Rabbit-mediated nutrient cycling and soil regeneration: integrating Nitrogen and Phosphorus dynamics, agroecosystem functioning, and sustainable management

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Abstract. Rabbit production systems and wild rabbit populations represent an underexplored yet significant component of nutrient cycling in agroecosystems. This paper synthesizes current knowledge on the role of rabbit droppings in nitrogen (N) and phosphorus (P) cycling, their effects on soil microbial communities, and their integration into regenerative agricultural systems. Rabbit excreta act as localized nutrient hotspots, enhancing soil organic carbon, mineral N forms, and plant-available P, while stimulating microbial activity and enzyme-mediated transformations. These processes accelerate N mineralization, nitrification, and P turnover, thereby improving plant nutrient uptake and productivity. However, the spatial heterogeneity of excreta deposition also introduces risks of nutrient losses through leaching and gaseous emissions. Beyond biogeochemical processes, integrating rabbit farming into crop rotations contributes to circular nutrient flows, increased soil organic matter, and improved soil health indicators, including microbial diversity and enzymatic activity. Evidence from degraded soils and experimental systems demonstrates that rabbit manure and its derivatives (e.g., biochar, liquid fertilizers) can significantly enhance soil functionality and crop yields. At the same time, rabbit population density plays a critical role in determining outcomes for soil biodiversity and ecosystem multifunctionality, with moderate densities promoting heterogeneity and high densities potentially causing degradation and disruption of key microbial symbioses. Overall, rabbit systems emerge as multifunctional agents linking animal management, soil biology, and sustainable crop production. Their effective use requires careful management of population density, spatial distribution, and integration into diversified crop-livestock systems.
Key Words: ecosystem multifunctionality, integrated crop-livestock systems, nitrogen cycling, nutrient hotspots, phosphorus cycling, rabbit manure, regenerative agriculture, soil biodiversity, soil enzyme activity, soil microbiome.

Introduction. Sustainable agricultural systems increasingly rely on the efficient recycling of nutrients and the restoration of soil biological functions (Bora et al 2025; Petrescu-Petrescu-Mag 2018). Within this context, animal excreta play a central role in mediating nutrient flows, linking aboveground biomass consumption to belowground biogeochemical processes (Mocanu & Petrescu-Mag 2025). While the contribution of large livestock to nutrient cycling has been extensively studied, the role of smaller herbivores such as rabbits remains comparatively underexplored, despite their widespread presence in both managed and natural ecosystems (Bud et al 2011).

Rabbit droppings represent a concentrated and biogeochemically active source of nitrogen (N) and phosphorus (P), capable of significantly altering soil chemical and biological properties at fine spatial scales. These inputs function as localized "fertility islands", where elevated concentrations of organic matter and nutrients stimulate microbial activity, accelerate nutrient transformations, and enhance plant growth (Petrescu-Mag et al 2011, 2012a, b). Through processes such as mineralization, nitrification, and enzymatic P release, rabbit-derived organic matter contributes to the availability of plant-accessible nutrients, while also influencing soil pH, structure, and microbial community composition (Bud et al 2011).

Beyond their direct effects on soil processes, rabbits can be integrated into agricultural systems as part of regenerative and circular farming strategies (Petrescu-Mag et al 2011, 2012a, b). By converting plant biomass into nutrient-rich manure, rabbits facilitate the return of nutrients to the soil, reducing dependence on synthetic fertilizers and promoting soil organic matter accumulation. When incorporated into crop rotations or integrated crop-livestock systems, rabbit production can contribute to improved nutrient use efficiency, enhanced microbial diversity, and long-term soil health restoration. However, these benefits are highly context-dependent and influenced by factors such as manure management, spatial distribution of excreta, and rabbit population density (Mocanu & Petrescu-Mag 2025).

At the same time, excessive rabbit densities or poorly managed systems can lead to negative outcomes, including overgrazing, disruption of plant communities, and alterations in soil microbial symbioses. The balance between beneficial nutrient inputs and potential ecosystem degradation highlights the need for a systems-level understanding of rabbit-mediated processes.

The aim of this paper is to synthesize current knowledge on the role of rabbit droppings in nitrogen and phosphorus cycling, evaluate their effects on soil microbial communities and ecosystem functioning, and assess their potential integration into regenerative agricultural systems for improving soil health and sustainability.

Role of rabbit droppings in nitrogen and phosphorus cycling

Rabbit droppings. Rabbit droppings represent a highly localized but biogeochemically active source of organic nitrogen (N) and phosphorus (P) in agroecosystems. Their effects are best understood by integrating what is known specifically for rabbits with broader work on animal excreta, nutrient cycling in pasture and arable systems, and soil-microbe interactions.

In semi-arid Spain, rabbit latrines (dense accumulations of pellets) were found to contain total N and P concentrations comparable to dung of larger stock animals, and to create soil "fertility islands" with significantly higher organic carbon, ammonium, nitrate, and plant-available P relative to surrounding soil, despite covering only ~0.1% of the surface area (Willott et al 2000). Barley grown in these enriched patches had higher biomass and lower root:shoot ratio, indicating greater nutrient supply and reduced need for extensive rooting (Willott et al 2000). This shows that even small, spatially concentrated inputs of rabbit faeces can markedly influence local N and P cycles and plant nutrition.

Composition and initial transformation of rabbit droppings. Rabbit pellets are rich in organic N and P, with K and Mg somewhat lower than in many stock manures (Willott et al 2000). Their relatively dry, compact form slows decomposition, especially in semi-arid climates, so the transformation of organic N and P to mineral forms (ammonium, nitrate, phosphate) is gradual (Willott et al 2000). Experiments with rabbit manure in water show that mineralization can release substantial concentrations of $N{-}NO_2^-$, $N{-}NO_3^-$, $N{-}NH_3$ and $P{-}PO_4^{3-}$, with diet strongly affecting nutrient release rates and stoichiometry (Adande et al 2017). Manure from rabbits fed *Panicum maximum* released the highest $P{-}PO_4^{3-}$ and high N forms, highlighting that feeding regimes regulate the N:P ratio of excreta and thus downstream cycling (Adande et al 2017).

When rabbit wastes are applied to soil, either as solid pellets or as liquid organic fertilizers (LOF combining urine and faeces), they increase soil pH, available P, and exchangeable K, while promoting rapid N mineralization and N uptake by crops (Zhang et al 2023; Azeez et al 2025). In maize, LOF from rabbit wastes produced grain yields and NPK uptake comparable to mineral NPK fertilizer, while reducing soil total N and C via strong plant uptake and mineralization, demonstrating high N cycling intensity (Azeez et al 2025).

Nitrogen cycling processes driven by rabbit droppings

Mineralization, nitrification and plant uptake. The organic N in rabbit faeces enters the soil organic matter pool and is progressively mineralized by heterotrophic microbes to ammonium (NH_4^+), then nitrified to nitrate (NO_3^-). Under rabbit latrines, soils show significantly elevated NH_4^+ and NO_3^- compared with adjacent control soils, indicating active N mineralization and nitrification in the microzones enriched by pellets (Willott et al 2000). Crop and pasture studies using rabbit manure show similar patterns: application increases soil total N, stimulates microbial activity, and enhances plant N uptake, often to the point that soil total N declines despite N inputs because N is rapidly transferred into biomass (Zhang et al 2023; Azeez et al 2025). This fits within the broader understanding that animal excreta act as hotspots for N cycling, combining high substrate supply with altered moisture and pH to accelerate microbial N transformations (Schröder et al 2016; do Nascimento et al 2024).

Microbial mediation and enzymatic controls. Nitrogen cycling from rabbit droppings is mediated by soil microbial communities whose metabolism is constrained by C:N:P stoichiometry. In intensively managed agricultural soils, increased N availability can induce microbial P limitation, which in turn suppresses the abundance of nitrification and denitrification genes (amoA, nirK, nirS, nosZ) and reduces potential rates of these processes (Cui et al 2020). When rabbit manure is applied, it simultaneously supplies N and P, and may alleviate such P limitations locally, thereby maintaining or enhancing microbial N cycling potential. More generally, animal waste-derived organic fertilizers are associated with higher activities of N-cycling enzymes such as urease, reflecting enhanced N mineralization capacity (Bhunia et al 2021).

Long-term experiments with organic fertilization show that manure inputs promote keystone microbial taxa involved in N mineralization, nitrification, and biological N fixation, and that these communities exert strong control on soil N cycling functionality and crop yields (Zhou et al 2024). Rabbit manure behaves similarly to other animal manures in raising soil total N, supporting copiotrophic microbes, and increasing the genetic potential for N transformations that link organic inputs to plant-available forms (Bhunia et al 2021; Enebe & Babalola 2021; Zhang et al 2023).

Loss pathways: leaching and gaseous emissions. As for other excreta, the same processes that make N available also create routes for loss. Reviews of nutrient cycling in pastures emphasize that excreta patches concentrate N, leading to elevated risks of leaching, runoff, and gaseous losses, especially if plant uptake is saturated or hydrological conditions favour transport (Schröder et al 2016; do Nascimento et al 2024). High localized NH_4^+ and NO_3^- around rabbit latrines or manure application bands are therefore likely to represent both a fertility resource and a potential source of N_2O and NO_3^- leaching, although direct measurements for rabbits in field soils are scarce. The balance between plant uptake (as demonstrated by increased biomass and lower root:shoot ratios (Willott et al 2000; Azeez et al 2025)) and these loss pathways will largely determine the net N retention in agricultural systems.

Phosphorus cycling processes associated with rabbit droppings

P inputs, fractionation and availability. Rabbit droppings provide P primarily in organic and inorganic forms that gradually enter different soil P fractions. Under rabbit latrines in semi-arid Spain, soil P concentrations were significantly higher than in surrounding soils, and this enrichment translated into greater plant P uptake and growth (Willott et al 2000). Similar increases in soil total P and available P are documented when rabbit manure fertilizer is applied in pot experiments, where it increased soil total P and organic C and raised electrical conductivity and pH (Zhang et al 2023). In maize systems, liquid fertilizers derived from rabbit wastes increased available P in soil while sustaining high grain yields (Azeez et al 2025).

At the mechanistic level, P from manure enters labile pools (e.g. resin- and bicarbonate-extractable P) and more stable pools (sorbed, occluded, or organically bound P), with microbial processes and soil aggregation controlling its partitioning (Hu et al 2025). Functional microbes (especially bacteria) regulate the transformation between labile and non-labile P fractions, and their diversity and gene abundance strongly influence P availability (Hu et al 2025). Organic inputs, including animal manures, stimulate these microbial communities and the expression of P-cycling genes (e.g. genes for polyphosphate formation and phosphate transport), which can either immobilize P in microbial biomass or facilitate its turnover and release (Enebe & Babalola 2021; Hu et al 2025).

Microbial P cycling genes and enzymes. The biogeochemical cycling of P is heavily mediated by microbial communities in the rhizosphere and bulk soil. Metagenomic analyses of fertilized maize rhizospheres show that composted organic inputs enhance the abundance of key P cycling genes such as ppk (polyphosphate kinase) and pst (phosphate transporters), reflecting increased microbial capacity for P immobilization and regulated release (Enebe & Babalola 2021). Soils fertilized with organic amendments tend to show higher activities of acid phosphatase and related enzymes that mineralize organic P, increasing the flux from organic to inorganic forms available to plants (Bhunia et al 2021). Given that rabbit manure increases soil organic P and stimulates bacterial diversity (Zhang et al 2023), similar enzyme-mediated pathways are likely important in rabbit-amended agricultural soils, where phosphatases break down organic P in pellets and associated necromass, and microbial uptake and release cycles buffer P availability over time.

Spatial heterogeneity and stoichiometric feedbacks. Rabbit latrines create pronounced spatial heterogeneity in P, generating "resource islands" that can structure plant communities and root distributions (Willott et al 2000). Pasture reviews emphasize that manure-derived P is often returned to soil away from the point of plant uptake, resulting in spatial decoupling and stock transfer losses at farm scale, even while creating local enrichment (Schröder et al 2016; do Nascimento et al 2024). For rabbits, this means that the pattern of latrine placement relative to crop rows or pasture use will control how effectively P islands are exploited.

The C:N:P stoichiometry of excreta and soils also feeds back on microbial processes. Experiments with sheep urine and dung demonstrate that different excrement types and mixtures shift soil and plant C:N:P ratios, often increasing total soil C, N, and P, while changing plant N:P ratios and indicating shifts in nutrient limitation status (Li et al 2021). Rabbit droppings, with N and P contents comparable to larger herbivores' dung (Willott et al 2000), are expected to exert similar stoichiometric effects at the patch scale. Where N inputs are high relative to P, microbial P limitation can develop, reducing the abundance of N cycling genes and suppressing nitrification and denitrification potential (Cui et al 2020); where P is plentiful relative to N, microbial immobilization of P may temporarily limit plant access but conserve P within the soil–microbe system (Enebe & Babalola 2021; Hu et al 2025).

***Effects on soil microbiome and soil functionality*.** Animal manures, including rabbit manure, consistently alter soil microbiome composition and functionality. In pot experiments, rabbit manure fertilizer significantly increased bacterial diversity and abundance, with strong correlations between bacterial α-diversity and soil total N, total P, organic C, and EC (Zhang et al 2023). Organic fertilizers based on animal wastes promote copiotrophic microbes that rapidly exploit labile C and nutrients, enhance enzyme activities involved in N and P cycling, and form plant-beneficial consortia that suppress soil-borne pathogens (Bhunia et al 2021).

At broader scales, grassland and cropping studies show that conversion from native, excreta-rich systems to intensive croplands reduces the abundance of microbial genes involved in N and P cycling and necromass recycling, indicating diminished functional resilience (Giménez et al 2025). Conversely, long-term organic inputs (green and animal manures) increase the influence of microbial keystone taxa on N and P cycling functions across soil profiles, enhancing soil multifunctionality and stabilizing yields (Zhou et al 2024). Rabbit droppings, by contributing organic C, N, and P in a form readily colonized and decomposed by microbes, fit into this pattern of strengthening microbially mediated nutrient cycling in agricultural soils.

Integration into agricultural N and P cycles. From a systems perspective, rabbit droppings participate in the four key processes that define nutrient cycling capacity in agricultural soils: receiving nutrients, making and keeping them available, supporting plant uptake, and allowing their removal in harvested crops (Schröder et al 2016). Rabbit excreta deliver N and P back to fields as part of a circular nutrient flow, offsetting mineral fertilizer needs and contributing to soil organic matter pools (Schröder et al 2016; Bhunia et al 2021; Harindintwali et al 2021). However, as with other manures, their contribution is constrained by spatial heterogeneity, possible mismatches between excretion sites and crop demands, and the risk of N and P losses through leaching and runoff when inputs exceed local uptake capacity (Schröder et al 2016; Harindintwali et al 2021; do Nascimento et al 2024).

Experimental evidence shows that rabbit-waste-based fertilizers can replace substantial proportions of mineral NPK while maintaining crop yields and improving soil chemical properties and microbial diversity (Zhang et al 2023; Azeez et al 2025). Rabbit latrines in semi-natural and semi-arid systems demonstrate how localized faecal inputs can rehabilitate poor soils, increase N and P availability, and support plant cover (Willott et al 2000). Together, these findings indicate that rabbit droppings function as small, powerful nodes in the larger N and P cycles of agricultural landscapes, linking animal feeding and movement patterns to soil biochemical processes and crop productivity.

Rabbit farming in regenerative crop rotations

Integrated rabbit farming in crop rotations. Integrating rabbit production into crop rotations fits squarely within the broader paradigm of regenerative and circular agriculture, which seeks to restore degraded soils by closing nutrient cycles, increasing biodiversity, and relying less on synthetic inputs (Mosier et al 2021; Khangura et al 2023; Prairie et al 2023). In a circular economy approach to rabbit farming in Indonesia, integrating intensive rabbit production with home gardens and crop production reduced the direct disposal of waste, decreased dependence on chemical fertilizers, and improved soil fertility while also raising farm income (Sunendar et al 2025). This type of system treats rabbits as both an economic enterprise and a source of organic amendments and biostimulants for soil regeneration. Regenerative agriculture literature identifies the integration of livestock with cropping, reduced tillage, continuous soil cover, and high plant diversity as key levers to restore soil organic carbon (SOC), improve structure, and rebuild nutrient cycling on degraded land (Teague & Kreuter 2020; Khangura et al 2023; Prairie et al 2023). Rabbits can occupy a niche within this integrated crop-livestock framework, especially where their manure and manure-derived products are cycled back into rotational crops.

Role of rabbit manure within integrated crop-livestock systems. Although most integrated crop-livestock (ICL) research focuses on ruminants, the core mechanisms by which animal enterprises regenerate soil are general: animals convert aboveground biomass into organic residues and excreta that feed soil biota, increase SOC, and enhance nutrient cycling (de Faccio Carvalho et al 2018; Teague & Kreuter 2020; Prairie et al 2023). Rabbit systems add value by producing a manure that is rich in nitrogen and phosphorus, relatively dry and easy to handle, and suitable for direct field application, composting, or transformation into biochar and liquid fertilizers (Cárdenas-Aguiar et al 2022; Zhang et al 2023; Wysokinski & Kożuchowska 2024). In pot experiments, rabbit manure fertilizer increased soil total N, total P, organic carbon, pH and electrical conductivity, while enhancing bacterial diversity and abundance compared with mineral fertilization alone (Zhang et al 2023). These changes in soil chemistry and microbiology are fundamental to reversing degradation, because they rebuild soil organic matter and microbial networks that underpin nutrient retention, aggregation, and resilience (Du et al 2020; Liu et al 2020; Jia et al 2022; Zhang et al 2023).

Field work with rabbit manure combined with mineral nitrogen in silage maize showed that increasing manure rates from 20 to 60 $t \cdot ha^{-1}$, together with moderate mineral N, significantly increased dry matter yields and nitrogen uptake; the combination of 60 $t \cdot ha^{-1}$ manure with 100 $kg \cdot ha^{-1}$ N was most productive, while 20 $t \cdot ha^{-1}$ manure with 150 kg·ha^{-1} N maximized nitrogen use efficiency (Wysokinski & Kożuchowska 2024). This illustrates how rabbit-based systems can deliver both high biomass production and improved nutrient use efficiency, essential criteria for regenerating degraded soils without exacerbating nutrient losses. At the same time, global syntheses of manure use show that organic amendments sharply increase microbial C and N pools (≈+88% and +84%) and enzyme activities related to C, N, P and S cycling (1.3-3.3-fold), while building SOC and total N over time (Du et al 2020; Liu et al 2020). Rabbit manure behaves as part of this broader class of organic inputs that accelerate biological activity and rebuild fertility on depleted soils.

Transforming rabbit wastes into soil-regenerating inputs. For degraded soils, the form in which rabbit wastes are returned to land is critical. Beyond raw manure, rabbit manure-derived biochar and mixed amendments can be powerful tools in reclamation contexts. In mining tailings in Spain, application of rabbit manure and rabbit-manure biochars at 10% (w/w) greatly increased soil microbial biomass and the geometric mean of key enzyme activities (dehydrogenase, β-glucosidase, phosphomonoesterase), with GMea rising 217-360-fold under pure manure and 81-270-fold under mixtures with low-temperature biochar (Cárdenas-Aguiar et al 2022). These shifts show a dramatic reactivation of microbial communities in extremely degraded substrates, demonstrating that rabbit-based products can jump-start soil biological functioning and carbon sequestration. Low-temperature biochar in particular may support longer-term SOC stabilization while still allowing high microbial activity (Cárdenas-Aguiar et al 2022), a combination that meta-analyses of regenerative practices identify as crucial for restoring both particulate and mineral-associated organic carbon pools (Prairie et al 2023).

When rabbit wastes are used as organic fertilizers in vegetable systems, they improve soil physicochemical properties and microbial communities across seasons. In *Brassica rapa* grown in pots, rabbit manure fertilizer increased soil total N, total P, organic C, pH and EC, reduced soil nitrate-N, and significantly increased bacterial diversity, with these microbial changes strongly correlated with N, P and C contents (Zhang et al 2023). Compared to chemical fertilizer, rabbit manure supported equal or higher yields in the second season, suggesting that its regenerative benefits accumulate as soil organic matter builds (Zhang et al 2023). These findings point to a strategy for degraded soils: use rabbit manure products not as one-off inputs but as recurring amendments within multi-year rotation schemes, so that microbial networks and SOC have time to recover.

Example of rabbit-manure impacts on soil and yield. Data are presented in Table 1.

Table 1

Soil and yield responses to rabbit-based amendments (Consensus 2025)

Parameter (relative to mineral fertiliser)	*Effect of rabbit manure or rabbit-based amendment*	*Citations*
Microbial enzyme activity (mining tailings)	GMea increased 81-360× with manure/biochar	Cárdenas-Aguiar et al (2022)
Soil total N, total P, organic C	Increased in vegetable soils with rabbit manure	Zhang et al (2023)
Bacterial diversity and abundance	Significantly increased under rabbit manure	Zhang et al (2023)
Crop yield (2nd season vegetables or maize)	Equal or higher yields vs. mineral NPK; higher N uptake and NUE in maize	Zhang et al (2023); Wysokinski & Kożuchowska (2024)

Integration into crop rotations for soil regeneration. Regenerative agriculture emphasizes diverse rotations, continuous soil cover, and integrated livestock as combined levers to rebuild SOC and soil function on degraded cropland (Teague & Kreuter 2020;

Mosier et al 2021; Khangura et al 2023; Prairie et al 2023). Meta-analysis of regenerative practices shows that no-till and cropping system intensification increase SOC in the top 0-20 cm by about 11-12%, and that integrated crop-livestock systems synergize with these practices: no-till plus integrated livestock raises particulate organic carbon by nearly 40%, and intensified rotations plus livestock increase mineral-associated organic carbon by 33-54% (Prairie et al 2023). Although these studies mainly involve grazing ruminants, the principle translates to rabbits in two main ways.

First, rabbits can be integrated as housed or semi-housed animals whose manure is collected and strategically applied within a planned crop rotation. In such systems, rabbit manure or manure-derived fertilizers are applied to specific phases of the rotation - such as cover crops, green manures, or high-biomass forage phases - that are designed to build organic matter. Evidence from paddy-upland rotations combined with pig manure shows that the combination of rotation and manure can enhance soil multifunctionality by over 200% and increase yields by more than 220%, largely through more complex and robust bacterial networks and improved C, N, and P cycling (Zhang et al 2025). Similar mechanisms are expected when rabbit manure is used within diversified rotations, particularly where water management and plant diversity support strong root growth and residue returns.

Second, rabbits can in some contexts function as grazers within cover-crop phases, analogous to ICL systems. Reviews of integrated crop-livestock highlight that grazing cover crops in rotation with cash crops can improve soil physical structure, enhance carbon inputs, and strengthen nutrient cycling, provided that grazing intensity is controlled to avoid overgrazing (de Faccio Carvalho et al 2018). For degraded soils, light to moderate grazing and high residual biomass are emphasized as ways to build soil cover, promote aggregation, and reduce erosion (de Faccio Carvalho et al 2018; Teague & Kreuter 2020). While the literature on rabbits as grazers is limited, the same design principles would apply: rotationally grazed forage strips within a crop rotation, combined with careful rest periods, could allow rabbits to contribute excreta directly in the field while maintaining protective ground cover and continuous roots.

Soil health mechanisms in degraded soils. Degraded soils are typically characterized by low SOC, weak aggregation, nutrient imbalances, and depleted microbial communities (Mosier et al 2021; Khangura et al 2023). Manure-based integration, including that derived from rabbit systems, addresses these constraints through several linked mechanisms. Meta-analyses across Chinese croplands show that manure application, compared with mineral fertilizers, increases yields on average by 7.6%, while improving pH, water-stable aggregation (+28.8%), SOC (+17.7%), total and available N and P, enzyme activities (urease, sucrase, catalase), and abundances of bacteria, fungi, and actinomycetes (Du et al 2020). Another global synthesis reports similar patterns: manure inputs strongly increase microbial C and N pools (~+80%), boost multiple enzyme activities 1.3-3.3-fold, and accelerate C and N cycling without disrupting overall soil C:N balance (Liu et al 2020). These changes reconstruct the biological engine of the soil, enabling faster recycling of organic residues, greater nutrient retention, and gradual rebuilding of structural stability.

Rabbit-based amendments act within this broader manure effect, with some specific advantages. Rabbit manure has been shown to markedly enhance enzyme activities and microbial biomass even in mine tailings, indicating high potential for restoring extremely degraded substrates (Cárdenas-Aguiar et al 2022). In vegetable systems, rabbit manure shifts microbial communities toward higher bacterial diversity, and the structure of bacterial communities is closely tied to total N, total P, organic C, and EC (Zhang et al 2023), suggesting that rabbit systems can help rebuild both chemical and biological soil quality indicators. Crop-livestock integration more generally has been found to improve soil health indices in sandy tropical soils, with integrated systems over time achieving soil health scores comparable to native vegetation in deeper layers (da Silva Vanolli et al 2025). This supports the expectation that rabbit-integrated rotations, especially on light or structurally degraded soils, can progressively restore function if maintained over multiple years.

Systems design and trade-offs in rabbit-crop integration. Designing rabbit-crop systems for soil regeneration involves balancing agronomic, environmental, and economic goals. The Indonesian case study on circular rabbit farming shows that integrating intensive rabbit production with household gardens and crop plots, guided by circular economy principles, yields an RC ratio greater than one, providing additional income while reducing waste disposal and synthetic fertilizer use (Sunendar et al 2025). At the same time, global analyses of manure use and microbial ecology caution that high manure loads restructure microbial communities, increasing bacterial diversity but sometimes reducing fungal diversity and potentially selecting for inhibitory taxa (Liu et al 2020; Guo et al 2022). This implies that manure rates and application frequencies should be tuned to local soil conditions and rotation design to avoid oversaturation, nutrient leaching, or undesirable shifts in soil biota.

Rotation design also modulates how effectively rabbit-derived nutrients are captured. Grassland-cropland rotation studies in mixed crop-livestock systems show that alternation of pastures and crops regulates microbial priming effects, organic matter composition, and abiotic properties in ways that influence carbon stabilization and nutrient cycling (Panettieri et al 2020). When rotations include high-rooting, high-residue crops or perennial phases, the combined effect of plant inputs and manure applications on SOC and soil structure is amplified (Mosier et al 2021; Prairie et al 2023; da Silva Vanolli et al 2025). Conversely, continuous annual cropping with heavy tillage may dissipate much of the benefit. Regenerative frameworks therefore recommend pairing rabbit manure use with reduced tillage, cover cropping, and perennial or forage phases, and, where feasible, with adaptive grazing management inspired by approaches like adaptive multi-paddock grazing, which emphasize short grazing periods, long recovery, and maintenance of high residual biomass (de Faccio Carvalho et al 2018; Teague 2018; Teague & Kreuter 2020).

Outlook and research needs. Evidence from rabbit-focused studies, broader manure meta-analyses, and integrated crop-livestock research converges on the conclusion that rabbit farming systems, when deliberately embedded into diversified crop rotations, can contribute meaningfully to the regeneration of degraded soils. They do so by supplying high-quality organic inputs, stimulating microbial and enzymatic activity, rebuilding SOC and nutrient stocks, and supporting improved yields and nutrient use efficiency. However, most soil-process data for rabbits come from pot experiments, specific field trials, or reclamation case studies; long-term, systems-level trials explicitly comparing rabbit-integrated rotations with conventional systems on degraded soils are still scarce. Regenerative agriculture reviews consistently call for such rigorous, region-specific comparisons to quantify benefits, trade-offs, and scalability (Teague & Kreuter 2020; Mosier et al 2021; Khangura et al 2023). For practitioners and researchers, promising directions include evaluating rabbit systems within no-till, cover-cropped rotations; testing combinations of raw manure, compost, and low-temperature rabbit-manure biochar; and monitoring soil health, ecosystem multifunctionality, and farm profitability over multiple rotation cycles.

Rabbit population density, soil biodiversity and enzyme activity: a synthesis focused on animal management and soil biological health. Rabbit populations act on soils through grazing, trampling, burrowing and concentrated deposition of feces and urine. These processes create spatially heterogeneous "microsites" that alter soil microbial communities, enzyme activities and soil animal habitats. Evidence on explicit rabbit density gradients is still limited, but several studies examining rabbit presence/absence, rabbit-induced microsites, and broader grazing intensity allow inferences on how increasing rabbit pressure shapes soil biodiversity and soil biochemical functioning.

Rabbits as soil disturbers and ecosystem engineers. Rabbits are classic "ecosystem engineers", modifying soil structure and resource distribution through digging (bioturbation) and biodeposition of excreta. In arid woodland in Australia, soils were compared among echidna foraging pits, rabbit foraging pits, and surface and subsoil microsites along a gradient of grazing-induced disturbance dominated by livestock and rabbits (Eldridge et al 2016). Bacterial community composition differed far more among microsites than along the broader grazing gradient: echidna pits, rabbit pits, and surface soils each harbored distinct microbial assemblages, with echidna pits enriched in Proteobacteria and depleted in Acidobacteria and Cyanobacteria compared with rabbit pits and surface soils (Eldridge et al 2016). Functional consequences mirrored these compositional patterns. Mean concentrations of multiple soil enzymes (a composite index of function) were highest in echidna pits and lowest in rabbit pits, indicating that the type of soil-disturbing mammal strongly influences the functional quality of microbial communities (Eldridge et al 2016). Rabbit-disturbed microsites did not enhance enzyme-based soil function relative to surrounding surface soils under moderate and high grazing disturbance, suggesting that at prevailing densities in this system, rabbit activity contributed little to soil functional recovery and may even dilute positive engineer effects.

In temperate grassland, a long-term experiment manipulating rabbit and invertebrate grazers showed that the presence of rabbits altered soil microbial community structure and functional gene profiles, but the magnitude of effects was smaller and more idiosyncratic than those of invertebrate grazing (Macdonald et al 2015). Exclusion of invertebrates clearly reduced microbial biomass and genes associated with key biogeochemical cycles, whereas treatments with rabbit grazing alone did not consistently change total phospholipid fatty acid (PLFA) biomass, likely because rabbit feces and urine create highly patchy nutrient hotspots (Macdonald et al 2015). These results indicate that increases in rabbit density primarily increase the intensity and spatial frequency of such patches, but their net effect on belowground functioning is variable and context dependent.

Rabbit density, soil health and disturbance gradients. Large-scale assessments of herbivore intensity across landscapes help frame how rabbit density fits into broader grazing effects. In eastern Australia, a survey of 451 sites along a semi-arid productivity gradient quantified recent herbivore activity using dung (including rabbit dung) and tracks, and related it to composite indices of soil stability, nutrient cycling and water infiltration (Eldridge et al 2017). Herbivore intensity had generally negative effects on all three soil health indices, strongest under low-productivity conditions; herbivore-specific analyses showed that most of the degradation signal was attributable to cattle, with weaker but detectable contributions from sheep, goats and rabbits (Eldridge et al 2017). While this study does not isolate rabbit density alone, it demonstrates that where rabbits are part of a high overall grazing pressure, increasing dung indicators of their activity aligns with declines in soil health, particularly in resource-poor soils. Mechanistically, such declines are associated with reduced aggregate stability, lower nutrient indices, and impaired infiltration (Eldridge et al 2017), all of which are underpinned by changes in microbial biomass, diversity and enzyme activity documented in other grazing studies (Meena & Rao 2021; Bansal et al 2024; Sun et al 2025).

Meta-analyses of grazing in Chinese grasslands further clarify how grazing intensity and duration influence the link between soil microbial diversity and ecosystem multifunctionality (EMF) (Yao et al 2023). Across 62 sites, EMF declined with increasing grazing intensity and duration; relationships between bacterial or fungal diversity and EMF shifted with grazing level, but the overall trend was that heavier, longer grazing compromised multifunctionality (Yao et al 2023). Although rabbit-specific contributions are not dissected, these findings imply that high rabbit densities, when adding to total grazing pressure, are likely to drive soil systems toward lower EMF, especially where plant cover and litter inputs are reduced.

Effects of rabbit-induced nutrient hotspots on soil microbial diversity. At finer scales, rabbit latrines and burrow systems profoundly modify soil nutrient status and selected components of edaphic biodiversity. In semi-arid Spain, rabbit faecal latrines occupied only ~0.1% of the ground surface but had much higher organic carbon, ammonium, nitrate, potassium, phosphorus and magnesium than adjacent soils, and strongly enhanced barley biomass in bioassays (Willott et al 2000). These nutrient-rich patches can act as local "fertility islands" that support distinct microbial communities and potentially elevated enzyme activities, mirroring the microsite effects seen in engineered pits (Eldridge et al 2016). Where rabbit densities are moderate, a mosaic of latrines and undisturbed soil likely increases spatial β-diversity of microbes and root-associated organisms by creating strong resource gradients.

However, high densities and large latrines can also disrupt key symbiotic components of soil biodiversity. In the alpine ecosystem of Teide National Park, soils influenced by large rabbit dropping aggregations around the endemic legume *Spartocytisus supranubius* showed altered rhizobial abundance and diversity compared with non-latrine soils (Pulido-Suárez et al 2021). While rhizobia in undisturbed rhizospheres were dominated by *Bradyrhizobium canariense*/*B. lupini* lineages, latrine-affected soils harbored additional *Bradyrhizobium rifense*/*B. cytisi* and frequent cohabitation by non-nodulating *Bosea* strains in nodules (Pulido-Suárez et al 2021). These compositional shifts suggest that intense rabbit activity can interfere with the legume-rhizobia symbiosis that provides the principal nitrogen input in this ecosystem, potentially impairing biological N fixation even as total soil N near latrines increases. This illustrates a key density effect: beyond some threshold, rabbit-generated nutrient enrichment and physical disturbance can erode specialized, functionally crucial components of belowground biodiversity.

Other work in the same insular alpine system shows that high rabbit pressure alters soil chemistry and plant community dominance. Plots exposed to rabbits exhibited reduced soil nitrogen and a shift from the legume *S. supranubius* to *Pterocephalus lasiospermus* as the dominant shrub; modeling suggested that rabbit densities should be kept below 0.5 rabbits ha^{-1} to protect endemic flora (Cubas et al 2018). Because soil microbial communities are tightly linked to vegetation composition and litter inputs, such density-driven shifts in plant dominance inevitably cascade to microbial assemblages, decomposer food webs and enzyme activities.

Soil enzyme responses to rabbit activity and grazing density*.* Direct measurements of enzyme activity under rabbit influence are rare but informative when combined with broader grazing and organic amendment studies. In the arid woodland study comparing echidna and rabbit foraging pits, mean enzyme concentrations (aggregating several C-, N- and P-cycling enzymes) were lowest in rabbit pits and highest in echidna pits; microsite differences varied with the broader grazing disturbance level, but across the gradient rabbits contributed little positive effect to enzyme-based soil function (Eldridge et al 2016). This suggests that at the densities present, rabbit-created pits did not act as strong hotspots of biochemical activity, perhaps because they were shallower, less organic-rich, or more exposed than echidna pits.

By contrast, where rabbit-derived organic matter is added deliberately as manure or biochar, soil enzyme activities can increase dramatically. In severely degraded mine tailings ameliorated with rabbit manure and rabbit-manure biochars at 10% (w/w), dehydrogenase, β-glucosidase and phosphomonoesterase activities, combined into a geometric mean enzyme activity (GMea) index, rose 217-360-fold with manure and 81-270-fold with low-temperature (300°C) biochar-manure mixtures (Cárdenas-Aguiar et al 2022). Microbial biomass also increased substantially (Cárdenas-Aguiar et al 2022). Although this study focuses on amendment rather than free-ranging density, it demonstrates that rabbit-derived inputs, if managed and distributed, can powerfully stimulate soil enzymatic machinery; unmanaged high densities that concentrate excreta in few locations may fail to realize these benefits at the field scale.

Grazing-density experiments with livestock provide parallel insights into how increasing animal pressure modulates enzyme activity and microbial community structure. In a mixed-grass prairie with over seven years of low, medium and high stocking densities, urease, β-glucosidase and alkaline phosphatase activities responded nonlinearly to stocking rate and landscape position (Bansal et al 2024). Low grazing density increased β-glucosidase by 75% relative to high density, and alkaline phosphatase was 60% greater at footslope than summit positions, reflecting interactions between trampling, moisture and nutrient redistribution (Bansal et al 2024). High grazing density at summits reduced total PLFA and increased microbial stress indicators (Bansal et al 2024). Translating this to rabbits suggests that low to moderate rabbit densities, especially in topographically favorable positions, are more compatible with high enzyme activities and low microbial stress, whereas high densities, particularly on vulnerable positions, risk suppressing microbial biomass and functional capacity.

Soil biodiversity, enzymes and ecosystem multifunctionality. The functional significance of changes in microbial diversity and enzyme activity induced by rabbit density can be evaluated in light of work linking soil biodiversity to multifunctionality. Long-term fertilization experiments in cropland show that increased microbial diversity, especially of bacteria and fungi, is associated with higher activities of C-, N-, P- and S-cycle enzymes and higher EMF, independent of soil physicochemical drivers (Luo et al 2018). Microcosm experiments that experimentally simplified soil communities (reducing bacterial richness by ~46% and eukaryote richness by ~83%) demonstrated strong declines in multifunctionality, particularly in plant productivity and nutrient retention; mineral fertilization could not compensate for biodiversity loss (Romero et al 2023). These findings imply that any management or grazing regime - including rabbit stocking decisions - that erodes microbial richness or selectively suppresses key functional groups is likely to impair EMF, even if nutrient inputs from excreta rise.

Meta-analyses of grazing in grasslands confirm that EMF generally declines with increasing grazing intensity and duration, and that bacterial and fungal diversity mediate these effects (Yao et al 2023). In some cases, higher bacterial diversity under moderate grazing correlated negatively with EMF, while fungal diversity under heavy grazing correlated positively, underscoring that not all increases in diversity are beneficial and that shifts in community composition and keystone taxa matter (Yang et al 2021; Yao et al 2023). For rabbit management, this nuanced picture suggests that density targets should aim not merely to maximize microbial diversity but to maintain community structures that support high EMF, including respiration, nutrient cycling and structural maintenance.

Management implications: linking rabbit density to soil biological health. Taken together, the literature points to several qualitative relationships between rabbit population density, soil biodiversity and enzyme-mediated soil function.

At low to moderate densities, rabbits act as one of several herbivores contributing to a heterogeneous mosaic of disturbance and nutrient inputs. Their latrines and burrows can create localized fertility islands with higher nutrients and distinct microbial assemblages, potentially increasing spatial β-diversity and supporting enzyme hotspots without strongly degrading aggregate soil health (Macdonald et al 2015; Eldridge et al 2016; Willott et al 2000). In such regimes, overall soil microbial diversity and EMF are more strongly governed by vegetation, climate and broader management (e.g. livestock density, tillage, organic amendments) than by rabbits alone (Eldridge et al 2016, 2017; Yao et al 2023).

As density increases, especially in low-productivity or fragile environments, cumulative grazing, trampling and concentrated excreta lead to declines in soil health indices, shifts in plant composition, and disruption of specialized microbial symbioses. Case studies in Tenerife document that elevated rabbit densities alter soil N, depress populations of a key N-fixing legume, and modify rhizobial community structure in ways likely to impair biological N fixation (Cubas et al 2018; Pulido-Suárez et al 2021). Large-scale surveys show that higher dung-based indicators of herbivore activity, including rabbits, are associated with lower soil stability, nutrient cycling capacity and infiltration, particularly in resource-poor sites (Eldridge et al 2017). In such contexts, microbial biomass declines, stress indicators rise, and enzyme activities important for C and nutrient cycling tend to be reduced or spatially restricted to a few hotspots (Eldridge et al 2016, 2017; Bansal et al 2024).

Conversely, when rabbit-derived organic matter is harnessed through controlled collection and application (as manure or biochar), it can substantially enhance microbial biomass, diversity and enzyme activities even in severely degraded substrates (Cárdenas-Aguiar et al 2022). This contrast highlights a central management lever: not only how many rabbits, but where and how their biomass and wastes are distributed. Controlled or lower-density populations that allow manure to be recovered and redistributed across fields are more likely to support high soil biodiversity and enzymatic function than overabundant, free-ranging populations that concentrate impacts and drive vegetation and microbial simplification.

Overall, the available evidence indicates that rabbit management is tightly linked to soil biological health. Maintaining rabbit populations at densities that avoid chronic overgrazing, protecting sensitive vegetation and symbiotic microbial guilds, and, where appropriate, integrating rabbit-derived amendments into soil management can help align wildlife or livestock objectives with the conservation and enhancement of soil biodiversity and enzyme-driven ecosystem functions.

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

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