral N treatments (Ikrarwati et al 2021; Zhang et al 2023; Khalafalla et al 2024; Azeez et al 2025). In black cumin, combining rabbit manure with urea-formaldehyde and biofertilizer markedly enhances soil P availability over time and leads to significant gains in shoot biomass, reproductive traits and photosynthetic pigments, indicating effective P supply and uptake (Khalafalla et al 2024). Kinetic modelling of P release in that system shows that pseudo-second-order equations best describe N and P release from the rabbit manure-urea-biofertilizer mixture, reflecting a controlled but sustained release pattern that aligns with plant demand (Khalafalla et al 2024).

Meta-analyses across manure types confirm that organic amendments strongly increase total, available and microbial biomass P, with particularly large increases in labile P fractions and phosphatase activities that mobilize organic P (Liu et al 2020; Chen et al 2024; Liu et al 2025). While most synthesized data focus on pig or poultry manure, the mechanism is generic: organic inputs supply P directly, provide carbon substrates for phosphate-solubilizing microorganisms and phosphatase-producing microbes, and adjust soil pH and redox conditions in ways that favor P desorption and mineral dissolution (Liu et al 2020; Tian et al 2021; Chen et al 2024; Liu et al 2025). Rabbit manure, which increases soil organic carbon, pH and electrical conductivity, fits this pattern and has been shown to significantly alter bacterial community structure, including enriching genera associated with N and P transformations (Zhang et al 2023). Such microbial shifts are central to P cycling, since microorganisms mediate the conversion between non-labile inorganic P, microbial biomass P and plant-available orthophosphate (Tian et al 2021; Chen et al 2024).

Stoichiometric perspectives further clarify the role of rabbit excreta in P transformation. Organic amendments modify soil C:N:P ratios and microbial biomass stoichiometry, which in turn regulate whether microbes immobilize P into biomass or mineralize organic P to available forms (Chen et al 2024). Manures with balanced or C-rich compositions can promote microbial growth and enzyme production, enhancing the conversion of insoluble P into available P, whereas high P inputs relative to C and N may exceed microbial and plant demand, increasing the risk of P accumulation and runoff (Wei et al 2022; Chen et al 2024; Liu et al 2025). Rabbit manure additions raise soil total N and P alongside organic C, suggesting potential for improved P mobilization, but application rate and background soil P status will determine whether net effects favor internal cycling or excess accumulation.

Effects on soil microbial communities and coupled N-P dynamics. Rabbit manure not only delivers N and P but also reshapes the soil microbial community that drives their cycling. In Chinese cabbage systems, rabbit manure fertilizer significantly increases bacterial diversity and abundance, with total N, total P, organic carbon and electrical conductivity positively

correlated with bacterial alpha-diversity (Zhang et al 2023). Rabbit manure and pig manure both reduce the relative abundance of certain bacterial taxa while rabbit manure specifically increases other groups in subsequent seasons, implying selective stimulation of functional guilds (Zhang et al 2023). Distance-based redundancy analysis attributes much of the variation in bacterial composition to soil EC, total N and organic carbon, whereas fungal communities are more strongly influenced by soil nitrate, EC, SOC and pH (Zhang et al 2023). These community shifts can feed back on N and P cycles by altering rates of mineralization, nitrification, denitrification, P solubilization and phosphatase activity.

Global syntheses show that manure generally doubles microbial C and N pools and increases activities of C-, N- and P-acquiring enzymes by 1.3-3.3 fold, thereby accelerating element cycling (Liu et al 2020). Application of rabbit manure or rabbit-based liquids in arable soils thus likely increases microbial biomass N and P and enzyme-mediated transformations, reinforcing tight coupling between N and P cycles through shared microbial pathways (Liu et al 2020; Tian et al 2021; Wysokinski & Kożuchowska 2024; Azeez et al 2025). In agricultural plant-soil systems more broadly, biogeochemical reviews emphasize that N and P cycles are highly interconnected via microbial processes, and that disruptions or enhancements to one cycle (for example via manure N inputs) can strongly influence P availability and retention (Tian et al 2021; Chen et al 2024; Zaman et al 2025). Rabbit excreta, by changing both nutrient supply and microbial functional composition, participate in these coupled dynamics, with implications for productivity, nutrient use efficiency and environmental losses.

Environmental risks and management considerations. While rabbit manure enhances N and P cycling and crop growth, its contribution to biogeochemical cycles also entails environmental risks. For N, substantial gaseous emissions during manure storage and after field application reduce the amount of N retained in soils and contribute to atmospheric pollution and climate forcing (Dinuccio et al 2019; Harindintwali et al 2021). For P, meta-analyses demonstrate that manures increase not only soil P fractions but also total P losses, especially via runoff when application rates are high or soils are already P-rich (Wei et al 2022; Liu et al 2025). Optimal manure rates in some systems minimize P runoff while still increasing P availability, underscoring the need for careful calibration of rabbit manure application to crop demand and soil P status (Wei et al 2022; Liu et al 2025).

More generally, reviews of soil quality and nutrient cycling stress that soils must be able to receive, retain and supply nutrients to crops without excessive losses, and that organic residues such as manures should be managed to support all four of these processes simultaneously (Schröder et al 2016). Integrated eco-strategies for carbon and nitrogen cycling highlight composting, combination with biochar and the use of N-fixing or P-solubilizing organisms as ways to reduce emissions and improve the fertilizer value of animal wastes (Harindintwali et al 2021; Tian et al 2021; Zaman et al 2025). These principles apply directly to rabbit excreta: pre-composting rabbit manure, combining it with mineral fertilizers at balanced ratios, or integrating it into broader organic-input strategies can enhance N and P use efficiency, strengthen soil health and limit leaching, runoff and gaseous losses (Liu et al 2020; Harindintwali et al 2021; Khalafalla et al 2024; Wysokinski & Kożuchowska 2024; Bora et al 2025; Zaman et al 2025).

Synthesis and research gaps. In agricultural soils, rabbit excreta function as a multifunctional biogeochemical input. They add substantial quantities of N and P, improve soil pH and cation exchange capacity in many degraded or acidic soils, stimulate diverse and active microbial communities, and support higher crop yields and nutrient uptake when applied at appropriate rates (Ikrrarwati et al 2021; Zhang et al 2023; Khalafalla et al 2024; Wysokinski & Kożuchowska 2024; Azeez et al 2025). At the same time, rabbit manure is a significant source of N losses as NH₃ and N₂O and, like other manures, can contribute to P accumulation and runoff if mismanaged (Dinuccio et al 2019; Liu et al 2020; Wei et al 2022;

Liu et al 2025). Through these pathways, rabbit excreta occupy a central position at the interface of soil, plant and atmospheric N and P cycles in agricultural landscapes.

However, several gaps remain. Few studies quantify the full N and P budgets of rabbit manure in field conditions, linking excreted nutrients to soil pools, gaseous emissions, leaching and crop uptake simultaneously (Dinuccio et al 2019). Comparisons among manure types in large meta-analyses rarely distinguish rabbit manure, leaving its specific P fractionation patterns and loss pathways underexplored relative to pig or poultry manure (Liu et al 2020; Wei et al 2022; Liu et al 2025). There is also limited work on how rabbit excreta interact with soil C:N:P stoichiometry and with phosphate-solubilizing and N-cycling microbial guilds at fine spatial scales (Tian et al 2021; Chen et al 2024). Addressing these gaps will be crucial for designing rabbit-integrated agricultural systems that harness the fertilizing potential of rabbit excreta while minimizing adverse impacts on N and P biogeochemical cycles (Table 3).

Table 3

Key roles of rabbit excreta in N and P cycling in agricultural soils (Consensus 2025)

| <i>Aspect</i> | <i>Main points related to N and P cycling</i> | <i>Citations</i> |
|----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Nutrient content and soil enrichment | Manure returns ~65% of dietary N; rabbit manure and derivatives increase soil total N, total P, organic C, pH, EC and CEC, enhancing available N and P. | Dinuccio et al (2019); Liu et al (2020); Ikrarwati et al (2021); Zhang et al (2023); Khalafalla et al (2024); Wysokinski & Kożuchowska (2024); Azeez et al (2025) |
| Plant uptake and fertilizer value | Rabbit manure and rabbit-based fertilizers support crop yields and NPK uptake comparable to mineral fertilizers and improve nitrogen use efficiency when combined with mineral N. | Zhang et al (2023; Khalafalla et al (2024); Wysokinski & Kożuchowska (2024); Azeez et al (2025) |
| Gaseous N losses | During storage and application, rabbit manure loses about one-third of excreted N as NH ₃ and a smaller portion as N ₂ O; incorporation reduces NH ₃ but may increase N ₂ O. | Dinuccio et al (2019); Liu et al (2020); Harindintwali et al (2021) |
| P availability and transformation | Rabbit manure increases total and available P and stimulates microbial communities and enzyme activities that mobilize P, fitting broader patterns of manure-driven labile P and phosphatase increases. | Liu et al (2020); Tian et al (2021); Wei et al (2022); Zhang et al (2023); Chen et al (2024); Khalafalla et al (2024); Liu et al (2025) |
| Microbial mediation and coupled cycles | Rabbit manure increases bacterial diversity and shifts community structure; manure generally doubles microbial C and N and boosts C-, N- and P-acquiring enzymes, tightening N-P coupling. | Liu et al (2020); Tian et al (2021); Zhang et al (2023); Chen et al (2024); Zaman et al (2025) |
| Environmental risks and management | Excessive or poorly timed applications contribute to NH ₃ and N ₂ O emissions and elevated P runoff; optimized rates, composting and integrated strategies are needed to balance fertility and environmental protection. | Schröder et al (2016); Dinuccio et al (2019); Liu et al (2020); Harindintwali et al (2021); Wei et al (2022); Liu et al (2025); Zaman et al (2025) |

Conclusions. Controlled rabbit grazing represents a nuanced management factor with both beneficial and detrimental potential effects on soil systems. The synthesis of current literature indicates that grazing intensity and management are the primary determinants of outcomes. High-density or uncontrolled rabbit grazing can degrade soil structure by reducing vegetation cover, increasing soil disturbance, and promoting the breakdown of stable macroaggregates. These processes lead to increased erosion risk, reduced carbon sequestration, and diminished soil fertility.

Conversely, well-managed, controlled grazing regimes - characterized by moderate stocking densities, rotational use, and attention to soil moisture conditions - can maintain or slightly improve soil aggregate stability. Under such conditions, positive processes such as root turnover, organic matter input, and microbial activity can offset the negative impacts of trampling and disturbance. Rabbits also contribute to spatial heterogeneity through the formation of pits and latrines, which may create localized zones of nutrient enrichment and microbial activity, although these effects are highly context-dependent.

Rabbit excreta play a significant role in nitrogen and phosphorus cycling, acting as concentrated nutrient inputs that enhance soil fertility and microbial processes. However, these benefits are accompanied by risks, including gaseous nitrogen losses and phosphorus accumulation, which require careful management to avoid environmental impacts.

Furthermore, the emerging concept of a soil-plant-gut microbiome axis suggests that rabbits may influence and be influenced by soil microbial communities, although direct empirical evidence remains limited. This highlights an important frontier for future research.

Overall, controlled rabbit grazing can be integrated into sustainable agricultural systems, but its success depends on precise management and monitoring. Key indicators such as soil aggregate stability, bulk density, and nutrient balances should be systematically evaluated. Significant research gaps remain, particularly regarding direct measurements of rabbit-specific impacts on soil aggregation and long-term nutrient dynamics, emphasizing the need for targeted experimental studies.

Conflict of interest. The authors declare that there is no conflict of interest.

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