From Water Remediation to Metabolic Reconnection: A Soil-Microbe-Agricultural System Explanation of Eutrophication

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Abstract Eutrophication is commonly understood as the excessive enrichment of nitrogen and phosphorus in aquatic systems, leading to algal blooms, oxygen depletion, habitat degradation, and water-quality deterioration. This article argues that eutrophication should not be treated merely as an end-point water-body problem, but as the aquatic manifestation of terrestrial metabolic rupture. Nitrogen and phosphorus are not pollutants by nature; they become pollution pressure when displaced from proper soil-plant-microbe-agricultural pathways and accumulated in water beyond ecological accommodation capacity. The article reconstructs the causal framework of eutrophication by redefining soil richness as the dynamic capacity to retain, slowly release, transform, and cycle nutrients. It further identifies microorganisms as the operating layer of soil fertility, mediating nutrient transformation, rhizosphere interaction, organic-matter decomposition, and aggregate formation. Long-term dependence on fast-acting chemical fertilizers may weaken plant-microbe mutualism and increase external-input dependence, while intensive livestock farming and monocropping generate spatial mismatch through localized metabolic overload and ecological impoverishment. The article concludes that eutrophication governance should move beyond nutrient removal and end-point remediation toward nutrient re-accommodation and pathway reorganization. Restoring soil organic matter, microbial networks, crop-livestock nutrient closure, and land-water transition zones is essential for returning nitrogen and phosphorus to agroecological cycles.

Keywords Eutrophication; nutrient-pathway misplacement; soil health; soil microorganisms; nutrient cycling; chemical fertilizer; crop-livestock integration; agricultural spatial mismatch; non-point-source pollution; nutrient re-accommodation

1 Introduction: Eutrophication Is Not Merely a Water-Body Problem

1.1 From excessive nitrogen and phosphorus to nutrient-pathway misplacement

Eutrophication is usually first understood as a water-environment problem. Its direct manifestation is the excessive accumulation of nutrients, especially nitrogen and phosphorus, in water bodies [1]. Such enrichment may induce abnormal algal growth, reduced water transparency, intensified oxygen depletion, degradation of benthic habitats, and deterioration of aquatic ecosystem structure. In lakes, reservoirs,

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estuaries, and coastal waters, eutrophication may further appear as algal blooms, odor problems, fish mortality, declining ecosystem services, and increased risks for water-resource use. In this sense, identifying eutrophication as nutrient excess in water bodies is practically reasonable. Without monitoring nutrient loads, algal responses, dissolved oxygen dynamics, and water-quality deterioration, basic warning and management schemes cannot be established [1-2].

However, if analysis remains at the level of “excessive nitrogen and phosphorus in water,” eutrophication is easily compressed into an end-point pollution problem. The appearance of excessive nutrients in water only shows that nutrients have already reached the aquatic system and triggered responses beyond its carrying capacity [3-4]. It does not explain why these nutrients entered water bodies in forms that were highly concentrated, rapidly released, and difficult to accommodate. Nor does it explain why they were not retained by soil, absorbed by crops, transformed by microorganisms, or reorganized by regional agricultural systems before reaching water bodies. In other words, “excessive nitrogen and phosphorus in water” describes the visible result of eutrophication, but it does not yet reveal the deeper mechanism by which nutrients escape from their original agroecological pathways.

Eutrophication research therefore requires a shift in perspective: from asking “what excessive substances are present in the water” to asking “within which pathways should these substances originally have been located.” Nitrogen and phosphorus are not pollutants by nature. Within the soil-plant-microbe cycle, they are basic elements of soil fertility and plant growth. Within the rhythm of crop uptake, they are necessary conditions for agricultural production [5]. Within organic-matter decomposition, rhizosphere interaction, and microbial transformation, they are material foundations for the continued operation of biological systems. Only when nitrogen and phosphorus detach from appropriate temporal, spatial, chemical, and ecological accommodation relations-exceeding the retention capacity of soil, the uptake capacity of crops, the transformation capacity of microorganisms, and the carrying capacity of regional ecosystems-do they shift from biologically functional resources into pollution pressure [6-7].

From this perspective, the key to eutrophication is not that nutrients are inherently wrong, but that nutrient pathways have been misplaced. Nitrogen and phosphorus may function as fertility in land, as production support during crop uptake periods, and as transformation materials within microbial cycling [5]. Yet beyond the retention capacity of soil, they appear as losses; in drainage ditches and runoff systems, they appear as overflow; and when rapidly accumulated in lakes, rivers, and coastal waters, they appear as eutrophication pressure. The same substance therefore has different systemic identities in different pathways. Its ecological meaning is not determined by the element itself, but by its systemic position, flow velocity, accommodation capacity, and transformation mechanism [6].

Excessive nitrogen and phosphorus in aquatic systems can thus be understood as the visible result of nutrients displaced from terrestrial nutrient cycles. It is not an isolated aquatic anomaly. Rather, it indicates that upstream soil systems, agricultural inputs, crop uptake, microbial activity, livestock-waste management, and regional nutrient circulation may have become disconnected [8]. When nutrients that should have been retained by land are no longer retained, when nutrients that should have been absorbed by crops miss the uptake rhythm, when nutrients that should have been transformed by microorganisms lack effective biological pathways, and when organic residues that should have returned to agricultural systems instead enter water bodies or waste-treatment systems, eutrophication is no longer merely “over-fertilized water.” It becomes the concentrated aquatic manifestation of disorder in terrestrial nutrient pathways.

Accordingly, this paper does not define eutrophication only as the excessive accumulation of nutrients within water bodies. It treats eutrophication as a problem of nutrient position, flow pathway, and systemic accommodation capacity. Only by relocating nitrogen and phosphorus from the category of “pollutants” back into the framework of “nutrient pathways” can we understand why the same elements function as fertility in soil but become pollution in water, why agricultural systems continuously input nutrients while also managing nutrients at the water end, and why eutrophication governance that merely pursues lower water-quality indicators may neglect the upstream rupture of agroecological cycles. The starting point of this paper is therefore clear: the essence of eutrophication is not the error of nutrients themselves, but the misplacement, escape, and overflow of nutrients from their proper pathways.

1.2 Why water management must return to land

If eutrophication is the aquatic expression of misplaced nutrient pathways, management cannot remain inside the water body. In practice, source control, sewage interception, dredging, aeration, ecological floating beds, constructed wetlands, aquatic vegetation restoration, and emergency algal control all have practical necessity. They can reduce nutrient loads that have already entered, or are about to enter, water bodies; alleviate water-quality deterioration; lower bloom risks; and buy time for aquatic ecosystem recovery [3][9]. Yet these measures mainly address nutrient pressure after eutrophication has already become visible. If management does not further ask why nutrients left the land, why they were not used by crops, why they were not transformed by microorganisms, and why they were not accommodated by regional agricultural systems, it may become repeated repair of end-point symptoms.

The aquatic symptom of eutrophication often originates from upstream terrestrial dysfunction. Healthy soil is not an inert support medium. It is a living system with adsorption, retention, slow-release, transformation, filtration, and recirculation functions. Soil organic matter, aggregate structure, clay minerals, root networks, microbial communities, and soil water together constitute the interface through which nutrients are accommodated [10-11]. They determine whether nitrogen and phosphorus are temporarily stored, slowly released, transformed into plant-available forms, or rapidly transported into runoff and groundwater during rainfall, irrigation, and drainage [7][11]. Once soil organic matter declines, aggregate structure is damaged, microbial networks deteriorate, and rhizosphere interactions weaken, the land's capacity to retain and allocate nutrients declines. Nitrogen and phosphorus then enter rivers, lakes, and coastal waters more easily through surface runoff, leaching, agricultural drainage, and ditch systems [12].

Therefore, the claim that water management must return to land does not simply shift responsibility for water pollution onto agriculture, nor does it deny the value of aquatic remediation. Rather, it requires eutrophication governance to trace upstream into soil-fertility structure, crop uptake capacity, agricultural input patterns, livestock-waste pathways, and regional nutrient-cycling arrangements [12-13]. Aquatic management can answer how nutrients already present in water should be handled. Terrestrial restoration asks why nutrients have left their original agroecological cycle. Without answering the latter question, the former will recur: water bodies are cleaned and then eutrophicate again; algal blooms are controlled and then return; nutrient loads are reduced and then replenished by new upstream inputs .

From the perspective of land, eutrophication does not only mean that water bodies contain too many nutrients. It also means that terrestrial systems have failed to retain those nutrients in the right place. Soil should be a key interface through which nutrients enter biological and agricultural cycles. Fertilizers, crop residues, livestock manure, domestic organic waste, and other nutrient-containing materials could, after proper treatment, return to agricultural circulation through microbial transformation, crop uptake, and soil organic-matter accumulation. However, when soil is degraded, crop and livestock systems are separated, manure cannot safely return to land, fertilizer input is mismatched with crop uptake rhythms, and regional land carrying capacity is insufficient, land can no longer perform its nutrient-accommodation function [8]. Water bodies are then forced to become downstream containers of surplus nutrients, and eutrophication becomes the aquatic consequence of terrestrial dysfunction.

Furthermore, returning water management to land means deepening the management objective from “reducing nutrients entering water bodies” to “restoring the land's capacity to retain and transform nutrients.” If nutrients in water are merely intercepted, removed, deposited, or transferred, while soil organic matter, rhizosphere microorganisms, farmland cover, buffer zones, crop-livestock integration, and regional nutrient loops remain unrecovered, management only moves nutrients from one location to another. It does not solve systemic overflow. Effective eutrophication governance should restore the upstream land's capacity for absorption, retention, transformation, and slow release, so that nutrients no longer rush uncontrollably into water bodies but are more fully recycled within agricultural systems.

Thus, eutrophication governance must address both the aquatic manifestation and the terrestrial source structure. Aquatic remediation deals with already visible ecological pressure; terrestrial restoration deals with the structural conditions that continuously generate that pressure. The former is remedial and often urgent; the latter is foundational and preventive. Only when both are placed within the same systemic framework can water management move beyond end-of-pipe engineering and become part of the reconstruction of soil vitality, agricultural organization, and regional nutrient-cycling capacity.

1.3 Core argument: eutrophication as the aquatic manifestation of terrestrial metabolic rupture

Based on the preceding analysis, this paper advances a central argument: water-body eutrophication is the aquatic manifestation of terrestrial metabolic rupture. Terrestrial metabolic rupture refers to the disruption of material relations that could have formed a cycle among soil, plants, microorganisms, animals, human consumption, and the return of excreta and organic residues to land. Under industrialized agriculture, urbanized lifestyles, separation between crop and livestock systems, and waste-treatment regimes, these relations are often cut apart [13]. Nutrients such as nitrogen and phosphorus should circulate through crop growth, animal feeding, organic-residue treatment, soil microbial transformation, and soil-fertility restoration. Yet in modern production and consumption systems, they frequently become displaced from agricultural circulation and enter water bodies, the atmosphere, sewage-treatment systems, waste-disposal systems, and environmental management systems [8].

In this sense, eutrophication is not simply a matter of insufficient water self-purification capacity. Such capacity is certainly important. But if upstream agricultural and domestic systems continuously deliver nutrient loads beyond the carrying capacity of water bodies, neither natural self-purification nor internal water remediation can solve the problem at its root. Interpreting eutrophication as an internal aquatic problem easily obscures the external pressure continuously imposed by terrestrial systems. It also obscures the rupture among nutrient input, uptake, transformation, and return within agricultural systems [6][8]. A water body is not an isolated space that passively suffers eutrophication; it is the downstream display surface of regional nutrient-cycling imbalance.

At the same time, this paper avoids defining nitrogen and phosphorus as enemies. They are indispensable elements for plants, microorganisms, animals, and humans [5]. In the right pathways, they constitute soil fertility, crop yield, microbial metabolism, and ecosystem productivity. In the wrong position, they cause algal blooms, oxygen depletion, and ecological degradation. Therefore, eutrophication governance should not aim at “eliminating nutrients.” If governance begins by treating nitrogen and phosphorus as pure pollutants, it conceals a deeper question: why have elements needed by life not been re-accommodated by biological and agricultural systems, but instead been forced into water-remediation systems?

The methodology of this paper follows from this point. The fundamental task of eutrophication governance is not to make nitrogen and phosphorus disappear, but to allow them to re-enter biogeochemical and agroecological pathways in which they can be retained by soil, transformed by microorganisms, absorbed by plants, used by animals, and accommodated by agricultural systems. In other words, governance should not only pursue lower nutrient concentrations in water. It should also ask whether nutrients have been repositioned into appropriate places, whether they have entered stable soil-plant-microbe cycles, whether overflow risks have been reduced, and whether regional agricultural systems have gained stronger self-accommodation capacity. Within this framework, eutrophication governance is no longer end-point pollution control. It becomes a process of reconnecting metabolic relations among land, water, and agricultural systems [14].

This argument also means that eutrophication is inherently cross-systemic. It occurs in water but is formed among land, agriculture, microorganisms, and social consumption structures. It appears as water-quality deterioration but is rooted in nutrient-cycling rupture. It requires aquatic restoration technologies but cannot rely only on them. It requires source control, but more fundamentally it requires the reorganization of nutrient-accommodation pathways. Therefore, this paper analyzes soil fertility, microbial networks, the selective effects of chemical fertilizers, spatial mismatch between intensive livestock farming and monocropping, the real root causes of eutrophication, and the reorganization of nutrient pathways. It seeks to show that eutrophication is not an isolated water-pollution problem, but the aquatic expression of combined imbalance among agricultural, soil, and microbial systems.

The theoretical goal of this paper is not to propose a single aquatic restoration technology, but to reconstruct the causal framework of eutrophication. It argues that eutrophication governance must move from “removing nutrients” to “rebuilding nutrient pathways,” from “end-point water remediation” to “terrestrial metabolic reconnection,” and from “pollutant control” to “restoration of agroecological cycles.” Only when nitrogen and phosphorus are returned to the continuous relations among soil, plants, microorganisms, animals, and regional agricultural systems can eutrophication move from a repeatedly managed end-point problem into a key entry point for the reorganization of agroecological systems.

2 Redefining Soil Richness

If Chapter 1 reframes eutrophication from “excessive nitrogen and phosphorus in water” to “nutrient-pathway misplacement,” this chapter reconstructs the basic concept underlying that reframing: what soil richness truly means. Eutrophication can be understood as the aquatic manifestation of terrestrial metabolic rupture only if soil is not treated as a physical medium that temporarily stores nutrients, but as a living system capable of retaining, transforming, slowly releasing, and recycling nutrients [10-11]. Once soil loses this organizational capacity, nitrogen and phosphorus shift from fertility into loss, from resources into pollutants, and from internal variables of terrestrial circulation into external pressures for water remediation.

Accordingly, this chapter does not define soil fertility simply by the amount of certain elements. It redefines soil fertility as the soil's capacity to organize agroecological cycles. Soil richness does not mean that soil contains large stocks of nitrogen, phosphorus, potassium, or other nutrients. It means that these elements are embedded in ecological relations through which they can be stably retained, released at proper rhythms, biologically transformed, and continuously replenished. Without this redefinition, later discussions of microorganisms, fertilizer selection effects, spatial mismatch in industrial agriculture, and the root causes of eutrophication would lack a conceptual basis. Only when richness is understood not as stock but as cycling capacity can we explain why land with high nutrient content may still be poor, why heavy fertilization does not necessarily generate true fertility, and why nutrients that land cannot hold eventually appear as eutrophication in water bodies.

2.1 Element content is not equal to soil fertility

In conventional agricultural management and soil evaluation, indicators such as nitrogen, phosphorus, potassium, organic matter, pH, salinity, and trace elements are often used to assess soil conditions. These indicators are necessary. Without measuring basic nutrient content, acidity, alkalinity, and organic-matter level, it is difficult to identify nutrient deficiency, acidification, salinization, or fertility decline, and difficult to provide basic guidance for fertilization and crop production [5]. However, these indicators mainly answer what exists in soil and how much of it exists. They do not fully answer whether soil can provide nutrients continuously, whether nutrients can be used stably, or whether soil has the capacity for self-renewal.

If a soil contains relatively high levels of certain elements but cannot retain them, allowing them to enter runoff and groundwater during rainfall or irrigation, such element content does not constitute true fertility. It is closer to an unstable stock temporarily present in soil, always at risk of shifting from an agricultural production condition into an environmental load. Similarly, if certain elements are present in soil but are difficult for microorganisms to transform, difficult for roots to absorb, or difficult to integrate into crop growth rhythms, their presence is only formal. The fact that soil contains an element does not automatically mean that crops can continuously, stably, and appropriately use it [11].

Furthermore, if crops can maintain short-term supply only through external fast-acting fertilizers, while soil itself lacks the capacity for sustained release, gradual replenishment, and internal cycling, such soil cannot be considered genuinely healthy even if short-term yield is maintained. Its productivity does not arise from the soil's own biotic system, but from continuous external compensation for functional deficits [10]. At this point, soil gradually changes from a living interface that organizes material cycles into a passive production substrate receiving external inputs. On the surface, crops still grow, nutrients are still applied, and the agricultural system still operates. Systemically, however, the soil's own cycling, transformation, and regulation capacities have begun to decline.

This is the fundamental limitation of equating element content with soil fertility. Element content is a static indicator, whereas soil fertility is a dynamic capacity. Static indicators can show how much material exists in soil at a given moment, but they cannot fully explain whether those materials are stable, usable, adjustable, and renewable. Nitrogen, phosphorus, and potassium in soil do not function as isolated chemical stocks. They are embedded in networks of mineral particles, organic matter, aggregate structure, root exudates, microbial communities, and soil water [11]. Outside this network, elements may become external inputs that stimulate short-term crop growth, or environmental risks that rapidly leave the field after rainfall, rather than true soil fertility [7].

Therefore, soil richness cannot be judged only by whether elements exist or whether certain indicators meet short-term crop requirements. The key question is whether these elements can be organized by the soil system: whether they can be retained without easy loss, transformed into plant-available forms, matched with crop uptake rhythms, and replenished through organic residues, microbial activity, and agricultural cycling. Element content is only the surface indicator of soil richness. The decisive issue is whether soil can incorporate these elements into biogeochemical and agroecological cycles. If soil cannot organize elements into cycles, higher nutrient stocks may mean higher overflow risks [11]. If soil has strong cycling capacity, even moderate nutrient release may support a more stable, durable, and healthy productive foundation.

2.2 True richness means that soil can hold nutrients

After distinguishing element content from true fertility, the core criterion of soil richness becomes clearer: truly fertile soil must first be soil that can retain nutrients. Retention does not mean permanently sealing nutrients so that they cannot move, release, or be used by plants. It means that soil can use organic matter, clay minerals, aggregate structure, microbial binding substances, root networks, and water-regulation mechanisms to retain nutrients in zones that plant roots can gradually access, and release them at appropriate times, speeds, and forms [15-17]. The emphasis is on the soil's capacity to regulate nutrient movement, not on simple storage.

The soil's ability to retain nutrients depends on multiple structures acting together. Organic matter enhances adsorption, complexation, and buffering capacity, provides carbon sources for microbial activity, and improves soil structure. Clay and mineral surfaces influence nutrient retention through adsorption and exchange. Aggregate structure improves pore distribution and creates a relatively stable spatial environment for water, air, and roots. Microbial metabolites and fungal networks promote particle binding and structural stability. Plant roots and root exudates continually regulate the rhizosphere environment, guiding microbial activity and nutrient transformation [18]. Soil retains nutrients through the combined operation of these physical, chemical, and biological processes.

Thus, nutrient retention is not static storage but dynamic regulation. Soil must prevent nutrients from being lost too quickly, while also preventing them from becoming completely unavailable. It must supply nutrients during periods of strong crop demand, while reducing nutrient overflow during non-uptake periods. It must maintain nutrient availability, while avoiding short-term high concentrations that exceed crop and microbial accommodation capacity. Truly fertile soil is not a warehouse filled with nutrients. It is a living system that allocates nutrients according to water dynamics, root demand, microbial activity, and seasonal rhythms [18-19].

This point is crucial for understanding eutrophication. Nutrients that land cannot retain do not disappear. They move through rainfall, irrigation, surface runoff, field drainage, and groundwater leaching into ditches, rivers, lakes, and coastal waters [12]. Once large amounts of nitrogen and phosphorus leave soil, they no longer function as fertility in land but as eutrophication loads in water. The other side of “over-nourished water” is often “failed nutrient retention on land.” When nutrient concentrations rise in a regional water body, it usually indicates that upstream land has failed to keep nutrients in proper agroecological positions, or that agricultural systems have introduced nutrients beyond soil accommodation capacity in specific times, spaces, and forms.

From this perspective, richness that soil cannot retain is not true richness. It is potential loss and pollution risk [7]. If soil contains abundant fast-acting nutrients but lacks organic-matter support, aggregate protection, microbial transformation, and rhizosphere regulation, such richness is only short-term chemical fullness, not long-term ecological fertility. It may stimulate crop growth in the short term, but in the long term it may weaken soil structure, alter microbial communities, increase loss risk, and push nutrients that should remain in farmland systems into water systems. Under such conditions, what agriculture calls “high fertility” may become an upstream condition for eutrophication.

Therefore, the standard of soil richness must shift from “how many nutrients are present” to “whether nutrients can be retained, slowly released, and continuously supplied.” A truly fertile soil is not the soil with the highest short-term test values, but one that can sustain crop growth over time, reduce nutrient overflow, maintain microbial activity, preserve aggregate structure, and renew organic matter. Its richness is not a one-time stock but a continuous organizational capacity; not high-concentration accumulation but stable cycling ability; not a short-term push of nutrients toward crops or water bodies, but a regulated, accommodative, and renewable nutrient pathway among soil, microorganisms, and plants.

2.3 Retention, slow release, transformation, and cycling as the dynamic structure of soil fertility

After distinguishing element content from true fertility and identifying nutrient-retention capacity as a core standard, soil fertility can be further understood as a dynamic structure composed of retention, slow release, transformation, and cycling. True soil fertility is not a sum of separate indicators, but a set of continuous and mutually supportive processes. Retention prevents nutrients from being rapidly washed away. Slow release aligns nutrient availability with plant uptake rhythms. Transformation converts nutrients among different chemical and biological forms so that they can become plant-available [5]. Cycling determines how crop residues, livestock manure, organic matter, and microbial activity replenish the soil system [6][8]. Together, these processes determine whether nutrient stocks can become biological productivity.

Retention is the foundational link of soil fertility. Without retention, nutrients cannot form a stable reserve in soil. Even when nitrogen, phosphorus, potassium, and other elements are heavily applied, they may be rapidly lost during rainfall or irrigation [7][15]. Retention depends on soil organic matter, clay minerals, aggregate structure, root distribution, and microbial activity. It keeps nutrients within zones accessible to roots, transformable by microorganisms, and protected by soil structure. Soils with weak retention often require more frequent external fertilization to maintain short-term yields, while also becoming more likely sources of nutrient input to water bodies.

Slow release is the coordination mechanism between soil fertility and crop growth rhythms. Crop nutrient demand varies across growth stages, and nutrient release also unfolds through time [5]. If nutrients are released too quickly before crops can absorb them, they may enter water bodies or groundwater, causing waste and pollution. If they are released too slowly or remain unavailable, crops may suffer deficiency and growth limitation. Healthy soil must maintain a dynamic balance between these extremes, preventing nutrients from becoming sudden high-concentration overflow while also preventing them from becoming inaccessible dormant stocks. Slow-release capacity reflects the soil's ability to regulate time.

Transformation is the key link through which soil fertility moves from material existence to biological usability. Nutrients in soil are not all immediately absorbable by plants. Some are in organic forms, some in insoluble forms, some adsorbed by minerals, some bound to organic matter, and some require microbial decomposition, mineralization, phosphorus solubilization, nitrogen fixation, nitrification, denitrification, or other processes before becoming available. Without transformation, elements may exist but remain unusable [5][18]. If transformation is imbalanced, nutrient release may become too rapid, gaseous losses may increase, or waterborne overflow may intensify [19]. Therefore, soil fertility cannot be understood apart from microbial processes. Microorganisms are not auxiliary variables of soil fertility. They are the operational mechanism that converts elements from static stocks into biologically usable resources.

Cycling is the regenerative mechanism that sustains soil fertility over the long term. Any farmland system that only exports crops, animal products, and organic residues, without safely returning straw, root residues, livestock manure, compost, biogas slurry and residue, and other organic materials to land, will gradually weaken its own renewal capacity [6]. Cycling allows soil to function not merely as a container receiving chemical fertilizers, but as a system capable of maintaining fertility through organic-matter accumulation, microbial activity, and reuse of agricultural residues. Without cycling, soil becomes increasingly dependent on external inputs; the stronger this dependence becomes, the weaker the internal cycle may become, producing a pathway of more input, more dependence, and more dysfunction [8].

Retention, slow release, transformation, and cycling are not four isolated indicators. They are a continuous agroecological process. When retention is weak, nutrients enter water bodies more easily. When slow release is weak, nutrient release and crop uptake become mismatched. When transformation is weak, elements exist but are difficult to use. When cycling is weak, soil becomes dependent on external inputs and cannot renew itself. When these links deteriorate together, soil fertility declines from dynamic capacity into surface stock, and agricultural systems decline from life-cycling systems into externally input-driven systems. Eutrophication is one downstream consequence of these ruptures [4][7].

Thus, the essence of soil fertility is not element accumulation, but the dynamic structure of retention, slow release, transformation, and cycling. Soil richness means that soil can organize nitrogen, phosphorus, potassium, organic matter, water, microorganisms, and root activity into a continuously operating agroecological cycle, rather than merely displaying high chemical content at a given moment. The next chapter turns to microorganisms because they are the operational mechanism of this dynamic structure. Retention requires microorganisms to help form aggregates and stabilize organic matter; slow release requires microbial regulation of nutrient-release rhythms; transformation directly depends on microbial metabolism; and cycling depends on microbial decomposition and reorganization of organic residues. Only by entering the microbial level can we understand why soil can retain nutrients, why it may fail to retain them, and why eutrophication is not an isolated aquatic imbalance but the external manifestation of terrestrial cycling dysfunction.

3 Microorganisms as the Operating System of Soil Fertility

Chapter 2 has argued that true soil fertility is not the static accumulation of elements, but a dynamic capacity composed of retention, slow release, transformation, and cycling. This leads to a deeper question: who performs this dynamic capacity? If soil is not merely a container storing nitrogen, phosphorus, potassium, and other elements, then there must be an internal mechanism that organizes elements, regulates water, connects plants, decomposes organic matter, and maintains structural stability. This mechanism is neither a single chemical reaction nor the physical property of soil particles alone. It is a living network formed by plant roots, soil microorganisms, water, organic matter, and mineral particles [20].

Within this network, microorganisms occupy a position similar to an operating system. They are not merely accessory organisms in soil, nor background factors in organic-matter decomposition. They are the key mediators connecting elemental existence with biological use. Many nutrients already exist in soil, but whether they can be absorbed by plants, released according to crop growth rhythms, retained near roots rather than rapidly lost, and incorporated into long-term cycles through organic matter and aggregate structure depends heavily on microbial participation. Without microorganisms, elements may still exist, water may still flow, and plants may still root in soil, but the soil's capacity to function as an agroecological system declines significantly. In this sense, microorganisms are not decorative variables of soil fertility. They are the core execution layer through which soil fertility is transformed from static stock into dynamic operational capacity.

3.1 The plant-microbe-water interaction network

To understand soil fertility, it is first necessary to abandon the simple image of soil as a rooting medium for plants. Soil is not an inert background that passively supports roots, stores water, and dissolves fertilizers. It is an active interface composed of plants, microorganisms, water, organic matter, and mineral particles. Plants absorb water and nutrients through their roots, while continuously releasing sugars, organic acids, amino acids, phenolic compounds, and other carbon sources into the rhizosphere through root exudates [21]. These exudates are not meaningless metabolic residues. They are important media through which plants establish relations with microorganisms. They modify rhizosphere chemistry, attract or select specific microbial groups, regulate nutrient dissolution and release, and influence plant adaptation to external environments.

Microorganisms perform transformation, connection, and stabilization functions within this interface. Bacteria, fungi, actinomycetes, mycorrhizal fungi, and other soil microorganisms participate in organic-matter decomposition, mineral dissolution, nitrogen cycling, phosphorus release, micronutrient activation, and aggregate formation [22-23]. They can decompose plant residues and animal organic residues, and they can also change the chemical forms of elements through metabolic activity. They may form mutualistic relations with plants, compete with plants for resources, or under specific conditions shift toward pathogenic or opportunistic communities [18][20]. The significance of soil microorganisms lies in the fact that they prevent nutrients from existing only in physical or chemical forms. They place nutrients within a network that is constantly read, transformed, contested, and regulated by biological processes.

Water is the medium through which this network operates. It connects dissolution, diffusion, migration, absorption, and metabolism. Without water, nutrients cannot move effectively, roots cannot absorb them, and microbial metabolism cannot proceed. Yet if water moves too rapidly, soil loses retention capacity, and nutrients escape from the rhizosphere into runoff, groundwater, or water bodies [7][12]. Water is therefore not merely a transport channel or an environmental condition. It is a key variable determining whether nutrients can remain in proper positions and be used at appropriate rates. Healthy soil does not require the complete prevention of water movement. It requires organic matter, aggregate structure, pore systems, root networks, and microbial activity to keep water movement in a state that nourishes without washing away, and transports without causing overflow.

Nutrient movement in soil therefore cannot be simplified into a linear process of "fertilizer dissolution-root absorption." After fertilizers enter soil, they do not move proportionally and directly into plant bodies. Their movement is jointly regulated by soil structure, pH, moisture, organic matter, microbial communities, root exudates, and crop growth stages. Plants are not machines that passively absorb elements, and microorganisms are not background agents subordinate to soil chemistry. Plants influence microorganisms through root exudates; microorganisms influence plants by transforming nutrients; water regulates material movement and metabolic velocity between them. The three are linked by exchange, competition, symbiosis, selection, and feedback [18][21].

This interaction network determines the real form of soil fertility. If plant roots are active, microbial communities are diverse, water regulation is stable, and organic-matter supply is continuous, elements in soil are more likely to enter agroecological cycles and form continuous processes of retention, slow release, and transformation. Conversely, if rhizosphere interactions decline, microbial functions weaken, and water movement becomes uncontrolled, even relatively high levels of inorganic nutrients in soil may fail to generate stable fertility [24-25]. These nutrients may either be rapidly consumed by crops as short-term stimulation or quickly leave the soil system during rainfall and irrigation, becoming nutrient loads in downstream water bodies [7].

Thus, soil fertility must be understood within the plant-microbe-water interaction network. Outside this network, elements are only chemical stocks, not necessarily biological resources; water is only a migration channel, not necessarily a nourishing mechanism; plants are only uptake endpoints, not necessarily participants in continuous cycling. Only when plants, microorganisms, and water form stable interactions in the rhizosphere can elements shift from “existing in soil” to “participating in biological production,” and only then can soil richness rise from surface content to systemic capacity.

3.2 How inorganic elements enter biological cycles through microorganisms

Within the plant-microbe-water interaction network, microorganisms occupy a key position because many inorganic elements do not naturally exist in forms that are directly absorbable, stably usable, and continuously recyclable by plants. Phosphorus in soil may be fixed in insoluble minerals or form poorly soluble compounds with calcium, iron, and aluminum [5]. Nitrogen constantly shifts among organic, ammonium, nitrate, and gaseous forms, under the regulation of mineralization, nitrification, denitrification, and nitrogen fixation. Elements such as iron, zinc, sulfur, and manganese often require microbial dissolution, redox transformation, chelation, or transport before they can enter plant uptake pathways more effectively. In other words, the existence of elements in soil does not automatically equal biological usability. Elements must pass through a series of biological transformations before they can enter plant growth and ecological circulation.

The first function of microorganisms lies in form transformation. They decompose organic residues, gradually transforming plant and animal remains, root residues, straw, manure, and other organic materials into humus, soluble organic matter, and inorganic nutrients. Through organic acids, enzymes, and other metabolites, they promote the release of poorly soluble minerals, allowing elements that were originally difficult for plants to use to enter absorbable or exchangeable states [18]. They also participate in the transformation of nitrogen from organic nitrogen to ammonium nitrogen, from ammonium nitrogen to nitrate nitrogen, and from atmospheric nitrogen to biologically available nitrogen. Without these microbial processes, many elements may exist in soil but remain inaccessible to plants [5].

Microorganisms also regulate the position of nutrients. Nutrients in soil are not evenly distributed, and the rhizosphere is an especially active microspace. Plant roots modify the rhizosphere environment through exudates, while microorganisms form specific communities around roots and influence the enrichment, release, and fixation of elements near the root zone [18][21]. Hyphal networks of mycorrhizal fungi can extend the effective absorption range of roots, helping plants access nutrients that are farther away or less mobile [22]. Certain bacteria can form biofilms in the rhizosphere, changing local element concentrations and water conditions. Microbial necromass also becomes an important component of stable organic matter and soil aggregates [23]. Thus, microorganisms do not merely change what nutrients are present; they also change where nutrients are, how quickly they are released, and whether they remain in positions accessible to roots.

More importantly, microorganisms influence the temporal rhythm of nutrient release. Fast-acting fertilizers provide nutrients in relatively direct, high-concentration, and rapidly released forms [5]. By contrast, microbial decomposition of organic matter and microbial transformation of minerals are more process-based. They can gradually release nutrients from organic residues, allowing nutrient supply to more closely match crop growth cycles [19]. This matching is not automatic. It is affected by temperature, moisture, pH, organic-matter quality, tillage practice, and microbial community structure [24]. Yet precisely because microbial activity is rhythmic and conditional, soil fertility can form a slow-release mechanism rather than depending only on one-time high-concentration input.

Therefore, the function of microorganisms is not simply to increase a certain nutrient. More accurately, they change the form, position, speed, and availability of nutrients. They transform dead organisms into new soil organic matter; convert poorly soluble minerals into elements potentially usable by plants; and transform carbon released by plant roots into microbial biomass, metabolic products, and structural stability. They participate both in nutrient supply and nutrient preservation, both in plant growth and soil structure formation. They allow elements to move, while also preventing them from being lost in an uncontrolled manner.

Without microbial participation, inorganic-element movement in soil easily falls into two forms of imbalance. The first is inaccessibility: elements exist, but plants cannot effectively absorb them [5][18]. Soil tests may not indicate deficiency, yet crops show growth constraints. The second is uncontrolled movement: elements enter soil in fast-acting, high-concentration, or unstable forms, exceed the accommodation capacity of plants and microorganisms, and then enter water bodies through runoff, leaching, or drainage systems [7][24]. The first appears as an internal utilization barrier within soil; the second appears as downstream eutrophication pressure. Although they seem to move in different directions, both indicate that elements have not been effectively incorporated into the soil-plant-microbe cycle.

Microorganisms are therefore the conversion layer through which inorganic elements move from existence to availability, and from loss risk to biological supply. They allow elements in soil not merely to be measured, but to be organized; not merely to dissolve temporarily, but to enter sustainable supply processes; not merely to move chemically, but to enter biological relations. If eutrophication is the uncontrolled overflow of nitrogen and phosphorus from terrestrial systems into aquatic systems, microbial dysfunction is one of its important preconditions. Only when microorganisms cannot sufficiently transform, retain, and allocate nutrients do inorganic elements more easily shift from biological supply into pollution load.

3.3 Why soil health cannot be judged without observing microorganisms

Since microorganisms play a central role in retention, transformation, slow release, and cycling, soil-health assessment cannot remain at the level of chemical indicators alone. If soil testing mainly focuses on nitrogen, phosphorus, potassium, organic matter, pH, and selected trace elements, while lacking observation of microbial community structure, functional diversity, activity, rhizosphere interactions, and organic-matter transformation chains, such assessment presents only part of the soil's condition [18]. It can show the stock of certain materials in soil, but it cannot fully reveal whether soil has continuous operational capacity. It can answer “how much is present now,” but not “whether transformation, supply, and cycling can continue.”

A soil sample may show adequate or even high levels of nitrogen, phosphorus, and potassium, but that does not necessarily mean the soil is healthy. If microbial diversity declines, mycorrhizal networks deteriorate, organic-matter decomposition chains are broken, aggregate structure lacks biological binding support, and pathogenic or opportunistic microorganisms become dominant, the soil may still be fragile. It may maintain yield in the short term through chemical fertilizers, but this yield increasingly depends on external inputs rather than internal cycling [24]. Over time, the soil may show poorer structure, reduced water and nutrient retention, increased disease incidence, lower nutrient-use efficiency, and greater sensitivity to climatic and management fluctuations [11].

This shows that soil health is not merely chemical sufficiency, but operational stability formed by chemical, physical, and biological processes together. Chemical indicators tell us what substances exist in soil. Physical structure tells us how water, air, and roots are distributed. Microbial indicators tell us whether these substances and structures are continuously organized by biological processes [18]. Without microbial observation, soil assessment may mistake short-term nutrient availability for long-term health, acceptable element content for stable fertility, and temporary crop sufficiency for normal soil cycling. This can lead management toward further external nutrient supplementation rather than restoration of internal transformation and cycling capacity [24].

More importantly, without observing microorganisms, it is difficult to know what kind of selection is taking place in soil. Different management practices select for different microbial communities. Long-term heavy application of fast-acting fertilizers, insufficient organic-matter input, excessive tillage, pesticide pressure, monocropping, and altered drainage structures may all reorganize soil microbial communities. Some microorganisms that previously participated in organic-matter decomposition, rhizosphere mutualism, mineral release, and structural stabilization may gradually decline. Others that are better adapted to high concentrations of fast-acting nutrients, low-organic-matter environments, or pathogenic and opportunistic expansion may gain advantage. Under such conditions, the soil has not simply gained or lost microorganisms. Rather, the social structure of the microbial community has shifted directionally. This shift further affects plant health, nutrient-use efficiency, soil structure, and environmental overflow risks.

Therefore, future soil-health assessment must examine not only the chemical account but also the biological account. The chemical account concerns element content, acidity or alkalinity, and nutrient status. The biological account concerns whether microbial communities are diverse, whether functions are complete, whether rhizosphere interactions are stable, whether organic-matter transformation continues, whether mycorrhizal networks remain intact, whether pathogenic microorganisms are abnormally dominant, and whether soil structure is maintained by biological processes. Only by placing these two accounts together can we determine whether soil is a living system with operational capacity or a chemical substrate that maintains short-term production through external inputs.

This evaluation shift has direct significance for eutrophication governance. If eutrophication governance returns only to the chemical input end of land, it may continue to understand the problem as excessive fertilization or imprecise nutrient management. These judgments are important but insufficient. The deeper issue is whether land still has the capacity to transform, retain, and incorporate nutrients into plant uptake rhythms through microbial networks [18-19]. If soil microbial networks have degraded, simply reducing fertilizer may cause yield instability; simply adjusting fertilizer ratios may not restore retention capacity; and simply removing nitrogen and phosphorus from water cannot repair the upstream biological mechanism of soil. Water management must return to land, and returning to land must ultimately return to the microbial networks within land.

Thus, without observing microorganisms, we can only see the stock status of soil, not its operational capacity; only the existence of elements, not whether they are organized by biological systems; only short-term nutrient-supply conditions, not long-term cycling mechanisms. The core of soil health is not merely how many nutrients exist, but who allocates them, how they are transformed, and whether they can be retained continuously. Microorganisms are the key answer to these questions. The next chapter further examines how this microbial operating system is selected, rewritten, and weakened when agricultural systems rely for long periods on fast-acting chemical fertilizers, and how this selection effect pushes soil-fertility problems toward water-body eutrophication.

4 The Selection Effect of Chemical Fertilizers

Chapter 3 has shown that soil fertility is not the simple sum of element contents, but a dynamic operational capacity maintained by plant roots, microorganisms, water, organic matter, and mineral particles. Therefore, upstream analysis of eutrophication cannot stop at the surface judgment that fertilizer application is excessive. It must further ask how long-term dependence on external fast-acting nutrients changes the biological relations inside soil. Does it merely supply elements needed by crops, or does it also rewrite the pathways through which plants acquire nutrients, the competitive rules of microbial communities, and the soil system's own cycling capacity?

This chapter does not simply deny the historical contribution of chemical fertilizers to modern agricultural productivity. Fast-acting fertilizers have played important roles in increasing yield per unit area, relieving short-term nutrient deficiency, and supporting high-intensity agricultural production [5][24]. The problem is that when fertilizer use shifts from a supplementary measure into the main pathway of nutrient supply, especially under long-term, high-dose, single-source, and fast-acting input patterns, the soil system may undergo structural transformation. Plant dependence on microbial mutualism may decline; the mechanisms maintaining soil organic matter and aggregate structure may weaken; microbial communities may be selected under new chemical environments and ecological pressures; and soil may gradually shift from a living system capable of endogenous retention, transformation, slow release, and cycling into a system dependent on external inputs for short-term production [25].

The key issue, therefore, is not only whether fertilizers are applied in excessive or insufficient amounts, but that they change the pathway through which nutrients enter crops. Once nutrient supply bypasses the soil biotic network, the interactions among plants, microorganisms, and water are reorganized. Soil may continue to produce, and may even maintain high yield in the short term, but its internal capacity to generate, preserve, and allocate fertility may decline at the same time. In this sense, chemical fertilizers are not only chemical inputs but also ecological selection pressures. They affect not only crop yield, but also the structure and direction of the soil living community. One of the upstream roots of eutrophication forms gradually through this long-term pathway rewriting.

4.1 Fast-acting nutrients and the weakening of plant-microbe mutualism

The direct function of fast-acting chemical fertilizers is to provide crops with readily absorbable nutrients such as nitrogen, phosphorus, and potassium [5]. During critical growth periods, under nutrient-deficient conditions, or when agricultural production requires rapid response, this mode of supply has clear efficiency advantages. It can bypass slow organic-matter decomposition, gradual mineral release, microbial transformation, and rhizosphere exchange, allowing plants to obtain available nutrients in a short time and increasing yield under certain conditions. For this reason, chemical fertilizers have become one of the most important yield-increasing tools in modern agriculture [24].

However, the advantage of rapid supply is also the source of its deeper influence. In healthy soil, nutrient acquisition is not a one-way extraction of elements by plants from soil. It is a process of exchange, regulation, and cooperation between plants and microorganisms through the rhizosphere. Plants provide carbon sources and signaling substances to soil microorganisms through root exudates [21]. In return, microorganisms support plants by decomposing organic matter, releasing phosphorus, participating in nitrogen cycling, dissolving minerals, improving the rhizosphere environment, enhancing stress resistance, and stabilizing soil structure. This process is slower, but it forms the biological foundation that allows soil fertility to be maintained over the long term.

When fast-acting nutrients are supplied continuously, sufficiently, or excessively, the pathway through which plants obtain nutrients changes. Plants no longer depend as strongly on microorganisms to release insoluble nutrients, decompose organic matter, or maintain rhizosphere exchange. They can directly absorb large amounts of ready-made inorganic nutrients from the soil solution. Under such conditions, part of the mutualistic relation between plants and microorganisms is replaced by external input. Plants may reduce carbon investment in certain symbiotic microorganisms, root-exudate composition may change, and the resources and niches available to rhizosphere microorganisms may shift accordingly. The result is not the immediate disappearance of all microorganisms, but the compression of the microbial network's position within the plant nutrient-acquisition system [22][24].

This means that fertilizers do not merely increase certain elements in soil. They also change the mediating structure between plants and soil. In systems dependent on organic matter and microbial transformation, plants must maintain cooperative relations with microorganisms to obtain stable and diverse nutrient supply [18][21]. In systems dominated by long-term fast-acting inputs, plants can meet short-term growth needs through external nutrients, and the indispensability of microbial mutualistic networks is weakened. Over time, microorganisms responsible for slow decomposition, mineral release, rhizosphere regulation, and structural maintenance may no longer be sufficiently mobilized by the production system.

This change does not mean that fertilizers necessarily kill microorganisms directly. It means that the benefit relations, dependency levels, and resource flows between plants and microorganisms are reorganized. The nutrient-supply chain originally formed by plants, microorganisms, and organic matter is partially replaced by external fast-acting inputs. Slow-cycling mechanisms sustained by rhizosphere mutualism are compressed by short-term efficient supply. Fertility generation that should be jointly completed by soil biotic networks is simplified into a direct channel between external input and crop absorption.

Therefore, the mechanistic influence of fast-acting fertilizers cannot be understood only as nutrient supplementation. It changes the pathway through which crops obtain nutrients [5][24]. Once the pathway changes, plant-microbe mutualism is reorganized. In the short term, this reorganization may appear as higher yield and sufficient nutrient supply. In the long term, it may weaken the soil system's capacity to generate fertility, maintain microbial diversity, and regulate nutrient-release rhythms. Eutrophication governance must return to fertilizer-use patterns not because fertilizers as substances are inherently harmful, but because long-term fast-acting input pathways may increasingly detach nutrients from the soil biotic network and eventually increase overflow risk [7].

4.2 How long-term fertilizer inputs reshape soil microbial communities

If fast-acting nutrients first weaken plant-microbe mutualism, the further impact of long-term fertilizer input is ecological selection on soil microbial communities. Selection does not mean that one input simply kills all members of a microbial group. It means that long-term management continuously changes soil environmental conditions and thereby changes the competitive advantages of different microbial groups. Soil microorganisms are not static assemblages. They respond to pH, salinity, carbon-nitrogen ratios, soluble nutrient concentrations, moisture conditions, organic-matter quality, root exudates, and tillage disturbance. When these environmental variables move in the same direction over time, microbial community structure also undergoes directional reorganization.

Long-term high-dose fertilizer input may first alter the chemical environment of soil. Continuous nitrogen application may increase acidification risk [26]; accumulation of certain salts may increase soil-solution concentration; and persistently high levels of fast-acting nutrients may change microbial competition for carbon, nitrogen, and phosphorus. At the same time, if organic-matter inputs are insufficient, microorganisms dependent on complex organic substrates face resource decline [24]. If crops are monocropped for long periods, root-exudate types and rhizosphere environments become more uniform. If tillage disturbance is frequent, fungal hyphal networks, aggregate structure, and relatively stable microbial habitats may be damaged. Together, these factors create new ecological selection pressures.

Under these pressures, some microbial groups may gradually lose advantage. Microorganisms that depend on complex organic-matter decomposition, participate in humus formation, maintain mutualistic relations with plant roots, promote slow nutrient release, sustain aggregate structure, and enhance system stability usually require continuous organic carbon input, relatively stable rhizosphere environments, and intact soil structure. When agricultural systems use fast-acting fertilizers to replace organic cycling, monocropping to replace diverse root inputs, and short-term yield targets to replace soil-life maintenance, the ecological conditions required by these microorganisms are weakened [27-28]. They do not necessarily disappear immediately, but may gradually become marginalized in competition.

At the same time, other microorganisms better adapted to high nitrogen, high salinity, low organic matter, strong disturbance, or uniform rhizosphere environments may gain opportunities to expand. These microorganisms are not necessarily all pathogenic, but their expansion may indicate functional simplification and opportunistic tendencies in the community. Some groups that respond rapidly to high concentrations of inorganic nutrients may become dominant in the short term. Some microorganisms adapted to low-carbon and high-nitrogen environments may alter organic-matter decomposition pathways. Certain pathogenic or opportunistic microorganisms may expand more easily when structure is degraded, rhizosphere mutualism is weakened, and plant stress resistance declines. Thus, changes in soil microbial systems should not be simplified into a binary process of “beneficial microbes decrease and harmful microbes increase.” They represent a broader rewriting of competitive rules within the underground biotic community [24-25].

Analytical caution is necessary here. Chemical fertilizers do not damage microbial systems in the same way under all conditions. When used rationally, combined with organic-matter input, crop rotation, cover cropping, conservation tillage, and water management, fertilizers can play a positive role as part of soil nutrient management [24]. The problem lies in long-term, high-dose, single-source, fast-acting inputs disconnected from organic cycling. In other words, the real target of critique is not the existence of fertilizers themselves, but the use of fertilizers to replace soil biotic networks and become the dominant pathway of crop nutrition, continuously altering the ecological selection conditions of microbial communities [24-25].

Therefore, the long-term influence of fertilizers is not only chemical but also ecological and selective. They change not merely the concentration of an element, but the competitive rules of the entire underground biotic community. Which organisms obtain carbon sources, which adapt to high concentrations of inorganic nutrients, which expand under low-organic-matter and high-disturbance conditions, and which lose niches because mutualistic relations are weakened together determine the future direction of soil microbial systems. Over time, soil may shift from a diverse mutualistic system toward an input-dependent, opportunistically expanding, and functionally impoverished system. The consequences appear not only as declining soil health, but also as weaker nutrient retention and cycling, making nutrients more likely to enter downstream water bodies during rainfall, irrigation, and drainage.

4.3 From fertilization to systemic dependence: explaining why soil becomes poorer through repeated input

The expression that soil becomes poorer through repeated fertilization should not be understood as a simple statement about element content. It does not necessarily mean that all nitrogen, phosphorus, potassium, or other elements in soil are declining, nor does it mean that fertilization immediately reduces yield. More accurately, it refers to the decline of the soil's own capacity to retain, transform, slowly release, and cycle nutrients, resulting in crop production that increasingly depends on external fast-acting inputs. A field may still show adequate nutrient levels in tests, and may still produce high yields after fertilization. Yet if it can no longer independently maintain fertility through organic matter, microorganisms, roots, and structure, it has entered functional impoverishment.

This functional impoverishment is the accumulated result of the processes described above. Long-term fast-acting fertilizers replace plant-microbe mutualism, allowing crop nutrient acquisition to bypass microbial transformation and organic cycling. High-dose and single-source inputs continuously alter soil chemistry, reorganizing microbial communities under new selection pressures. Insufficient organic-matter input weakens aggregate structure and reduces water and nutrient retention [11][17]. Declining rhizosphere interactions lower the coordination between nutrient-release rhythms and plant uptake demand. Eventually, soil may not immediately lack elements, but it increasingly lacks the ability to organize elements into agroecological cycles.

Once this structure is formed, agricultural systems fall into systemic dependence. Short-term crop yield depends on chemical fertilizers, while internal soil cycling continues to deteriorate because it is no longer sufficiently mobilized or supplied with organic inputs. The more soil cycling capacity deteriorates, the more external fast-acting inputs are needed to maintain yield. The more external inputs become the main pathway, the more plant-microbe-organic matter relations are marginalized [21][24]. Fertilizers therefore move from an initial supplementary measure to a necessary condition for maintaining system operation. Without fertilizers, yield declines rapidly; with continued fertilizer use, short-term yield can be maintained, but the soil biotic network may not recover. This is the condition in which production dependence and ecological degradation occur simultaneously.

This also explains why simply increasing fertilization precision cannot fully solve the problem. Precision fertilization can reduce waste, lower part of the loss risk, and improve input efficiency. However, if soil lacks organic matter, has impoverished microbial functions, degraded aggregate structure, and weakened rhizosphere interactions, nutrients may still lack stable accommodation mechanisms even when applied more precisely. The real issue is not only whether fertilizers enter soil, but whether, after entering soil, they can be retained, transformed, slowly released, and cycled. If soil has shifted from an agroecological cycling system into an external-input-dependent system, management must restore internal mechanisms at the same time as it adjusts external input quantities.

This mechanism is directly connected to water-body eutrophication. The direct manifestation of eutrophication is the excessive accumulation of nutrients such as nitrogen and phosphorus in water bodies [1-2]. Yet these nutrients often leave farmland and enter water bodies because soil accommodation capacity has declined. When soil cannot stably absorb and retain input nutrients, when plant uptake rhythms are mismatched with fast-acting nutrient release, when microorganisms cannot sufficiently transform surplus nutrients, and when organic matter and aggregate structure are insufficient to buffer water erosion, excess nitrogen and phosphorus more easily enter rivers, lakes, and coastal waters through runoff, leaching, drainage ditches, and groundwater [7][12]. Under such agricultural structures, chemical fertilizers are not only yield-increasing tools; they may also become part of the nutrient-overflow chain [24].

Therefore, one of the upstream roots of eutrophication cannot be reduced simply to “too much fertilizer.” A more accurate statement is that long-term inappropriate fertilizer-use patterns gradually turn soil from a cycling agroecological system into an external-input-dependent system, weakening the land's capacity to accommodate nutrients. Excess fertilizer certainly increases overflow risk. But the deeper risk is that once soil loses retention, slow-release, transformation, and cycling functions, nutrients more easily shift from production materials into pollution loads even when input does not increase without limit. The problem is not only input quantity, but accommodation pathway; not only chemical concentration, but biological network; not only fertilization behavior at the field end, but whether the soil system still has the capacity to keep nutrients within agroecological cycles.

This chapter has thus completed the analytical shift from fertilizers as nutrient supplements to fertilizers as ecological selection pressures. Under rational use, chemical fertilizers can serve agricultural production. But when they replace soil biotic networks for long periods, compress plant-microbe mutualism, rewrite underground community competition, and create external-input dependence, they weaken the soil's own fertility-generation mechanisms. The next chapter moves this logic to the level of agricultural spatial organization. If long-term fertilizer input rewrites soil biotic networks at the micro level, intensive livestock farming and monocropping generate localized metabolic overload and localized ecological impoverishment at the macro-spatial level. Together, they drive nutrient-cycling rupture and eventually appear as eutrophication pressure in aquatic systems.

5 Spatial Mismatch Between Intensive Livestock Farming and Monocropping

The preceding sections have shown, from the perspectives of soil fertility and microbial networks, that eutrophication is not simply a problem of excessive nutrients in water bodies. It is the downstream manifestation of declining terrestrial capacity to retain, transform, slowly release, and cycle nutrients. The analysis must therefore move further. If soil cannot retain nutrients, why does modern agriculture continue to produce increasing pressure that the land cannot hold? If microbial networks and soil structures are degrading, why does the production system continue to intensify material input, output, and spatial compression? These questions require a shift from micro-level soil mechanisms to macro-level spatial organization.

The central argument of this chapter is that intensive livestock farming and monocropping are not two unrelated agricultural phenomena, but two typical spatial expressions of industrial agriculture. Intensive livestock farming produces localized metabolic overload: large amounts of feed, animals, manure, urine, organic load, nitrogen and phosphorus pressure, and potential pollutants are compressed into limited areas. Monocropping, by contrast, produces localized ecological impoverishment: large areas of land are governed by the same crop, the same root type, the same management rhythm, and similar chemical inputs [27-28]. The former overwhelms the system's assimilation capacity; the latter weakens its regenerative capacity. Together, they undermine the self-organizing and nutrient-cycling capacity of agricultural systems, making nutrients more likely to shift from production resources into overflow loads and eventually appear as eutrophication pressure in aquatic systems [13].

The formation of eutrophication should therefore not be explained only by a particular pollution source, rainfall event, drainage ditch, or livestock facility. At a deeper level, it points to the spatial mismatch of modern agriculture. Material inputs can be concentrated across regions; products can be sold over long distances; capital and technology can rapidly organize production. Yet soil accommodation, microbial transformation, water-environment capacity, and ecological recovery remain local, rhythmic, and bounded. When industrial agriculture rewrites the spatial structure of biological systems through concentration and simplification, nutrient cycling shifts from a distributed, slow, and accommodative ecological process into a localized, high-pressure, rapidly overflowing environmental problem requiring end-of-pipe remediation.

5.1 Intensive livestock farming: localized metabolic overload

The core feature of intensive livestock farming is the concentration of large numbers of animals within limited spaces, supported by external feed, facility-based management, disease control, standardized production, and market circulation systems. Compared with traditional dispersed livestock raising, intensive livestock farming can improve management efficiency, stabilize product supply, reduce some unit production costs, and integrate animal products more easily into large-scale markets. However, from the perspective of material circulation, intensive livestock farming is not merely an improvement in production efficiency. It also changes the spatial distribution of animal metabolic residues [8][13]. Nutrients that were once dispersed across broader land areas and could be gradually accommodated by grasslands, croplands, and village-level circulation systems are compressed into a small number of farms and surrounding zones.

Within this spatial structure, large amounts of feed are imported from outside. After digestion and assimilation by animals, part of this feed is transformed into meat, eggs, milk, and other products, while another part becomes manure, urine, organic load, ammonia, wastewater, pathogen risk, and potential pharmaceutical residues [13].

Products can be exported through cold-chain logistics and market networks, and feed can be continuously imported through interregional trade. Yet manure return, waste treatment, energy recovery, and soil-water accommodation cannot expand without limit in the same way as products and feed. Manure requires land for assimilation; wastewater requires treatment capacity; ammonia and odor are constrained by surrounding environmental capacity; biogas and organic fertilizer utilization depend on infrastructure, transport radius, and regional demand. Thus, the pollution problem of intensive livestock farming is not only a question of whether treatment facilities are adequate. It is a structural mismatch between input radius and accommodation radius.

This mismatch sharply increases material pressure in localized space. A region that could originally accommodate only a certain amount of manure, nitrogen, phosphorus, and organic load is forced, through external feed input and concentrated animal production, to bear metabolic outputs far beyond what local land, crops, soil microorganisms, and water environments can process. When localized metabolic output exceeds regional accommodation capacity, pollution is no longer an accidental event. It becomes a predictable consequence of spatial organization. Even when livestock farms build manure-treatment facilities, material pressure may still overflow in different forms if surrounding land is insufficient for safe return, organic fertilizer demand is unstable, energy-recovery pathways are absent, wastewater treatment is limited, or ecological buffering systems are weak.

The specificity of intensive livestock farming lies in the fact that it transforms animal metabolism, which should be embedded in land circulation, into localized high-pressure load [8][13]. Animals do not only consume nutrients that local land can continuously supply and recover. They consume material imported through a much broader feed system. Their metabolic outputs do not naturally return to the land that supplied them, but accumulate around livestock facilities. In this way, feed-origin areas, animal-production areas, manure-accommodation areas, and product-consumption areas are separated from one another. One end of the system exports grain and feed; another end concentrates manure and pollution pressure; the consumption end receives products without assuming responsibility for complete material return. Nutrient cycling is thereby cut apart, and metabolic residues are localized, concentrated, and transformed into management objects.

The eutrophication risk of intensive livestock farming should therefore not be understood only as irregular discharge by individual farms, nor attributed merely to insufficient end-point treatment capacity. The deeper problem is that intensive livestock farming produces localized metabolic overload through spatial concentration, compressing nutrients that should circulate in a distributed manner into high-concentration, high-pressure, difficult-to-accommodate overflow loads. When nitrogen, phosphorus, and organic matter in manure cannot be reabsorbed by land, energy systems, and microbial processes, they move through runoff, leaching, ditches, wastewater discharge, and groundwater into water bodies [7]. Eutrophication is not simply the result of a single discharge act. It is the downstream manifestation of mismatch between intensive livestock spatial structure and regional accommodation capacity.

5.2 Monocropping: localized ecological impoverishment

If the problem of intensive livestock farming is excessive concentration of materials in localized space, the problem of large-scale monocropping is excessive impoverishment of biological relations in localized space. Monocropping improves management efficiency and yield predictability through unified crop types, varieties, sowing times, fertilization, pesticide application, and mechanical operations. It makes agricultural production easier to standardize, scale up, and integrate into market systems. It also facilitates input supply, pest-control planning, harvesting, processing, logistics, and sales. Yet from an ecosystem perspective, this uniformity is not only a simplification of management. It is also a compression of biological relations in land.

In diversified cropping or integrated agricultural systems, different plants have different root depths, root morphologies, root exudates, nutrient demands, microbial partners, and growth rhythms. They provide more complex habitats and food sources for soil microorganisms, insects, soil fauna, and other organisms. They can also form richer ecological networks through crop rotation, intercropping, cover cropping, residue return, and rhizosphere interactions [27-28]. By contrast, large-scale monocropping simplifies root types, root exudates, microbial carbon sources, ecological niches, and habitats for insects, birds, and soil animals. The land may appear to remain covered by plants, but its biological relations are compressed into a narrow production channel.

This impoverishment of relations weakens the system's buffering capacity. A single crop means that once pests or pathogens adapt to that crop environment, they can spread more easily across large areas. A single root structure reduces the use of water and nutrients across different soil layers. A single microbial food source makes underground communities more vulnerable to functional impoverishment [20][27]. The lack of diverse plant residues and organic-matter inputs also weakens aggregate structure, organic-matter accumulation, and slow-release nutrient supply. To maintain output, the system must rely more heavily on external control, including fertilizers, pesticides, herbicides, irrigation, mechanical disturbance, and standardized management. Thus, the more monocropping pursues controllability, the more it may weaken its own ability to maintain stability through internal ecological relations.

Monocropping does not mean the absence of life. It means that biological relations are severely compressed. It simplifies a rich ecological network into a single high-yield crop pathway; reduces diverse root systems and microbial interactions into production relations centered on one crop; and turns soil, as a living community, into a substrate supporting the yield of a particular crop. In this process, soil is no longer a field where many living beings jointly organize nutrient cycling. It increasingly becomes a channel through which external inputs are converted into crop output. Microorganisms no longer receive diverse and stable carbon sources and niches, and plants no longer maintain soil ecological structure through complex interactions. The land still produces food or cash crops, but it becomes less capable of self-maintenance, self-repair, and self-regulation.

This localized ecological impoverishment is internally connected to eutrophication. When monocropping weakens soil retention, slow release, and transformation capacity, nutrients more easily detach from the plant-microbe-organic matter network. When large amounts of chemical fertilizers enter such relation-poor soil, surplus nutrients beyond crop uptake lack sufficient ecological accommodation mechanisms and therefore migrate more easily with water into ditches, rivers, lakes, and groundwater. Monocropping is therefore not only a biodiversity issue. It also changes how nutrients stay and transform in land. The poorer the biological relations, the more the system depends on external inputs; the more the system depends on external inputs, the more likely nutrients are to overflow when uptake rhythms and accommodation capacities are mismatched. Eutrophication is one indirect consequence of this relational impoverishment in aquatic systems.

5.3 Assimilation overload and regenerative weakness

Intensive livestock farming and monocropping appear to be different agricultural organizational forms. The former concentrates animals; the latter concentrates crops. The former appears as excessive manure, organic load, and nitrogen-phosphorus pressure; the latter appears as deficient biological relations, rhizosphere networks, and ecological buffering. The problem of the former looks like material excess, while that of the latter looks like relational deficiency. Yet at the system level, they jointly constitute the dual structure of modern agricultural spatial mismatch: one overwhelms assimilation capacity, and the other weakens regenerative capacity.

Intensive livestock farming overwhelms assimilation capacity because large amounts of animal metabolic outputs are concentrated in limited spaces. Manure, urine, wastewater, organic matter, nitrogen, phosphorus, ammonia, and potential pollutants form localized high-pressure loads, while the accommodation capacities of land, water bodies, energy systems, and microbial transformation processes remain bounded[8][13]. Once localized metabolic output exceeds regional assimilation capacity, the system must depend on external management chains: collection, transport, treatment, storage, land application, energy recovery, and water-pollution control. If any link in this chain is insufficient, surplus nutrients overflow into the environment. In other words, intensive livestock farming compresses materials that could have been gradually absorbed across a broader ecosystem into localized burdens that are difficult to assimilate.

Monocropping weakens regenerative capacity because the biological relations through which agricultural systems buffer disturbance and restore cycling are compressed. Soil lacks diverse root inputs; microorganisms lack diverse carbon sources and niches; insects and soil animals lack complex habitats; and cropping systems lack the regulatory effects of rotation, intercropping, cover, and residue cycling. As a result, when nutrient imbalance, pest pressure, soil-structure degradation, or climatic fluctuation occurs, the system finds it difficult to recover through internal ecological relations. It can only depend on fertilizers, pesticides, irrigation, and mechanical management to maintain output. It does not lack production capacity, but that capacity increasingly depends on external control rather than internal biological networks.

Although these two processes move in opposite directions, they reinforce each other. If manure from intensive livestock farming cannot be effectively returned to land, it becomes pollution [13]. If monocropped land lacks healthy soil structure and microbial networks, even organic fertilizer or nutrient inputs may not be sufficiently retained, transformed, and cycled. The livestock end has large amounts of nutrients needing accommodation, while the cropping end lacks ecological capacity to receive them. The cropping end depends on chemical fertilizers to maintain output, while organic nutrients from livestock are unable to return reliably to land because of spatial distance, treatment costs, unstable quality, and incomplete return systems. Thus, nutrients are not absent. They are excessive in the wrong places and functionally unavailable where they are needed [6][8].

Eutrophication is therefore not caused only by a single pollution source. It is a systemic overflow jointly driven by localized material excess and localized ecological impoverishment. Intensive livestock farming places metabolic loads beyond local accommodation capacity on certain areas, while monocropping deprives other areas of the ecological basis for absorbing and transforming nutrients. The former concentrates nutrients excessively; the latter simplifies land excessively. The former produces overflow pressure; the latter weakens accommodation capacity. Together, they reduce the self-organizing capacity of agricultural systems, causing nutrients that should circulate among soil, plants, microorganisms, and animals to enter water bodies, the atmosphere, and end-point treatment systems.

This paired structure shows that eutrophication governance cannot merely ask where nitrogen and phosphorus are discharged. It must also ask why some places bear excessive nitrogen and phosphorus, and why other places lose the capacity to accommodate them. If governance only targets livestock-farm discharge without rebuilding the soil accommodation capacity of cropping systems, nutrient cycling remains broken. If governance only reduces chemical fertilizer use in cropland without addressing concentrated manure and missing return pathways, pollution pressure remains [8][13]. Effective governance must address both assimilation overload and regenerative weakness: redistributing, treating, and re-embedding excessive materials, while restoring, reconnecting, and strengthening impoverished ecological relations. Only then can eutrophication governance move from end-point load reduction toward system reorganization [6][14].

5.4 How industrial agriculture weakens ecosystem self-organization

The simultaneous emergence of intensive livestock farming and monocropping is not an accidental technical choice. It is the spatial expression of industrial agricultural logic within biological systems. Industrial production pursues controllability, standardization, scale, and efficiency. It tends to concentrate similar objects, simplify complex relations into manageable links, compress natural rhythms into production schedules, and rely on external inputs to stabilize output. In factory production, this logic can improve efficiency because raw materials, machines, processes, and products can be highly standardized. When directly applied to agroecosystems, however, it may weaken the self-organizing capacity of biological systems.

The stability of ecosystems does not primarily arise from a single efficient link. It arises from diverse relations, slow cycles, redundant structures, and distributed accommodation. Diverse relations provide multiple complementary pathways, allowing other pathways to maintain basic function when one pathway is disrupted. Slow cycles allow nutrients, water, and organic matter to be gradually transformed among soil, plants, microorganisms, and animals, rather than overflowing rapidly in high concentrations. Redundant structures enable systems to withstand disturbances without collapsing when a single species, technology, or input fails. Distributed accommodation allows animal metabolism, plant residues, soil transformation, and water purification to be coordinated across broader spaces. Industrial agriculture tends precisely to compress these ecological mechanisms.

In intensive livestock farming, animals are concentrated, feed is centrally imported, manure is centrally produced, and metabolic pressure is centrally managed. In monocropping, crops are unified, root relations are simplified, microbial food sources become single, and pest-control systems depend on external chemical inputs. Both increase the controllability of local production links, but reduce the self-organizing capacity of the whole system. Self-organization refers to the ability of a system to maintain nutrient cycling, pest suppression, water regulation, soil-structure maintenance, and disturbance recovery through internal relations rather than entirely through external commands and inputs. When diverse relations are compressed, the system increasingly requires continuous human inputs of energy, chemicals, facilities, and management costs to maintain surface stability.

This explains why industrial agriculture often produces new vulnerabilities while increasing output. Standardized cropping improves management efficiency but reduces ecological buffering [27-28]. High-density livestock farming strengthens product supply but increases localized metabolic load. Fertilizers and pesticides improve short-term controllability but may weaken soil biotic networks. Waste treatment and end-point remediation relieve part of the pressure but do not necessarily reconstruct circular pathways. Production efficiency appears to rise, but the system becomes more prone to nutrient overflow, pest outbreaks, soil degradation, water-body eutrophication, and rising management costs. Industrial agriculture is not incapable. Its problem is that its capacity is concentrated on producing more and controlling local processes, rather than on making cycles more complete and systems more resilient.

From the perspective of eutrophication, the problem of industrial agriculture is not merely pollution discharge. It is that concentration and simplification rewrite the spatial structure of biological systems. Concentration produces localized material excess; simplification produces localized relational impoverishment. Material excess requires external accommodation; relational impoverishment requires external control. When external accommodation is insufficient, pollution enters water bodies. When external control intensifies, soil biotic networks may further degrade [24-25]. Eutrophication is therefore not an isolated imbalance in water. It is the downstream echo of industrial agricultural spatial logic. Abnormal algal proliferation, oxygen depletion, and ecosystem degradation in water reflect the upstream failure to distribute, retain, transform, and cycle nutrients properly in agricultural systems.

This chapter completes the transition from micro-level mechanisms to spatial structure. Chapter 4 showed that long-term inappropriate fertilizer input may weaken soil microbial networks through ecological selection, reducing land's nutrient-accommodation capacity. This chapter has further shown that intensive livestock farming and monocropping continue to produce accommodation pressure at the macro-spatial level: the former causes localized metabolic overload, while the latter causes localized ecological impoverishment. Together, they weaken the ecosystem's ability to absorb, regulate, and recover by itself. The next chapter therefore turns to the real root of eutrophication: nitrogen and phosphorus are not natural pollutants, and eutrophication is not merely a water-environment problem. It is the systemic manifestation of soil retention failure, nutrient-cycle rupture, and agricultural spatial mismatch.

6 The Real Root of Eutrophication

The previous chapters have analyzed eutrophication from four connected dimensions: soil fertility, microbial mechanisms, fertilizer selection effects, and the spatial organization of industrial agriculture. Chapter 2 argued that soil richness cannot be reduced to element content, but should be understood as the capacity for retention, slow release, transformation, and cycling. Chapter 3 further explained that microorganisms are key mediators of soil-fertility operation and important conversion layers through which inorganic elements enter biological cycles. Chapter 4 analyzed how long-term, high-dose, single-source, fast-acting fertilizer input changes plant-microbe mutualism and gradually produces external-input dependence. Chapter 5 showed spatially that intensive livestock farming produces localized metabolic overload, while monocropping produces localized ecological impoverishment; together, they weaken agricultural self-organization.

On this basis, the present chapter performs the diagnostic function of the whole article. Eutrophication is not an isolated problem caused by the natural fragility of water bodies, nor is it the result of nitrogen and phosphorus being naturally harmful. More precisely, eutrophication is the aquatic manifestation of nutrient-cycle rupture, soil-retention failure, agricultural spatial mismatch, and misplaced causal diagnosis. Nitrogen and phosphorus are originally fundamental elements of biological cycles [5]. Only when they leave proper time, space, form, and accommodation relations do they shift from fertility to load, from resource to pollutant, and from life-support condition to ecological risk [6-8].

Understanding eutrophication therefore requires asking not only why there is too much nitrogen and phosphorus in water, but also why nitrogen and phosphorus failed to remain in terrestrial biological networks; why they were not absorbed by crops; why they were not transformed by microorganisms; why they were not retained through organic matter, aggregate structure, roots, and soil biological processes; and why the pathways among livestock, cropping, human consumption, waste return, and land did not close. Only by placing these questions within the same system does the real root of eutrophication become visible: the problem lies not in nutrients themselves, but in the misplacement of nutrient pathways.

6.1 Nitrogen and phosphorus are not natural pollutants, but misplaced resources

Eutrophication governance must first reset the basic understanding of nitrogen and phosphorus. Nitrogen and phosphorus are not natural pollutants. They are indispensable elements of biological systems. Crop growth requires nitrogen for proteins, chlorophyll, nucleic acids, and other substances, and phosphorus for energy transfer, cell division, root development, and physiological metabolism [5]. Microbial reproduction, organic-matter decomposition, soil-structure formation, and nutrient transformation also depend on nitrogen and phosphorus. Animal and human life processes likewise rely on the continuous cycling of these elements [6]. Therefore, nitrogen and phosphorus do not possess an inherent pollutant identity.

The problem arises when nitrogen and phosphorus leave their proper positions. In soil, they can appear as fertility. During crop uptake periods, they support growth. In organic-matter decomposition and microbial transformation, they are conditions for biological reproduction. In integrated crop-livestock systems and manure-return pathways, they are part of material circulation [6][13]. Yet when nitrogen and phosphorus enter rainfall runoff, drainage ditches, groundwater, lakes, reservoirs, and coastal waters in high-concentration, rapidly released, poorly retained, and poorly absorbed forms, they shift from biological resources into ecological pressure [4][7]. They are no longer gradually accepted by crops and microbial networks, but passively received by aquatic systems, driving abnormal algal growth, oxygen depletion, water-quality deterioration, and degradation of aquatic ecosystems.

The same element therefore has different systemic identities in different pathways. Nitrogen and phosphorus within the soil-plant-microbe cycle are fertility and biological resources. Nitrogen and phosphorus outside crop uptake rhythms are surplus and load. Nitrogen and phosphorus beyond soil-retention capacity are loss risks. Nitrogen and phosphorus accumulated excessively in water bodies appear as pollution pressure. Pollution is not merely an inherent property of a substance. It is a relational result formed when a substance enters the wrong position, concentration, time, and accommodation system.

This distinction is fundamental for eutrophication governance. If nitrogen and phosphorus are directly defined as enemies, governance easily shifts toward simple reduction, interception, removal, and indicator suppression. Such governance can reduce aquatic nutrient loads to some extent, but it may not solve why nutrients overflow in the first place. If nitrogen and phosphorus are understood as misplaced resources, the governance object is no longer merely surplus nutrients, but the question of why nitrogen and phosphorus failed to enter proper cycles. The governance goal thus shifts from eliminating nitrogen and phosphorus to correcting their positions, and from pollutant removal to nutrient-pathway reconstruction [6][14].

This section therefore establishes the basic judgment of the article: the root of eutrophication is not the nutrient element itself, but nutrient-pathway misplacement. Nitrogen and phosphorus become aquatic pollution pressure not because they are inherently harmful, but because they are not retained, transformed, absorbed, and cycled in time by land, plants, microorganisms, and agricultural systems. Effective governance should not aim to make nitrogen and phosphorus disappear. It should aim to return them to proper agroecological pathways. Only in this way can eutrophication governance move beyond result reduction and touch the structural causes of nutrient overflow.

6.2 Water-body eutrophication as the manifestation of soil-retention failure

If nitrogen and phosphorus are not natural pollutants but misplaced resources, the next question is why these resources become misplaced. From the land-water perspective, one key cause of eutrophication is the decline of soil capacity to retain, slowly release, transform, and cycle nutrients. Excessive nutrients in water bodies are not only a water problem. They are the downstream manifestation of upstream land systems failing to accommodate nutrients. In other words, water-body eutrophication is largely the visible expression of soil's inability to retain nutrients [7][15].

Healthy soil is not a passive medium supporting crop roots. It is a complex system capable of regulating nutrients, water, and biological processes [10-11]. Through organic matter, clay particles, aggregate structure, root networks, microbial binding substances, and soil-fauna activity, it forms adsorption, retention, slow-release, and transformation capacities. During rainfall, irrigation, and agricultural disturbance, healthy soil can slow water movement, increase infiltration, reduce runoff, and retain a considerable share of nitrogen and phosphorus around the rhizosphere and soil aggregates, allowing gradual release and use during crop growth. Such soil does not merely contain nutrients. It organizes nutrients within biological relations that are usable, retainable, and recyclable.

When soil structure degrades, this capacity declines. Loss of organic matter weakens aggregate structure and water-nutrient retention. Destruction of aggregates makes soil more prone to compaction, erosion, and runoff. Monotonous root systems reduce the use of water and nutrients across different soil layers. Weakened microbial networks affect organic-matter decomposition, release of poorly soluble nutrients, mineralization, and structural stabilization. Under these conditions, even temporarily high concentrations of nitrogen and phosphorus in soil do not indicate true fertility. On the contrary, these nutrients may remain unstable because retention and transformation mechanisms are weak, and may enter water bodies more easily during rainfall, irrigation, or drainage.

Eutrophication should therefore not be explained as the unilateral insufficiency of water-body self-purification. Self-purification matters, but if upstream systems continuously deliver nutrient loads beyond aquatic carrying capacity, even strong water remediation becomes passive and repetitive. Eutrophication means that water bodies are forced to receive surplus nutrients that should have been processed by terrestrial biological networks [4][7]. Nitrogen and phosphorus entering rivers, lakes, and coastal waters might otherwise have remained in soil organic matter, been transformed by microorganisms, been absorbed by crops, or entered slow cycles through manure return, straw incorporation, and soil aggregates. When these terrestrial processes fail, water becomes the pressure-bearing end of nutrient rupture.

This also means that eutrophication governance conducted only inside water bodies often addresses results that have already overflowed. Dredging, aeration, algal removal, floating-bed systems, and aquatic ecological restoration can alleviate local water-quality pressure, but they do not automatically restore upstream soil-retention capacity [3][9]. As long as soil still cannot retain nutrients, as long as farmland continuously loses nitrogen and phosphorus during rainfall, and as long as agricultural systems continue to push excessive, fast-acting, and poorly accommodated nutrients into ditches and rivers, aquatic remediation will continue to face new input pressure.

Water management must therefore return to soil structure and soil biotic networks. This does not mean transferring blame for water pollution simply to farmland or farmers. It means re-identifying the upstream mechanism of eutrophication. True water management must not only reduce the nutrients entering water bodies, but also restore the land's capacity to absorb, retain, slowly release, and transform nutrients. It must not only repair aquatic ecology, but also restore soil organic matter, aggregate structure, root diversity, and microbial networks. Only when land regains nutrient-accommodation capacity will water bodies cease to function continuously as downstream pressure spaces for nutrient overflow.

6.3 From non-point-source pollution to nutrient-cycle rupture

Agricultural non-point-source pollution is a common concept used to explain eutrophication. It emphasizes dispersed sources, complex pathways, strong spatiotemporal variation, and governance difficulty [7][12]. Unlike industrial point-source pollution, agricultural non-point-source pollution usually does not originate from a single discharge outlet. It arises from the combined effects of cropland, livestock farming, village life, drainage ditches, rainfall runoff, and groundwater migration. This concept is necessary for identifying the spatial dispersion of pollution sources and the difficulty of governance. Yet if analysis stops at non-point-source pollution, it may remain at the level of result description. This article further argues that the deeper structure behind non-point-source pollution is regional nutrient-cycle rupture [6][8].

Nutrient-cycle rupture refers to the detachment of nitrogen, phosphorus, and other nutrients from the biological pathways in which they should circulate among soil, plants, microorganisms, animals, human consumption, and organic residues. These nutrients instead leak into water bodies, the atmosphere, and treatment systems in dispersed, uncontrolled, and poorly accommodated forms. Chemical fertilizer inputs are not fully absorbed by crops, and surplus nitrogen and phosphorus leave fields through runoff and leaching [7][24]. Livestock manure is not safely treated and rationally returned to land, becoming localized high-concentration pollution load [13]. Domestic wastewater and organic residues do not return to land systems, but enter sewage treatment and discharge systems [6]. Cropping and livestock farming are spatially separated, causing one place to lack fertility while another accumulates manure. Degraded soil microbial networks further weaken nutrient transformation and retention. On the surface, these appear as multiple dispersed pollution sources. In substance, they are distributed leakages from a regional nutrient system that has lost closure [8].

Non-point-source pollution is therefore not simply the sum of many small pollution sources. If understood only as a collection of dispersed emissions, governance tends to focus on point-by-point reduction, ditch-by-ditch interception, regional assessment, and end-point load suppression. These measures are necessary, but they do not explain why pollution persists. The deeper questions are: why do fertilizer nutrients not enter crops and soil cycles? Why does livestock manure not become organic fertilizer and a soil-improvement resource? Why do crop residues, household organic matter, and agricultural by-products fail to return to land? Why cannot cropping areas and livestock areas form nutrient loops at the regional scale? Why are soil microbial systems unable to transform nutrients into stable fertility? These questions point not to one pollution source, but to the rupture of cycling pathways as a whole.

From this perspective, eutrophication is the aquatic expression of nutrient-cycle rupture. Nitrogen and phosphorus entering lakes, rivers, and coastal waters do not suddenly emerge within water bodies [4][7]. They pass through a series of terrestrial failures: not absorbed, not retained, not transformed, not returned to land, and not cycled. Every instance of excessive fertilizer input, manure failing to return to land, declining soil organic matter, spatial separation between cropping and livestock farming, and rapid drainage transport may become a node through which nutrients escape from agroecological cycles. When these nodes accumulate at the regional scale, water bodies show nutrient excess, algal blooms, and ecosystem degradation.

Governance of non-point-source pollution therefore cannot rely only on end-point interception. Buffer strips, ecological ditches, wetlands, sedimentation ponds, and wastewater-treatment facilities can reduce nutrient loads entering water bodies, but they mainly re-intercept nutrients after they have already left farmland or livestock systems [29-30]. To reduce leakage fundamentally, regional nutrient cycling must be reconstructed so that nutrients re-enter continuous soil-plant-microbe-animal pathways. Fertilizer reduction should be combined with restoration of soil organic matter. Livestock-manure utilization should match safe return and crop demand [13]. Cropping structure should coordinate nutrient uptake and ecological buffering. Village wastewater and organic residues should, wherever possible, be integrated into regional recycling design [6][14]. Only then can non-point-source pollution governance move from dispersed pollution control toward systemic closure.

The concept of non-point-source pollution therefore needs to be deepened into nutrient-cycle rupture. The former identifies the spatial dispersion of pollution sources; the latter reveals the systemic mechanism of pollution formation. The former tells us why governance is difficult; the latter tells us where the root lies. If eutrophication governance sees only non-point-source pollution, it may remain trapped in dispersed interception and end-point reduction. If it sees nutrient-cycle rupture, it will move toward regional nutrient-pathway reorganization, rearranging relations among fertilizers, manure, crops, soil, water bodies, and microorganisms. This is the diagnostic core emphasized in this article.

6.4 Misplaced causal diagnosis in existing governance approaches

Existing eutrophication governance has developed a wide range of technical and management approaches, including source control, wastewater treatment, fertilizer reduction, livestock-manure utilization, ecological ditches, wetland buffer zones, dredging, aeration, algal removal, ecological restoration, and integrated watershed management. These measures have their own value and should not be dismissed. Source control can reduce external input; wastewater treatment can lower point-source discharge; fertilizer reduction can reduce excessive application; manure utilization can relieve livestock pollution; wetlands and buffer zones can intercept part of the nitrogen and phosphorus load; dredging and aeration can improve internal water conditions in some cases; and ecological restoration can help recover aquatic system structure. The problem is not that these measures are wholly ineffective, but that they often do not sufficiently address the deeper causes of eutrophication.

Current governance tends to remain at two levels: reducing nitrogen and phosphorus entering water bodies, and removing nutrients already present in water bodies. The first includes control of fertilizers, wastewater, manure, and runoff input. The second includes dredging, algal removal, aeration, ecological purification, and aquatic restoration. These pathways can alleviate pressure at the water end, but they tend to frame the problem as excessive pollutant load borne by water bodies, without sufficiently asking why pollutants formed, why they overflowed, why they were not absorbed by land systems, and why they did not enter agricultural cycles. Governance objects are thus located in the loads themselves, while causal diagnosis stops at load input rather than tracing back to soil biotic systems and agricultural spatial structures.

This misplaced diagnosis first appears as insufficient attention to soil-retention capacity. Many governance schemes focus on nitrogen and phosphorus loss from farmland, but not necessarily on why soil has lost retention capacity. They focus on fertilizer reduction, but do not always rebuild organic matter, aggregate structure, rhizosphere microorganisms, and slow-release fertility mechanisms at the same time. They focus on drainage outlets and ditch interception, but do not necessarily reconstruct absorption, transformation, and retention processes inside farmland [12]. As a result, governance may reduce part of the outflow load, but it does not fundamentally restore the land's ability to retain nutrients. As long as soil lacks living structure, new nutrient overflow will continue to occur [10-11].

Misplaced diagnosis also appears in the underestimation of plant-microbe interactions. Eutrophication governance often treats nitrogen and phosphorus as calculable, reducible, and interceptable pollution loads, but less often places them back within soil microbial networks [18-19]. Without observing microbial community structure, functional diversity, rhizosphere interactions, and organic-matter transformation, it is difficult to judge whether land has truly recovered nutrient-cycling capacity. Even if inputs are reduced, nutrients may remain misplaced in time and space if soil microbial networks are still impoverished and plant uptake and soil transformation remain insufficient. Governance sees input quantity, but not fully operational capacity.

Misplaced diagnosis further appears in insufficient treatment of agricultural spatial structure. The spatial mismatch produced by intensive livestock farming and monocropping cannot be solved by a single end-point technology. The livestock end produces large amounts of manure requiring return to land, but the cropping end may be unable to accommodate it because of soil impoverishment, crop uniformity, transport radius, and application costs [8][13]. Cropping systems depend on chemical fertilizers, while organic nutrients from livestock cannot return stably to soil. Some regions have material excess, while others have ecological relational poverty. If governance only requires livestock farms to meet discharge standards and croplands to reduce fertilizer use, without reconstructing regional crop-livestock integration and nutrient loops, the system will continue moving nitrogen and phosphorus from one link to another rather than returning them to agroecological cycles.

The problem in existing governance is therefore not that it is entirely wrong, but that its causal diagnosis is not deep enough. It sees aquatic exceedance, but not sufficiently terrestrial metabolic rupture. It sees pollution loads, but not sufficiently nutrient-pathway misplacement. It sees end-point remediation, but not sufficiently reconstruction of soil biotic systems. It sees source-control indicators, but not sufficiently regional agricultural spatial structure. Such governance can relieve symptoms, but it easily falls into repeated investment, recurring treatment, and localized improvement. Water improvement may depend on continuous engineering maintenance, while land systems do not truly recover accommodation capacity. Pollution-load reduction may appear in statistical tables, while nutrient cycling remains unclosed.

Eutrophication governance therefore needs a logical upgrade: from pollutant-reduction logic to nutrient-pathway reorganization logic. Pollutant-reduction logic focuses on how to reduce, intercept, and remove nitrogen and phosphorus after they move toward water bodies. Nutrient-pathway reorganization logic asks how nitrogen and phosphorus can avoid misplacement, remain within soil biotic networks, be absorbed by crops and microorganisms, and return to land through crop-livestock integration and organic-matter cycling. The former treats results; the latter reorganizes relations. The former relieves pressure; the latter addresses the root. The former centers on improvement of aquatic indicators; the latter centers on recovering the cycling capacity of the land-microbe-agricultural system. Only through this shift can eutrophication governance move from end-point repair toward systemic reconstruction[6][14].

7 From Eutrophication Governance to Nutrient-Pathway Reorganization

The previous chapter argued that the real root of eutrophication does not lie in the natural harmfulness of nitrogen and phosphorus, nor in the inherent fragility of water bodies. It lies in systemic overflow produced by nutrient-cycle rupture, soil-retention failure, agricultural spatial mismatch, and misplaced causal diagnosis in governance. On this basis, the present chapter moves from diagnosis to the reconstruction of a governance framework. Eutrophication governance cannot abandon source control, interception, wastewater treatment, ecological restoration, or internal water-body remediation. However, these measures should not be understood as a fragmented list of technologies, nor reduced to the objective of making nitrogen and phosphorus in water decline as quickly as possible. What needs to change is the definition of the governance object: from excessive nutrients in water bodies to misplaced nutrient pathways, and from pollutant removal to nutrient re-accommodation.

This chapter therefore does not reject existing management technologies. Instead, it relocates them within a broader framework of nutrient-pathway reorganization.

Source control is not only about preventing nitrogen and phosphorus from entering water bodies, but also about finding new accommodation positions for nutrients [6][14]. Soil restoration is not only about improving farmland quality, but also about recovering the land's capacity to retain, slowly release, transform, and cycle nutrients. Crop-livestock integration is not only about manure utilization, but also about turning animal metabolic outputs back into inputs for crop production [13]. Buffer strips, wetlands, and ecological ditches are not merely end-point interception facilities, but ecological interfaces for nutrient re-absorption, re-sedimentation, and re-transformation between land and water. Only within this framework can eutrophication governance move from end-point repair toward systemic reconstruction.

7.1 Source control is not the endpoint: the key is rebuilding accommodation pathways

Eutrophication governance must first recognize the necessity of source control. As long as external nitrogen and phosphorus loads continue to enter water bodies at high intensity, any internal water-body restoration will be difficult to sustain [1][3]. Even if dredging, aeration, algal removal, ecological floating beds, or wetland purification temporarily improve water quality, continued input from upstream farmland runoff, livestock manure, domestic wastewater, and industrial discharge will cause nutrients to accumulate again, pushing the water body back into the cycle of abnormal algal growth, declining transparency, oxygen depletion, and ecological degradation. Source control is therefore the premise of eutrophication governance and the basic condition for reducing continuing pressure on water bodies.

However, source control is not the endpoint of governance. Conventional source-control logic often asks how nitrogen and phosphorus can be prevented from entering water bodies, but asks much less frequently where the controlled nutrients go afterward. If fertilizer reduction in farmland simply lowers input without restoring soil organic matter and microbial transformation capacity, crop production may shift toward other forms of external compensation. If livestock manure no longer enters water bodies but is merely piled near farms, moved into low-efficiency treatment links, or converted into another waste burden, pollution has not truly disappeared [13]. If wastewater treatment transfers nutrients from water into sludge, while the sludge lacks safe, stable, and traceable utilization pathways, governance has merely changed the form of pollution rather than reorganizing nutrient pathways [14].

Effective source control must therefore be designed together with accommodation pathways. It cannot only cut off the channel through which nutrients enter water. It must also arrange subsequent destinations for nutrients that are intercepted, reduced, or recovered. Excess nitrogen and phosphorus in farmland should be managed through soil-structure improvement, better synchronization between nutrient release and crop uptake, and ecological buffering systems. Nutrients in livestock manure should enter land-return pathways that match land assimilation capacity after composting, maturation, anaerobic digestion, digestate treatment, and nutrient-balance accounting [13]. Nutrients in domestic wastewater and organic residues should, wherever safe and feasible, enter soil improvement, landscaping, energy recovery, or regional recycling systems. Only then does source control become not merely the prevention of pollution entering water, but the return of misplaced nutrients to systemic positions.

This shift expands eutrophication governance from emission control to nutrient-accommodation design. Governance should not only ask how much nitrogen and phosphorus have been reduced at a discharge outlet or in a watershed. It should also ask whether the reduced nutrients have been reorganized: whether they have become organic fertilizer, compost, digestate, crop nutrients, or soil organic matter; whether they have entered monitorable, traceable, and sustainable agricultural cycles; and whether they have reduced rather than displaced systemic pressure. If nutrients after source control lack accommodation pathways, the system merely transfers pollution from one space to another. If nutrients after source control re-enter agroecological cycles, governance truly moves from pollutant reduction to pathway recovery.

Source control must therefore serve nutrient re-accommodation rather than simply block the routes into water bodies. The first step of eutrophication governance is to reduce aquatic loads, but the deeper task is to rebuild terrestrial nutrient-accommodation capacity. Only when source control is co-designed with soil restoration, manure utilization, crop demand, regional crop-livestock structure, and land-water transition zones can it avoid becoming pressure transfer and instead become the starting point of nutrient-pathway reorganization.

7.2 Soil microbial recovery and organic-matter reconstruction

If one upstream cause of eutrophication is the decline of soil retention and transformation capacity, then governance cannot remain within water bodies, nor can it stop at reducing fertilizer application alone. The first root-cause pathway is to restore soil biotic networks, especially organic matter, aggregate structure, rhizosphere microorganisms, and soil biodiversity. Only when soil regains its capacity for retention, slow release, transformation, and cycling can nutrients be prevented from entering water bodies in high-concentration, fast-release, and poorly accommodated forms.

Organic-matter reconstruction is the foundation of this process. Organic matter is not only a nutrient source, but also a key support for soil structure, microbial food webs, and water-regulation capacity. With increased soil organic matter, aggregate formation becomes easier, pore systems become more stable, water and nutrient retention improve, and microorganisms receive a continuous carbon source. Under such conditions, nitrogen and phosphorus are less likely to remain only in fast-acting, free, and easily lost forms. They are more likely to be incorporated into organic matter, microbial biomass, mineral-associated forms, and rhizosphere cycling. Such soil can gradually release nutrients when crops need them and reduce nutrient overflow during non-uptake periods, thereby lowering runoff and leaching risks.

Microbial recovery is the key through which organic-matter reconstruction becomes operational soil capacity. Without microbial participation, organic materials are difficult to decompose and humify stably; poorly soluble nutrients are difficult to release; rhizosphere exchange is difficult to form; and soil structure is difficult to maintain through biological binding substances. Restoring mycorrhizal fungi, nitrogen-fixing microorganisms, phosphate-solubilizing microorganisms, organic-matter decomposers, and diverse rhizosphere microbial communities is not an ecological decoration added to soil [18][22]. It is the restoration of the operating system of soil fertility. It determines whether nutrients can move from inventory to usability, from loss-prone forms to retainable forms, and from external-input dependence to endogenous cycling supply.

Soil microbial recovery and organic-matter reconstruction can be promoted through multiple coordinated pathways. First, organic-matter inputs should be increased through straw return, green manure, compost, matured organic fertilizer, safe manure use, and crop-residue recycling, so that soil regains a continuous carbon source. Second, high dependence on single fast-acting fertilizers should be reduced, allowing plant-microbe mutualism to regain ecological position rather than being replaced by long-term external inputs. Third, soil cover should be protected to reduce bare-soil exposure and rainfall erosion, preventing nutrients and microbial communities from being frequently disturbed. Fourth, excessive tillage, compaction, and chemical disturbance should be reduced to maintain stable soil pores, water, aeration, and microhabitats. Fifth, diversified cropping, rotation, intercropping, and root-type enrichment should provide microorganisms with more complex carbon sources and habitats.

The purpose of these measures is not to increase a single nutrient index, nor to understand soil restoration as adding another kind of fertilizer. Their core is to restore soil as a living interface of circulation. Truly healthy soil should organize external inputs, crop residues, microbial metabolism, mineral weathering, water movement, and plant uptake into a relatively stable circular process. Such soil is neither a nutrient-deficient barren system nor an over-enriched but leaky system. It is a living system capable of dynamic coordination among retention, slow release, transformation, and cycling.

Soil microbial recovery is therefore not an ecological supplement outside eutrophication governance, but an upstream foundational project of eutrophication governance. Excessive nutrients in water often indicate insufficient accommodation capacity on land; recovery of terrestrial accommodation depends on the joint reconstruction of organic matter, structure, roots, and microbial networks. Only when soil regains the ability to retain, transform, and supply nutrients to crops can eutrophication governance stop endlessly intercepting escaped nutrients and begin reducing nutrient overflow at its source.

7.3 Crop-livestock integration and regional nutrient closure

The second root-cause pathway is to rebuild regional nutrient closure between cropping and livestock systems. A major contradiction in modern agriculture is that intensive livestock farming concentrates animal metabolic outputs in limited spaces, while monocropping often depends heavily on external chemical fertilizers. The former creates manure-treatment pressure; the latter creates fertilizer dependence and the risk of soil-biotic-network degradation. The former has large amounts of organic nutrients with no proper destination, while the latter has large areas of land lacking organic matter and biological activity. Once they are spatially separated, they simultaneously produce pollution and fertility deficiency, forming a systemic mismatch in which one side overwhelms assimilation capacity and the other lacks regenerative capacity [8][13].

The significance of crop-livestock integration lies in reconnecting this broken pathway. Animal metabolic outputs should not be naturally treated as pollution burdens. After safe treatment and rational allocation, they can become inputs for crop production and soil improvement. Nitrogen, phosphorus, potassium, organic matter, and trace elements in livestock manure can, after maturation, composting, anaerobic digestion, solid-liquid separation, hygienic treatment, and nutrient-content assessment, enter cropland, orchards, grasslands, and horticultural systems [13]. They can replenish soil organic matter, improve soil structure, reduce partial dependence on chemical fertilizers, and re-embed animal metabolism into plant production [6][13]. This is not simply waste utilization, but the reclosure of regional nutrient pathways.

However, crop-livestock integration should not be crudely understood as applying manure to land whenever manure exists. Without safe treatment, manure may carry pathogen risks, antibiotic residues, heavy metals, or high salinity. Without nutrient-balance accounting, application rates may exceed crop demand and soil carrying capacity [13]. Without assessment of land assimilation capacity, local over-application may lead to nitrogen and phosphorus leaching, runoff, and secondary eutrophication. If transport distance is excessive, land-return costs and energy consumption may offset part of the ecological benefit. If application timing does not match crop uptake rhythms, manure nutrients may still become loss loads. Thus, real crop-livestock integration is not the transfer of livestock pollution to farmland, but the return of nutrients to land under safe, appropriate, site-specific, timely, and traceable conditions.

Regional nutrient closure requires a systemic ledger. This ledger should jointly calculate livestock scale, manure production, treatment capacity, land assimilation capacity, crop nutrient demand, baseline soil fertility, water-environment capacity, transport radius, and pollution risk. Livestock scale cannot be determined only by market demand, facility capacity, and short-term profit. It must correspond to surrounding land accommodation, cropping structure, and water-soil environmental capacity. Fertilization schemes in cropping areas cannot be based only on yield targets and chemical fertilizer experience. They should incorporate livestock manure, organic-matter recovery, soil microbial activity, and regional nutrient balance. Only when the livestock end and the cropping end enter the same systemic ledger can manure utilization avoid becoming another form of pollution transfer.

This regional closure also means that the scale of agricultural governance must be adjusted. A single livestock farm may not be able to complete all manure accommodation by itself, and a single farmer may not be able to establish a stable organic fertilizer supply and use system. Therefore, systems for manure collection, treatment, transport, testing, application, and supervision need to be planned at township, watershed, county, or larger regional scales. Through regional composting centers, biogas facilities, organic fertilizer processing, manure-return services, nutrient-balance platforms, and farmland carrying-capacity assessment, dispersed animal metabolic outputs can be transformed into organized soil nutrient inputs. Governance then no longer merely requires each actor to emit less, but reorganizes nutrient relations among actors.

The key to regional nutrient closure is therefore not applying manure wherever manure exists, but placing livestock scale, land carrying capacity, crop demand, and treatment capacity into the same systemic ledger. Only on the basis of safe treatment, nutrient balance, land assimilation capacity, transport radius, and pollution-risk assessment can crop-livestock integration become an upstream root-cause pathway for eutrophication governance. Otherwise, resource utilization may become over-application, recycling may become secondary pollution, and nutrient closure may become another form of pathway misplacement.

7.4 Reconstructing buffer strips, wetlands, ditches, and land-water transition zones

Even if soil systems and agricultural spatial structures are gradually restored, nutrients still migrate through rainfall, irrigation, drainage, and surface runoff. Eutrophication governance therefore cannot focus only inside farmland or only inside water bodies. It must also focus on the transition zones between them. The relation between cropland and rivers, lakes, ditches, reservoirs, and coastal waters is not a simple boundary relation. It is a continuous interface of nutrient migration, sedimentation, uptake, transformation, and redistribution [12]. If this interface is hardened, channelized, simplified, or cut off, nutrients move more rapidly from land into water. If it is reconstructed, it can become a buffer and reprocessing interface for regional nutrient cycling [29-30].

Vegetated buffer strips are among the most direct land-water transition facilities. Vegetation along field margins, riparian zones, ditches, and slope runoff pathways can slow runoff, intercept sediments, absorb part of nitrogen and phosphorus, and promote nutrient retention and transformation through roots and microbial activity. Compared with bare farmland or hard drainage boundaries, vegetated buffer strips provide nutrients with a second opportunity for interception and reuse. Their significance is not only blocking pollutants, but extending the residence time of water and nutrients within terrestrial ecological interfaces, allowing materials that would otherwise flow out rapidly to re-enter roots, microorganisms, organic matter, and sedimentation processes.

Ecological ditches and optimized farmland drainage pathways are also important. Conventional drainage systems often pursue the rapid removal of excess water to maintain short-term field conditions, but rapid drainage also accelerates nitrogen and phosphorus delivery to rivers and lakes [7][12]. Ecological ditches, through vegetation, gentle slopes, sedimentation spaces, sediment microorganisms, and water-flow regulation, transform drainage systems from transport channels into slow-release and transformation channels. If farmland drainage pathways can shift from straight, hardened, and rapid forms toward ecological, retention-based, and staged purification forms, they can provide more opportunities for sedimentation, uptake, and microbial transformation before nutrients enter open water.

Constructed wetlands, pond systems, and riparian restoration further expand the function of land-water transition zones. Wetlands can reduce part of nutrient loads through plant uptake, microbial reactions, sedimentation, and hydrological regulation, while also providing space for biodiversity recovery [30]. Ponds and small retention systems can temporarily store nutrient-containing water during rainfall and drainage peaks, reducing short-term concentrated impacts on downstream water bodies. Riparian restoration can reduce the hardening of land-water boundaries and allow rivers to regain a degree of self-buffering and ecological filtering capacity. These systems are not simply end-point engineering facilities. They establish multi-layered ecological interfaces between land and water.

It must be emphasized that buffer strips, wetlands, and ecological ditches should not be understood as the last line of defense replacing soil restoration and agricultural structural adjustment. If upstream inputs remain excessive, soil continues to degrade, and livestock manure continues to overflow in a disorderly manner, even large buffering systems will be overwhelmed. These facilities should be incorporated into nutrient-pathway reorganization rather than isolated as end-point interception measures. Their proper role is to extend nutrient migration pathways, reduce overflow speed, increase opportunities for re-absorption and re-transformation, and provide protective transition spaces for water bodies on the basis of soil retention, crop-livestock closure, and source control.

The core of reconstructing land-water transition zones is therefore not only intercepting pollution, but changing the way nutrients move from land into water. Past governance often separated farmland and water into two systems: farmland produces, and water receives consequences. Reconstructing land-water transition zones restores ecological interfaces between them, allowing nutrients to be re-accommodated by vegetation, soil, wetlands, ditch microorganisms, and sediment systems after leaving farmland. In this way, eutrophication governance is no longer only internal water remediation or farmland emission reduction, but a continuous governance chain extending from farmland interiors to field margins, drainage systems, riparian zones, and water bodies.

Buffer strips and wetlands should therefore not be treated as end-point repair projects, but as ecological interfaces between land and water. Their true value lies in offering misplaced nutrients a second chance to enter agroecological cycles, transforming the land-water boundary from a pipeline of rapid pollution transport into a transitional system of uptake, sedimentation, transformation, slow release, and reorganization.

7.5 From nutrient removal to nutrient re-accommodation

The governance framework proposed in this chapter can ultimately be summarized as a methodological shift from nutrient removal to nutrient re-accommodation. Conventional governance first asks how nitrogen and phosphorus in water bodies can be reduced, how total nitrogen, total phosphorus, and chlorophyll levels can be lowered, how algal blooms can be suppressed, and how water can become clearer. These questions are necessary for water-quality improvement, but they are mainly located at the result end. This article asks further: where should these nitrogen and phosphorus have been? Why did they leave soil, crops, microorganisms, and organic-matter cycles? How can they return to appropriate agroecological pathways? Only when this second set of questions is raised can eutrophication governance move from end-point repair to system reconstruction.

"Nutrient removal" is the language of end-point governance. It focuses on water-quality indicators, pollution-load reduction, and ecological-risk mitigation. It usually treats nitrogen and phosphorus as objects to be excluded, intercepted, or removed. Its emphasis is therefore on reducing input, lowering concentration, improving transparency, and restoring water quality. Such governance is indispensable in emergency contexts and high-load water bodies, but its limitation is that it does not necessarily change upstream nutrient pathways. If nutrients after removal do not enter new cycling positions, or are merely transferred to sludge, storage sites, waste-treatment systems, and other management links, the system has not truly recovered.

"Nutrient re-accommodation" is the language of systemic governance. It recognizes that nitrogen and phosphorus create pollution pressure when they accumulate excessively in water, but it also asks where they reasonably belong within biological and agricultural systems. Nitrogen and phosphorus can enter soil organic matter, crop biomass, microbial biomass, compost, matured organic fertilizer, crop-livestock recycling systems, and the vegetation and microbial processes of buffer strips, wetlands, and ecological ditches. The governance goal is not to make nitrogen and phosphorus disappear from the system, but to return them from wrong positions to positions where they can be retained, transformed, slowly released, and cycled.

This shift also changes the evaluation criteria for technology. Under nutrient-removal logic, technology is mainly judged by reduction efficiency, removal rate, and short-term water-quality improvement. Under nutrient-re-accommodation logic, technology must answer deeper questions: does it restore soil accommodation capacity? Does it enhance microbial transformation? Does it reduce dependence on external fast-acting inputs? Does it allow livestock manure to enter crop production safely? Does it reduce regional nutrient leakage? Does it form a sustainable circular pathway?. A technology that rapidly lowers aquatic nutrients but merely transfers pressure elsewhere cannot be considered a fundamental solution. A pathway that works more slowly but restores relations among soil, crops, microorganisms, and regional cycling may have deeper governance value.

The goal of eutrophication governance should therefore not be only to make water clear. Clear water is a necessary result, but not the whole objective. The deeper goal is to prevent water bodies from being forced to receive surplus nutrients that should have been processed by terrestrial biotic networks; to prevent farmland from becoming merely a channel of external fertilizer input and nutrient leakage; to prevent livestock manure from remaining a localized pollution burden; to return safely treated manure into soil systems as nutrient resources; to re-engage microorganisms, organic matter, roots, and land-water transition zones in nutrient regulation; and to shift regional agriculture from a linear structure of input-production-loss-treatment toward an agroecological pathway of input-uptake-transformation-cycling-regeneration.

This chapter has therefore moved from governance technologies to governance logic. Source control is not the endpoint; the key is rebuilding accommodation pathways. Soil microbial recovery is not an auxiliary project, but an upstream foundation. Crop-livestock integration is not simple land application, but regional nutrient closure. Buffer strips, wetlands, and ditches are not end-point repairs, but land-water ecological interfaces. Ultimately, eutrophication governance should move from nutrient removal to nutrient re-accommodation, from pollutant reduction to nutrient-pathway reorganization, and from water-end restoration to the recovery of cycling capacity in the land-microbe-agricultural system. Only in this sense is eutrophication governance not merely an environmental project, but a process through which agriculture relearns how to accommodate its own metabolic products.

8 Conclusion: The Root of Water Management Lies in Soil, and the Root of Soil Restoration Lies in Biotic Networks

8.1 Eutrophication is a symptom at the water end

This article has argued that eutrophication should not be understood merely as a water-environment problem caused by excessive nitrogen and phosphorus in water bodies. Its direct symptoms indeed appear at the water end: nutrient enrichment, algal blooms, declining transparency, oxygen depletion, habitat degradation, and ecological-service loss. These symptoms require monitoring, emergency response, water-quality improvement, and ecological restoration. However, the visible form of eutrophication is not identical with its root cause. What appears as excessive nutrients in water often originates from the failure of terrestrial systems to retain, transform, absorb, and cycle nutrients.

The water body is therefore the manifestation surface of a wider metabolic disorder. Nitrogen and phosphorus enter water not because they are inherently pollutants, but because they have left the positions in which they could function as fertility, plant nutrients, microbial resources, and organic-cycle components. Once they escape from soil-plant-microbe pathways and accumulate rapidly in aquatic systems, they become eutrophication pressure. In this sense, eutrophication is not only excessive nutrition in water, but the downstream expression of misplaced nutrient pathways.

Recognizing eutrophication as an aquatic symptom changes the direction of governance. Aquatic remediation remains necessary, but it cannot be treated as sufficient. If upstream agricultural systems continue to leak nutrients, if soil remains unable to retain them, if manure lacks return pathways, and if monocropped land lacks biological accommodation, water bodies will repeatedly receive the consequences. The question is therefore not only how to reduce nutrients in water, but how to stop water from becoming the default receiver of nutrients that land systems failed to accommodate.

8.2 The root lies in the rupture of land-microbe-agricultural spatial structures

The deeper root of eutrophication lies in the rupture of land, microbial, and agricultural spatial structures. Soil richness is not static element stock, but the dynamic capacity to retain, slowly release, transform, and cycle nutrients. Microorganisms are the operating layer of this capacity. They convert elements from mere existence into usability, from loss risk into biological supply, and from chemical inventory into biological circulation. When soil organic matter declines, aggregate structure degrades, root diversity is reduced, and microbial networks become impoverished, the land loses its ability to retain and regulate nutrients.

Modern agricultural management can intensify this rupture. Long-term dependence on fast-acting fertilizers may weaken plant-microbe mutualism, reshape microbial selection pressures, and turn soil from an endogenous cycling system into an external-input-dependent system. Intensive livestock farming concentrates metabolic outputs in limited spaces, causing localized metabolic overload. Monocropping reduces biological relations in localized spaces, weakening ecological regeneration capacity. One produces more than the system can assimilate; the other leaves the system less able to regenerate. Together, they transform nutrients from circulating resources into environmental loads.

Thus, eutrophication cannot be adequately explained by water fragility alone, nor by nutrient input alone. It is produced by a systemic mismatch: material flows are concentrated and accelerated, while biological relations are simplified and weakened; nutrients are imported, transformed, consumed, and discharged across separated spaces, while the local capacity for soil retention, microbial transformation, and ecological buffering remains limited. The root is not a single source, but a broken structure of nutrient circulation.

8.3 The fundamental solution is not eliminating nutrients, but restoring nutrient cycles

The fundamental direction of eutrophication governance is therefore not to eliminate nutrients, but to restore nutrient cycles. Nitrogen and phosphorus are not natural enemies. They are misplaced resources when they appear in the wrong position, concentration, time, and accommodation system. Governance should not begin by treating them only as substances to be removed. It should ask how they can be returned to soil, crops, microorganisms, organic matter, livestock-crop recycling systems, and land-water transition interfaces.

This requires a shift from pollutant-reduction logic to nutrient-pathway reorganization logic. Pollutant-reduction logic asks how much nitrogen and phosphorus can be reduced from water bodies. Nutrient-pathway reorganization asks where nitrogen and phosphorus should go after being controlled, intercepted, recovered, or transformed. It asks whether soil can retain them, whether microorganisms can transform them, whether crops can absorb them, whether manure can safely return to land, whether buffer zones and wetlands can provide second-stage accommodation, and whether regional agricultural systems can close nutrient loops.

Restoring nutrient cycles does not mean ignoring pollution risks. On the contrary, it requires stricter attention to safety, scale, timing, form, and carrying capacity. Manure return must be based on hygienic treatment, nutrient balance, land assimilation capacity, and pollution-risk assessment [13]. Soil restoration must be based on organic matter, microbial networks, structure, cover, and diverse cropping systems. Source control must be linked to accommodation pathways. Aquatic remediation must be connected with terrestrial reconstruction. Only under these conditions can nutrient cycling become genuine restoration rather than another form of nutrient displacement [6][14].

8.4 Sustainable agriculture depends on returning matter to agroecological pathways

The final judgment of this article is that sustainable agriculture depends on returning matter to agroecological pathways. Eutrophication reveals a broader problem of industrial agricultural modernization: production systems have become increasingly capable of mobilizing materials, concentrating animals, standardizing crops, applying nutrients, and transporting products, but less capable of keeping nutrients within biological and regional cycles. Agriculture has improved output, but its pathways of return, retention, transformation, and accommodation have often been weakened.

A sustainable agricultural system should not be defined only by yield, efficiency, or short-term pollution reduction. It should be defined by whether nutrients can be retained by soil, transformed by microorganisms, absorbed by plants, returned through animal and organic residues, buffered at land-water interfaces, and circulated within regional ecological capacity. Its central ability is not simply to produce more, but to leak less; not simply to control more, but to organize better; not simply to remove pollutants, but to re-place misplaced resources.

For this reason, water management ultimately returns to soil, and soil restoration ultimately returns to biotic networks. Water bodies become eutrophic when they are forced to receive nutrients that land systems failed to retain. Land becomes leaky when soil organic matter, microbial activity, root diversity, and ecological structure decline. Agriculture becomes unsustainable when material flows continue to be accelerated while biological relations continue to be simplified. The path forward is therefore not a single stronger removal technology, but the rebuilding of nutrient pathways among soil, microorganisms, plants, animals, water, and regional governance.

Eutrophication, then, is not only a warning sign of aquatic degradation. It is a diagnostic signal showing that agricultural systems must relearn how to accommodate their own metabolism. The purpose of governance is not merely to make water clear, but to make nutrients return to the places where they can support biological production rather than damage aquatic systems. Only when matter re-enters agroecological pathways can eutrophication governance move beyond repeated end-point repair and become a foundation for sustainable agricultural modernization.

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