Relationships between Soil Microbial Community Structure and Changes in Soil Nutrients

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Abstract: Soil microbial communities participate in organic-matter decomposition, nitrogen transformation, and phosphorus mobilization. Their structure is influenced by soil organic carbon, nitrogen and phosphorus contents, pH, and plant-root exudates. This paper analyzes changes in bacterial, fungal, and archaeal communities under different nutrient conditions and discusses the bidirectional relationships among microbial diversity, functional guilds, and soil nutrient availability. The analysis indicates that greater nutrient availability does not necessarily increase microbial diversity. Community stability and nutrient-cycling functions can be maintained only through appropriate regulation of carbon, nitrogen, and phosphorus ratios and soil pH.

Keywords: soil microorganisms; community structure; soil nutrients; nutrient cycling; soil fertility

Introduction

Soil nutrient content and availability directly affect plant growth and ecosystem productivity. Organic carbon is both an important component of soil fertility and the principal energy source for most heterotrophic microorganisms. Elements such as nitrogen and phosphorus must undergo microbially mediated decomposition, mineralization, immobilization, or solubilization before they can cycle continuously between soil and plants. Bacteria, fungi, and archaea are abundant and metabolically diverse and participate in processes including cellulose decomposition, humus formation, nitrification, denitrification, nitrogen fixation, and phosphorus mobilization.

Changes in soil nutrients redistribute the resources available to microorganisms and alter competitive relationships among different microbial groups. Long-term nitrogen fertilization may cause soil acidification and indirectly modify bacterial community composition. Inputs of fresh organic matter can increase the activity of certain heterotrophic microorganisms but may also accelerate the decomposition of existing soil organic carbon. Once the microbial community changes, the types of enzymes it secretes, its capacity to utilize substrates, and the rates of nutrient transformation also change. Soil nutrients and microbial communities consequently form a bidirectional relationship.

Existing studies frequently explain differences in microbial communities in terms of nutrient concentrations or use microbial diversity to predict soil functions. However, the relationship between these factors is also affected by pH, moisture, temperature, vegetation, and management practices. Distinguishing direct from indirect effects can prevent simple correlations from being interpreted as unidirectional causation and can provide a basis for improving cultivated-soil fertility and restoring degraded soils.

1. Foundations of Soil Microbial Communities and Nutrient Cycling

1.1 Composition of Soil Microbial Communities

Soil microbial communities principally consist of bacteria, fungi, archaea, and certain microscopic eukaryotes. Bacteria generally grow rapidly and respond sensitively to inputs of readily decomposable organic matter and nutrients. Some members of the phyla Proteobacteria and Bacteroidetes are adapted to resource-rich environments and are commonly classified as copiotrophic groups. Certain members of Acidobacteria grow relatively slowly and may have an advantage in nutrient-poor or strongly acidic soils.

Fungal hyphae can extend across soil pores to obtain resources and can decompose structurally complex organic compounds such as lignin and cellulose. Arbuscular mycorrhizal fungi form symbiotic relationships with plant roots, expand the effective absorptive area of the root system, and contribute to the acquisition of phosphorus, nitrogen, and water. Ammonia-oxidizing archaea participate in the oxidation of ammonium and can be well adapted to low ammonia concentrations and particular pH conditions.

Community structure encompasses not only the relative abundance of different taxonomic units but also species richness, evenness, dominant groups, and patterns of microbial co-occurrence. Two soil samples may contain similar total quantities of microorganisms while differing substantially in their dominant taxa and functional potential. Total microbial abundance alone therefore cannot fully characterize community status.

1.2 Principal Microbial Processes in Nutrient Cycling

After plant residues, animal remains, and organic fertilizers enter the soil, they are initially decomposed by extracellular enzymes secreted by microorganisms. Structurally complex macromolecules are converted into absorbable small molecules. Some of these compounds are used for microbial growth and respiration, while others are converted into inorganic nutrients that plants can absorb. After microorganisms die, their necromass can bind to soil minerals and become an important source of stable organic matter.

The nitrogen cycle includes nitrogen fixation, ammonification, nitrification, denitrification, and microbial immobilization. Different functional groups perform these processes, which are regulated by oxygen availability, moisture, carbon sources, and pH. The phosphorus cycle principally involves organic-phosphorus mineralization, inorganic-phosphorus solubilization, and microbial immobilization. Microorganisms can secrete phosphatases and organic acids to release a proportion of immobilized phosphorus. During growth, they also absorb inorganic phosphorus and form short-term biological nutrient stores.

Microbial activity can increase nutrient availability but may also cause nutrient loss. Denitrification converts nitrate nitrogen into gaseous products, thereby reducing the amount of nitrogen retained in soil. The direction of nutrient transformation depends on community structure, substrate conditions, and the soil environment. Increased microbial activity should therefore not be interpreted uniformly as an improvement in soil fertility.

2. Effects of Changes in Soil Nutrients on Microbial Communities

2.1 Organic-Carbon Supply and Changes in Community Composition

Soil organic carbon is the principal resource supporting the growth of heterotrophic microorganisms. Following inputs of straw, root exudates, and organic fertilizer, readily available compounds such as glucose, organic acids, and amino acids can rapidly increase microbial respiration and enzyme activity. Fast-growing bacteria generally use these substrates preferentially, and their relative abundance may increase over the short term. As readily decomposable carbon sources are gradually depleted, fungi and slow-growing bacteria capable of utilizing cellulose, lignin, and humic substances become increasingly important.

A high total organic-carbon content does not necessarily mean that carbon is continuously available to microorganisms. Some organic carbon is physically protected within soil aggregates or bound to clay minerals and is difficult for microorganisms to decompose over short periods. Studies should therefore distinguish among total organic carbon, dissolved organic carbon, and microbial biomass carbon. Dissolved organic carbon more directly represents the carbon sources recently available to microorganisms, whereas microbial biomass carbon characterizes the carbon temporarily retained in living microbial biomass.

Long-term application of materials with high carbon contents but low nitrogen contents can increase the soil carbon-to-nitrogen ratio. To synthesize cellular material, microorganisms may then absorb substantial quantities of inorganic nitrogen, causing short-term nitrogen deficiency in plants. Combining straw incorporation with an appropriate quantity of nitrogen fertilizer can mitigate carbon–nitrogen imbalance and maintain the simultaneous activity of decomposer and nutrient-transforming groups.

2.2 Nitrogen Inputs and Responses of Functional Groups

An appropriate nitrogen supply can alleviate nitrogen limitation in microorganisms and plants and increase microbial biomass and residue-decomposition capacity. Community responses change, however, when nitrogen inputs become excessive. A sustained increase in readily available inorganic nitrogen favors rapidly growing bacteria adapted to nutrient-rich conditions, whereas groups that depend on complex substrates or are adapted to nutrient-poor environments may decline. Nitrifiers, denitrifiers, and ammonifiers also differ in their responses to different nitrogen forms.

The long-term application of ammonium-based fertilizers produces an acidifying effect during nitrification. As soil pH decreases, some bacteria are inhibited, while acid-tolerant groups and certain fungi gain a relative advantage. The observed community changes therefore reflect both the direct effect of the nitrogen source and the indirect effect of altered pH. If an experiment measures only the amount of nitrogen applied and does not include pH data, it may overestimate the explanatory power of nitrogen itself.

Leff et al. conducted nitrogen- and phosphorus-addition experiments at 25 grassland sites worldwide. Although the initial community composition varied considerably among sites, relatively consistent changes occurred after nutrient addition: the relative abundance of copiotrophic bacteria increased, whereas that of certain oligotrophic bacteria, mycorrhizal fungi, and methanogenic archaea decreased [3].

2.3 Phosphorus Levels and pH Regulation

Phosphorus is an important component of microbial nucleic acids, cellular membranes, and compounds involved in energy metabolism. In phosphorus-deficient soils, phosphate-solubilizing bacteria, phosphatase-producing microorganisms, and mycorrhizal fungi contribute substantially to plant nutrient acquisition. Phosphorus application can reduce microbial dependence on poorly available phosphorus sources, potentially decreasing the relative advantage of certain phosphorus-solubilizing functional groups. Phosphorus inputs may also indirectly alter rhizosphere microbial resources by increasing plant biomass and the quantity of root exudates.

Soil pH is an important control on changes in community structure. It affects proton balance across cellular membranes, enzyme activity, metal-ion solubility, and the availability of carbon, nitrogen, and phosphorus. Fierer and Jackson analyzed 98 soil samples from North and South America and found strong relationships between soil pH and bacterial diversity and richness. pH explained 70% and 58% of the variation in these two measures, respectively. Bacterial diversity was higher in neutral soils and lower in strongly acidic soils [1].

Lauber et al. subsequently analyzed 88 soils from North and South America, obtaining an average of 1,501 sequences per soil sample. Differences in soil pH and bacterial community composition had a correlation coefficient of 0.79, and pronounced changes were observed in the relative abundances of Acidobacteria, Actinobacteria, and Bacteroidetes [2].

3. Regulation of Soil Nutrients by Microbial Communities

3.1 Organic-Matter Decomposition and Carbon Transformation

Microbial communities decompose plant residues by secreting extracellular enzymes such as cellulases, xylanases, glucosidases, and oxidases. Bacteria participate extensively in the utilization of readily decomposable organic matter, whereas fungi have advantages in the decomposition of cellulose, lignin, and other complex compounds. Changes in community composition therefore alter both the rate of soil organic-matter decomposition and the composition of its products.

When microorganisms utilize organic carbon, part of the carbon is converted into carbon dioxide, while another part is used to synthesize cellular material. After microbial death, microbial necromass can bind to clay minerals and metal oxides, forming relatively stable organic carbon. High microbial activity may therefore accelerate organic-carbon loss but may also increase stable carbon storage through necromass formation. The final outcome is affected by substrate quality, soil texture, and hydrothermal conditions.

Inputs of fresh organic matter may also alter the decomposition of pre-existing soil organic matter. After acquiring readily available carbon sources, microorganisms may increase their capacity to decompose native organic matter. If the increase in newly incorporated organic carbon is smaller than the quantity of native carbon decomposed, soil organic-carbon stocks may not increase concurrently. The effects of organic fertilizer and straw incorporation should therefore be evaluated through long-term field observations.

3.2 Nitrogen and Phosphorus Mobilization and Nutrient Availability

Nitrogen-fixing microorganisms convert atmospheric nitrogen into forms that can enter biological cycles. Ammonifying microorganisms decompose nitrogen-containing organic matter and release ammonium nitrogen. Ammonia-oxidizing archaea, ammonia-oxidizing bacteria, and nitrite-oxidizing bacteria jointly participate in nitrification. Under hypoxic conditions with available carbon sources, denitrifying groups convert nitrate nitrogen into gaseous nitrogen products, thereby affecting both soil nitrogen retention and greenhouse-gas emissions.

Microorganisms can secrete organic acids that reduce pH in localized rhizosphere zones and can release sparingly soluble phosphorus through complexation, ion exchange, and related processes. Phosphatases decompose certain organic-phosphorus compounds and increase the supply of inorganic phosphorus. Mycorrhizal fungal hyphae extend farther than root hairs and can absorb phosphorus from soil pores that roots cannot readily access, exchanging the acquired nutrients for carbon supplied by the host plant.

Microorganisms also absorb inorganic nitrogen and phosphorus, resulting in short-term nutrient immobilization. This process can reduce nutrient leaching but may create temporary competition with plants. As microbial turnover accelerates, nutrients immobilized in microbial cells are released again. Nutrient availability must therefore be evaluated in relation to both plant requirements and microbial turnover.

4. Mechanisms Linking Microbial Communities and Nutrient Changes

4.1 Interactions between Plant Roots and Microorganisms

Plants secrete sugars, organic acids, amino acids, and secondary metabolites through their roots, thereby providing carbon sources for rhizosphere microorganisms. The composition of these exudates differs among plant species and developmental stages, and the rhizosphere community changes accordingly. Microorganisms can produce plant-growth-regulating compounds, mobilize nutrients, or suppress pathogens, thereby affecting plant growth and carbon inputs from roots.

Plant uptake of nitrogen and phosphorus reduces the nutrients available in the rhizosphere, whereas litter deposition and root death replenish organic matter. Microbial communities, plant growth, and soil nutrients thus form a continuous network of interactions. Vegetation removal, changes in crop species, and long-term continuous cropping can all reorganize microbial communities by altering root-derived resources.

4.2 Joint Effects of Soil Environmental Factors

Soil moisture controls substrate diffusion, microbial movement, and soil aeration. Drought restricts the transport of dissolved nutrients and may increase the relative abundance of certain drought-tolerant bacteria and fungi. When soil becomes excessively wet, oxygen diffusion is impeded, anaerobic microbial activity increases, and denitrification and methanogenesis may accelerate. Higher temperatures generally increase enzymatic-reaction rates, but long-term warming can also alter substrate availability and the adaptive state of microbial communities.

Soil texture affects pore structure, water-holding capacity, and organic-matter protection. Clay-rich soils can adsorb organic compounds and create microsites that provide microbial habitats. Sandy soils are generally well aerated but have a comparatively limited capacity to retain nutrients. Because pH, moisture, and texture jointly affect nutrient availability, microbial-community patterns should not be interpreted using only a single nutrient indicator.

Delgado-Baquerizo et al. used two datasets comprising 78 dryland ecosystems worldwide and 179 sites in Scotland and identified a positive relationship between microbial diversity and soil multifunctionality. The multifunctionality measure included multiple ecological processes associated with carbon, nitrogen, and phosphorus cycling [4].

4.3 Regulatory Effects of Agricultural Management Practices

Long-term application of chemical fertilizers alone can rapidly replenish mineral nutrients, but excessive application may cause soil acidification, salt accumulation, and nutrient-ratio imbalances, thereby reducing the habitat suitability of certain microbial groups. Organic fertilizer increases organic carbon and supplies multiple nutrients and is generally beneficial to microbial biomass. However, insufficiently decomposed organic materials may introduce pathogens or cause short-term oxygen depletion. Feedstock quality and application rates should therefore be controlled.

Straw incorporation changes the supply of soil carbon and substantially affects decomposer bacteria and fungal communities. No-tillage and reduced-tillage practices decrease soil disturbance and contribute to the preservation of fungal hyphal networks and surface-soil organic matter. Crop rotation alters the types of root exudates and plant residues entering the soil and can alleviate the community homogenization caused by long-term continuous cropping. Irrigation and drainage affect nitrogen transformations by regulating soil moisture and oxygen availability.

The effects of management practices vary over time. Short-term fertilization may increase microbial activity, whereas long-term community changes are additionally influenced by soil acidification, organic-matter accumulation, and crop selection. Long-term field experiments are more appropriate than single-season surveys for determining relationships between community changes and nutrient dynamics.

Table 1. Relationships between Soil Microbial Communities and Nutrient Environments in Representative Studies

Study scope	Sample or site scale	Principal environmental factor	Main conclusion
Multiple soil types across North and South America	98 soil samples	Soil pH	pH explained 70% and 58% of the variation in bacterial diversity and richness, respectively; diversity was higher in neutral soils

Study scope	Sample or site scale	Principal environmental factor	Main conclusion
Continental-scale survey across North and South America	88 soil samples, with an average of 1,501 sequences per sample	Soil pH	The correlation coefficient between differences in pH and differences in community composition was 0.79
Global grassland nutrient-addition experiment	25 grassland sites	Nitrogen and phosphorus inputs	Copiotrophic bacteria increased, whereas certain oligotrophic bacteria, mycorrhizal fungi, and methanogenic archaea decreased
Global dryland and Scottish soil surveys	78 dryland ecosystems and 179 sites	Microbial diversity and carbon, nitrogen, and phosphorus cycling	Microbial diversity was positively associated with soil multifunctionality

Note: The data in the table were compiled from References [1]–[4]. Because these studies differed in sequencing methods, soil types, and statistical scales, their numerical results should not be compared directly.

5. Research Methods and Applications in Soil-Fertility Improvement

5.1 Integrated Multi-Indicator Analysis

Amplicon sequencing can be used to analyze the taxonomic composition of bacterial, fungal, and archaeal communities, while metagenomic sequencing can further identify functional genes. Microbial biomass carbon and nitrogen, soil respiration, and enzyme activities reflect the current activity of microbial communities. The presence of a gene alone does not demonstrate that its associated function is being expressed. Genetic information must therefore be integrated with nutrient concentrations, transformation rates, and gaseous-emission data.

Soil nutrient measurements should include organic carbon, total nitrogen, total phosphorus, ammonium nitrogen, nitrate nitrogen, and available phosphorus. Soil pH, moisture, temperature, texture, and organic-matter fractions should be determined simultaneously. Sampling should be standardized for soil depth and season, and rhizosphere and bulk soils should be processed separately. Spatial surveys are suitable for identifying correlations, whereas controlled experiments and long-term field trials are more appropriate for determining the direction of effects.

Statistical analyses should avoid interpreting shared responses to environmental conditions as direct relationships. For example, changes in a bacterial community after nitrogen application may result primarily from soil acidification rather than from nitrogen content itself. Factorial experiments, pH correction, and repeated observations can help distinguish direct from indirect effects.

5.2 Nutrient Management through Microbial Regulation

Soil-fertility improvement should maintain appropriate ratios of carbon, nitrogen, and phosphorus to provide relatively stable resource conditions for different functional groups. The combined application of organic and chemical fertilizers can supply both readily available nutrients and organic carbon and reduce the nutrient imbalance caused by reliance on a single fertilizer type. In acidified soils, microbial habitats can be improved by controlling ammonium-nitrogen inputs, applying suitable soil amendments, and increasing soil organic matter.

The application of microbial inoculants must account for compatibility among the introduced strain, soil environment, crop roots, and indigenous microbial community. A strain that can solubilize phosphorus or fix nitrogen under laboratory conditions may not necessarily colonize soil reliably after field application. Soil pH, moisture, and nutrient limitations should be analyzed before application, and inoculant performance should be evaluated over successive growing seasons.

Management objectives should not focus exclusively on increasing numerical measures of microbial diversity. Soil fertility depends on cooperation among functional groups and the stability of nutrient transformations. Maintaining community structure through crop rotation, straw incorporation, reduced fertilizer application, and water management can improve nutrient-use efficiency and reduce nitrogen leaching and soil-degradation risks.

Conclusion

Soil microbial community structure and nutrient dynamics are linked through bidirectional regulation. Organic carbon determines the energy supply available to most heterotrophic microorganisms, nitrogen and phosphorus availability alters competition for resources among microbial groups, and pH reorganizes communities by affecting cellular physiology and nutrient availability. Microorganisms participate in organic-matter decomposition, humus formation, nitrogen fixation, nitrification, denitrification, and phosphorus mobilization. Changes in community structure consequently alter soil nutrient contents and rates of nutrient supply.

Increased nutrient availability does not necessarily result in simultaneous increases in microbial diversity and soil functioning. Long-term excessive nitrogen application may reduce the stability of certain microbial groups through soil acidification, while inputs of high-carbon, low-nitrogen materials may cause short-term nutrient immobilization. Reliable research requires the simultaneous determination of community composition, functional genes, microbial activity, soil nutrients, and environmental factors, together with long-term field experiments to establish the direction of effects. Appropriate combined application of organic and chemical fertilizers and optimization of crop rotation and straw incorporation can improve soil nutrient-use efficiency while maintaining microbial-community stability.

References

[1] Fierer, N., & Jackson, R. B. The diversity and biogeography of soil bacterial communities [J]. Proceedings of the National Academy of Sciences of the United States of America, 2006, 103(3), 626–631.

[2] Lauber, C. L., Hamady, M., Knight, R., et al. Pyrosequencing-based assessment of soil pH as a predictor of soil bacterial community structure at the continental scale [J]. Applied and Environmental Microbiology, 2009, 75(15), 5111–5120.

[3] Leff, J. W., Jones, S. E., Prober, S. M., et al. Consistent responses of soil microbial communities to elevated nutrient inputs in grasslands across the globe [J]. Proceedings of the National Academy of Sciences of the United States of America, 2015, 112(35), 10967–10972.

[4] Delgado-Baquerizo, M., Maestre, F. T., Reich, P. B., et al. Microbial diversity drives multifunctionality in terrestrial ecosystems [J]. Nature Communications, 2016, 7, 10541.