

**Review Article**

Soil Biogeochemical Cycles and Their Influence on Crop-Environment Dynamics in Changing Climates

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Abstract

Soil biogeochemical cycles regulate nutrient availability, soil organic matter dynamics, greenhouse-gas exchange, and crop productivity, but their functioning is increasingly modified by climate change. This review synthesizes the major processes controlling carbon (C), nitrogen (N), phosphorus (P), sulfur (S), and silicon (Si) cycling in agricultural soils and examines how these interconnected cycles influence soil-crop-environment relationships under changing climatic conditions. Warming, drought, excessive soil moisture, altered precipitation, and elevated atmospheric CO₂ can modify microbial activity, organic-matter turnover, nutrient mineralization and immobilization, redox conditions, nutrient losses, and greenhouse-gas emissions. Their effects are strongly context dependent and vary with soil texture, pH, organic-matter content, drainage, microbial communities, crop type, and management. The review further evaluates how plant nutrient acquisition, rhizosphere processes, and plant-soil-microbial feedbacks connect biogeochemical cycling with crop performance and environmental outcomes. Conservation agriculture, organic amendments, biochar, and microbial inoculants may improve nutrient retention and soil resilience, but their effectiveness depends on soil, climate, amendment properties, and management history and may involve agronomic or environmental trade-offs. We identify major knowledge gaps concerning interactions among elemental cycles, responses to compound climate extremes, microbial regulation of nutrient transformations, and the transferability of management practices across agroecosystems. Integrating long-term field experiments, process-based modelling, molecular approaches, and high-resolution soil monitoring will be essential for developing climate-resilient nutrient-management strategies.

Keywords: Soil biogeochemical cycle, soil-plant interaction, nutrient cycling dynamics, climate change impact and agroecosystem sustainability.

1. Introduction

Soil biogeochemical cycling regulates the transformation and movement of nutrients and other elements, thereby influencing soil health, crop productivity, and ecosystem sustainability, which includes carbon (C), nitrogen (N), phosphorus (P), sulfur (S) and silicon (Si) during shifting climatic conditions, is the biogeochemical cycling of the soil. These cycles are closely interconnected and are mostly facilitated by microbial communities in the soil, which have an influence on nutrient availability, plant growth, and plant resistance to environmental stress [1]. The cycles are important in maintaining life on the planet as they ensure that there are available nutrients and elements that are needed to maintain the ecosystem, growth and reproduction. This requires Plant-Soil system biochemical cycling, which

facilitates nutrient and other components to be transported throughout the plants and soil to influence the ecosystem constituents and their productivity [2]. The interactions involving the biotic and the abiotic environment make us aware of the complexity of interactions that determine ecological stability and resilience [3]. The conceptualization of biogeochemical cycles also emerged as scientists traced paths of elements in varying environmental conditions to learn about the movement of nutrients and elements within the compartments of natural systems and the role biological processes play [4]. The growth in the realization of the complexity and significance of biogeochemical cycling to the environment can be traced in the historical context of the studies on the subject matter. In its early years, particular

cycles such as C and N cycles were primarily investigated in the studies concerning the management of soils and the atmosphere [5]. Advances in molecular biology, isotopic methods and remote sensing have provided us with the opportunity to study these cycles at various scales, including microbial processes within soils up to the global circulation of C and N. The accessibility of information has increased, and we can now determine related feedback loops, along with understanding that natural cycles of nutrients and other elements have been broken by human-constructed disruptions, including industrial agriculture and deforestation [6]. The presence of biogeochemical cycling is required because the ecosystems remain healthy, as it encourages desirable processes such as primary productivity, recycling of nutrients/elements and soil formation [7]. The cycles enable plants to grow by exchanging nutrients and elements, which in turn affect the structure and functioning of terrestrial and aquatic ecosystems. This requires Plant-Soil system biochemical cycling, which facilitates nutrient and other components to be transported throughout the plants and soil to influence the ecosystem constituents and their productivity. The interactions involving the biotic and the abiotic environment make us aware of the complexity of interactions that determine ecological stability and resilience [8].

An example of such an interaction and the importance of microbial communities may be the interdependence of plants and soil [9]. Unlike microbial populations that decompose organic material and bring nutrients and elements in the soil in forms accessible to plants, plants absorb nutrients and elements in the soil to conduct their own metabolic processes [10]. This interdependence highlights the necessity to preserve the biogeochemical integrity of the environment when things are changing by preserving life-sustaining processes. In addition to environmental impacts, biogeochemical cycling is also significant in addressing the problem of food security in the world, global warming and biodiversity degradation (**Figure 1**). The role played by the C cycle in stabilizing the atmospheric level of CO₂ is very significant in combating climate change [11]. Equally, the N and P cycles have impacts on the quality of water and harvests, hence there is a need to have sustainable practices of nutrient management. The Si cycle, as well as the C cycle, is now closely associated at the global level and the advantages of Si in crop vegetation and plant functionalities, and ecosystem processes are now well-established in the literature [12]. The level of species diversity renders the ecosystem more resilient, as well as contributes to the faster recovery of the ecosystem aftershocks. Consequently, any disproportion in the biogeochemical cycling due to any natural processes or other anthropogenic factors is a great threat to the stability of the ecosystem and human health. Climate change is becoming an acknowledged problem in the world's food security issues due to its far-reaching effects on climate patterns, changes in rainfall, and regular and severity of adverse weather conditions [13]. These climate changes degrade soil health both directly and indirectly, lowering crop yield and increasing yield variability, particularly in highly climate-sensitive regions, which has led to the rise of the so-called

climate-smart agriculture (CSA), an integrated and adaptable approach that is designed to promote sustainable increased agricultural production, enhance resiliency to climatic variability, and mitigate greenhouse gas emissions [14]. Climate change factors (**Figure 1**), which include temperature rises, changes in precipitation, droughts and extreme weather changes, fundamentally influence the soil biogeochemical cycles, and thus impact the structure, functioning and transformation of the microbial communities along with the nutrient cycles. High temperatures and drought will likely reduce the rate of soil respiration and enzyme activity, causing a disruption in C, N and P cycling, and ultimately threatening the soil fertility [15]. The phosphorus levels also interact with the high level of CO₂, and these levels are likely to aggravate P limitation and consequently suppress the CO₂ fertilization effects on plants. The heterogeneity of assessing the impacts of changes in moisture regimes on soil microbial processes, e.g., nitrification and nitrogen fixation, is novel as they are either changing microbial communities and nutrient availability (which must be managed adaptively). The primary mechanisms being used to maintain a steady balance of nutrient cycling and agroecosystem sustainability in a changing environment are the utilization of microbial functions, sustainable soil management and technological monitoring [16].

Despite the rapidly expanding literature on soil responses to climate change, existing reviews commonly examine individual elemental cycles, microbial processes, crop responses, or management practices in isolation. Consequently, a major synthesis gap remains in understanding how C, N, P, S, and Si cycles interact simultaneously with climate drivers and plant-soil-microbial feedbacks in managed agroecosystems. This review addresses that gap by integrating five major biogeochemical cycles within a soil-crop-environment framework. Specifically, we (i) compare the principal transformations and crop functions of C, N, P, S, and Si; (ii) distinguish the effects of warming, drought, excessive soil moisture, altered precipitation, and elevated CO₂ on these processes; (iii) examine mechanistic links among nutrient cycling, crop performance, and environmental losses; (iv) critically evaluate the context dependence and trade-offs of major soil-management strategies; and (v) prioritize research needs for predicting and managing biogeochemical responses under future climates.

2. Overview of Soil Biogeochemical Cycles

Nutrient and element balances in the ecosystems are a function of biogeochemical cycles, especially in Plant-Soil systems, where the balance is regulated by the cyclic processes [11]. The C, N, P, S, and Si cycles are also critical processes that facilitate the movement and storage of nutrients and elements, which ensure that the plants and soil organisms receive the necessary elements to grow, produce energy and develop the structure of the body [10]. The interaction of biotic and abiotic variables is complicated by the fact that each cycle in the specific processes and pathways in which the cycles operate. Each cycle is briefly examined in the parts that follow, along with some underlying mechanisms, its

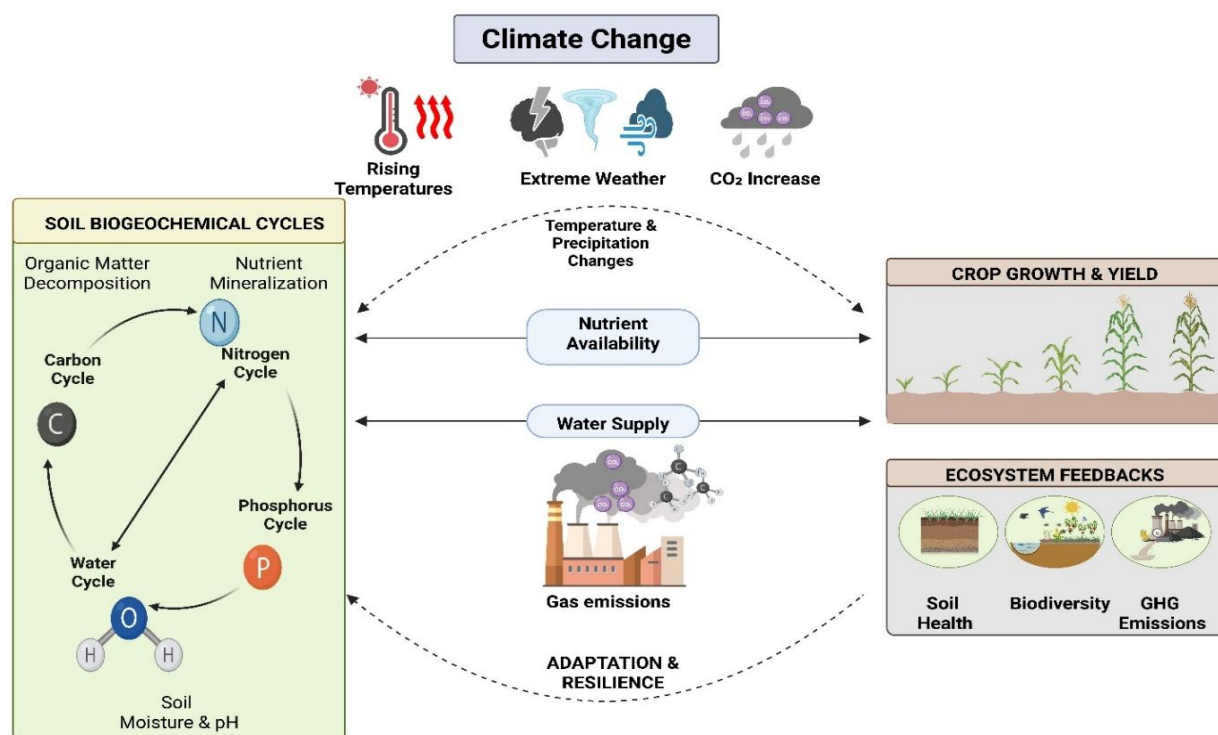


Figure 1. A Conceptual Framework of Soil Nutrient Cycling and Crop-Environment Interactions in Climate Change on a Systems-Based Conceptual Framework [7, 10, 11, 15].

importance for plant nutrition, and particular difficulties. Each section is broken up into three subsections for uniformity and clarity. A brief nutrient/element profile is provided in each of the first subsections, summarizing information on the element's natural plant availability, its importance in plant nutrition, molecular transformation processes, element limitations and management, and the effects of land use on the element's biogeochemical cycle. Selected elements from the first subsection are then covered in greater detail in the second and third subsections [17].

Although plant root, microorganism (bacteria, fungi) and soil animal respiration are significant sources of global CO₂ emissions, CO₂ is also sequestered in soils [18]. At the global level, the absorption of C by the atmosphere through the photosynthesis of land plants and the release of C through the soil respiration are quite balanced. The C cycle plays a critical part in the Plant-Soil systems, and it mediates the storage and movement of C between the atmosphere, the soil, and the vegetation. At a short time scale (i.e. up to hundreds of years), global warming has been observed to have substantial effects on increasing heterotrophic soil respiration, which may be harmful to the global carbon budget [15]. Soil carbon sequestration begins with photosynthetic fixation of atmospheric CO₂ into plant biomass and the subsequent transfer of plant-derived C to soil through roots, rhizodeposition, litter, and crop residues. The persistence of this C in soil depends on the balance between organic-matter inputs and microbial decomposition and on stabilization mechanisms such as mineral association, aggregation, and physicochemical protection. Decomposition therefore should not be regarded as a sequestration process itself, because

microbial mineralization can return organic C to the atmosphere as CO₂. Long-term soil C accumulation occurs when stabilized C inputs exceed C losses through respiration, erosion, leaching, and disturbance. During photosynthesis, plants absorb the CO₂ in the atmosphere and convert it into organic compounds, which are stored in the bodies of plants. These chemicals are decomposed by microorganisms as they break down plants and other organic materials into carbon, which is incorporated by the soil as organic matter (SOM) [19]. This SOM (along with humus) serves as a very important C reservoir, enhancing soil fertility and water retention. Examples of the agricultural methods that enhance the biological C sequestration in soils include conservation agriculture, cover crops and biomass recycling.

Chemical soil weathering removes CO₂ from the atmosphere and regulates the CO₂ concentrations in the atmosphere at a multimillion-year scale. Enhanced silicate weathering has been investigated as a potential approach to atmospheric CO₂ removal in the atmosphere is to increase the chemical weathering of the same, such as through liming [20]. The N cycle is important to Plant-Soil systems because it converts inorganic air N into the forms needed by plants. Free-living bacteria such as *Azotobacter* and symbiotic bacteria such as *Rhizobium* are commonly associated with leguminous plants and are involved in N fixation [21]. Biological nitrogen fixation is mediated by diazotrophic microorganisms that reduce atmospheric N₂ to ammonia (NH₃), which is rapidly protonated to ammonium (NH₄⁺) under biological and soil conditions and subsequently enters plant-soil N cycling. Abiotic processes such as lightning, industrial fixation, although to lower extents, also influence the availability of N. Lightning provides the energy required

to form NO (nitrogen oxides) when the N_2 in the atmosphere reacts with oxygen. NOx reacts with oxygen to produce nitrogen dioxide (NO_2) after cooling, and as a result, the reaction of NOx and ozone produces nitric acid (HNO_3) through chemical reactions [22]. This acid eventually produces NO_3^- (nitrate) in soil form that can be readily taken up by plants. Significant are the processes of nitrification and denitrification, which manage the conversion and movement of N in the soil following the process of N fixation. Nitrification is an aerobic microbial process in which ammonia/ammonium (NH_3/NH_4^+) is first oxidized to nitrite (NO_2^-) and subsequently to nitrate (NO_3^-). Nitrate is an important plant available form of N, although both NH_4^+ and NO_3^- can contribute to plant N nutrition. Denitrification, on the other hand, restores nitrate in the atmosphere by changing it into gaseous forms of nitrogen (N_2 or N_2O) [16]. On the one hand, this has increased the food supply due to the intensive application of N fertilization, making it possible to produce many crops with a small amount of land. Yet, in numerous agricultural Plant-Soil systems, the abundance of reactive N (i.e., all N compounds except N_2) has created ecological hazards, including the release of greenhouse gas N_2O , soil health loss or eutrophication [23]. Because there is no theoretically available N in the rocks from which most soils evolved, annual harvest-related N removal from agricultural Plant-Soil systems must be supplied to maintain productivity.

In each agricultural Plant-Soil system, the N fertilization rate should be adjusted to the N requirements of a particular crop to maximize crop yields and minimize N losses [24]. Synthetic fertilizers are typically the preferred method in this situation, particularly in intensive agricultural systems, due to their accessibility, ease of application and transportation, and affordability. The Haber-Bosch process, which uses hydrogen (H_2) from natural gas (CH_4) to react with N_2 under high temperature and pressure to form NH_3 , fixes N_2 during the manufacturing of industrial N fertilizer [25]. Numerous additional N sources, such as compost or manure, are utilized in agricultural Plant-Soil systems in addition to synthetic N fertilizers. A comparative summary of N sources and their respective contributions to crop productivity and soil [26].

The P cycle relies mostly on the weathering of phosphate-bearing rocks to release P into the soil, unlike the N and C cycles, which have a sizable gaseous phase. After entering the soil, organic P is transformed into inorganic forms that plants can use through a process known as mineralization. However, because of its great attraction for soil particles, which immobilizes it in forms that cannot be absorbed, P availability is frequently restricted [27]. An example is that the negatively charged phosphate ions are bound to positively charged components in the soil such as silanol groups (in clay minerals), carboxyl groups (in organic matter) and iron (Fe) and aluminium (Al) oxides.

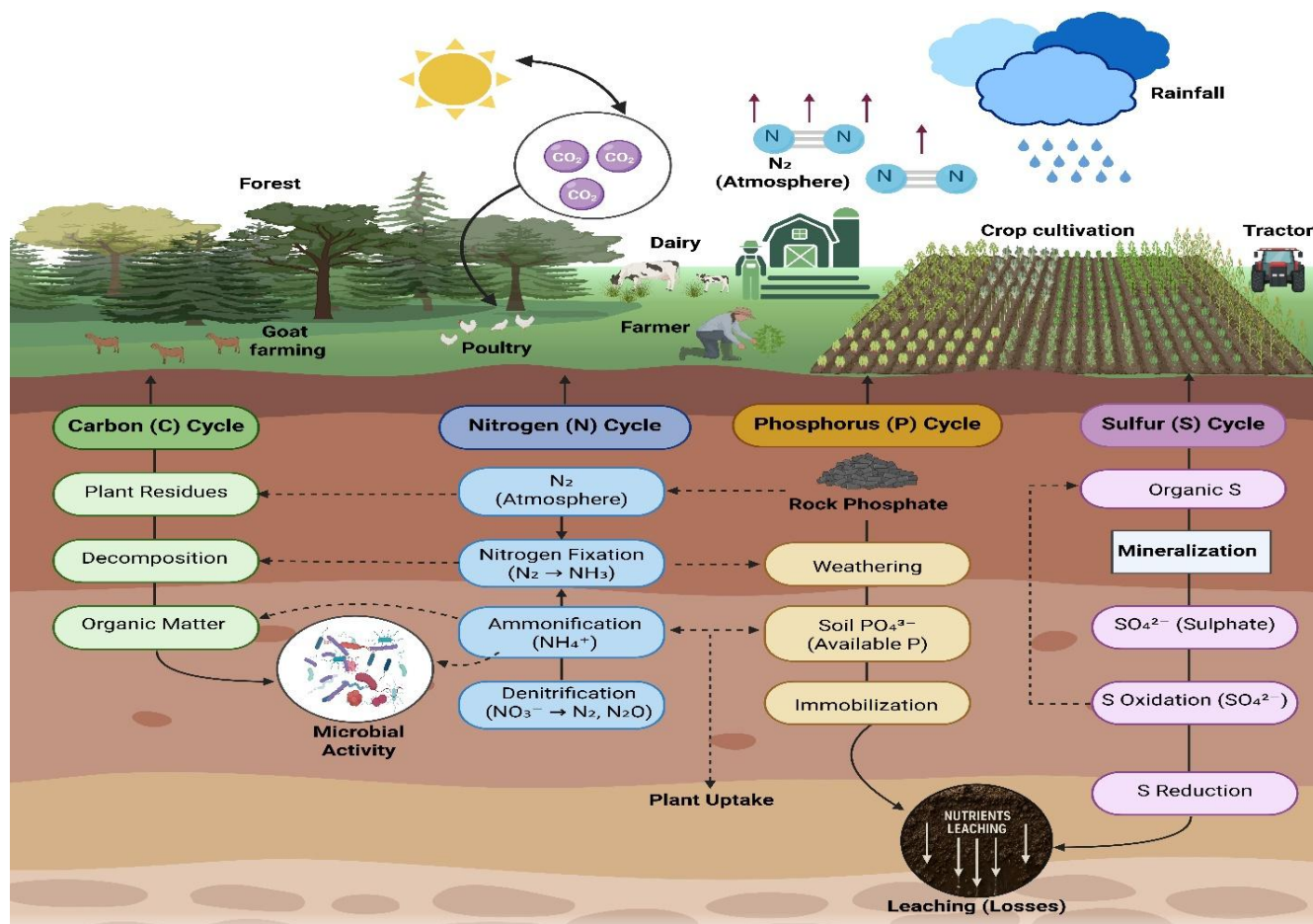


Figure 2. Agroecosystems: Important Cycles of Soil Biogeochemistry (C, N, P and S) [7, 35, 36, 37, 45].

Table 1. Soil Biogeochemical Cycles of Major Processes, Key Major Processes and their roles in crop productivity.

Nutrient Cycle	Major Processes	Role in Crop Productivity	References
Carbon	Decomposition, respiration, Photosynthesis,	Critical element of any organic matter, it improves soil structure and water-retention capacity and has a prospective use in climate change management.	[34]
Nitrogen	N fixation, nitrification, denitrification,	Important chlorophyll, nucleic acids, phytohormones, and vital parts of proteins.	[35]
Phosphorus	Weathering, mineralization, precipitation	Important in the formation of DNA and RNA, cell membrane formation and energy delivery (ATP).	[36]
Sulfur	Weathering, mineralization, atmospheric deposition	Vital in the synthesis of amino acids, protein synthesis, enzyme generation and chlorophyll generation.	[37]

Moreover, during the formation of minerals, they remain immobile when the phosphates are in association with minerals, such as calcium (Ca), iron (Fe) and aluminium (Al). Biochar, rock phosphate and phosphate-solubilizing microbes are soil additives that enhance P accessibility [28]. These interventions are particularly important in agricultural systems where crop yields may be limited by P deficits, which will be achieved using mined rock phosphate, an exhaustible and non-renewable mineral. China, Morocco and the United States produce about 70 per cent of all phosphates in the world today. The Mediterranean Sedimentary Phosphate Province (including Morocco, Spain, Algeria, and Tunisia) and the Western Phosphate Fields (the United States) have the world's greatest phosphate resources, with deposits thought to persist for over a millennium. Despite these enormous resources, a sustainable management of global P resources is necessary due to variables like rising P demand, geopolitical limits, rising prices, and ecological consciousness against the backdrop of global change. Since the majority of the world's phosphates are used in the creation of synthetic P fertilizers, agriculture is crucial to the demand for these fertilizers [29]. Overuse of synthetic P fertilizers degrades soil health and contributes to eutrophication in water bodies through P discharge from agricultural fields. Before deciding on P fertilizer rates, farmers should evaluate the P status (i.e., plant availability) of their soils and the P demands of certain crops in order to prevent P fertilizer misuse. Precision farming and the application of bio-inoculants (fungi and bacteria) are potential methods to improve crop P utilization efficiency [30].

Soil minerals and rocks are formed through volcanic eruptions, geothermal vents and the release of soil minerals and rocks through weathering. Human activities, including agriculture and the burning of fossil fuels, have a great effect on the biogeochemical S cycle, in (Figure 2). Climate, vegetation, soil processes (such as leaching, adsorption-desorption, precipitation and oxidation-reduction reactions), and soil microbial activity all significantly affect the concentration of SO_4^{2-} in soils [31]. In Plant-Soil systems, S cycling entails the chemical and microbiological modification of S molecules. The most plant available form of S, SO_4^{2-} , is produced when microorganisms oxidize S molecules under aerobic conditions. The S cycle is completed by sulfate reducing bacteria in anaerobic environments to produce H_2S . S is required in plant nutrition as it is the building block of

essential amino acids such as methionine and cysteine. These amino acids are required in enzymatic processes and protein synthesis [32]. In the 19th and 20th centuries, S inputs to agricultural Plant-Soil systems were mostly as atmospheric wet (also known as “acid rain”) and dry depositions, which were caused by industrial SO_2 emissions and had detrimental effects on the environment, including air pollution and the acidification of terrestrial and aquatic ecosystems [32]. Industrial S emissions are declining due to more stringent emission laws in several nations worldwide. Si is advantageous to plants, strengthening their resilience to stress and so improving plant performance and ecosystem functioning, particularly under stressful situations [33].

3. Soil Biogeochemical Processes and Crop Growth

Soil biogeochemical processes play a vital role in crop production, which includes nutrient supply and uptake by crops, mediation of nutrient cycling by soil microbes and soil organic matter contribution to soil fertility. The basis of ecosystem productivity and sustainable agricultural practices is based on these interactions. Biogeochemical activities in soil play a vital role in crop development because they mediate nutrient availability, in (Table 1), affect the uptake of plants, and is known to add to the general soil fertility [15]. These are highly interconnected and environmentally sensitive processes that are very dependent on climatic variation. Plant growth and crop yield depend mostly on the availability of nutrients in the soil [38]. Carbon, hydrogen, and oxygen constitute the major non-mineral elements of plant biomass, whereas mineral nutrients acquired primarily from soil represent a smaller but physiologically essential fraction. Their relative proportions vary among species, organs, developmental stages, and whether composition is expressed on a fresh- or dry-matter basis; therefore, a universal 96%:4% partition should not be assumed [39].

Altered climatic conditions due to altered precipitation cycles and concentration of carbon dioxide influence the process of nutrient mineralization, decomposition and leaching in the soil. First, higher CO_2 may enhance organic matter accumulation, enhance nitrogen fixation and improve soil characteristics, hence improving mineral liberation. Nevertheless, the drastic extreme conditions, such as drought or waterlogged soil, may hamper the balance of nutrients and

reduce the availability of mineral nutrients for plants. As an example, drought causes a decrease in soil moisture, and hence in the movement of nutrients such as nitrate, sulfate, calcium, magnesium and silicon to the root of plants [40]. This also affects the growth and functioning of roots, which further prevents the acquisition of nutrients. Sustainable agriculture aims at enhancing the efficiency of nutrient utilization by ensuring improved estimates of the nutrients available in the plants and improved crop responsiveness to the administered nutrients. Some of the main sources of nutrient supply and cycling to plants include microorganisms found in soil, including fungi, bacteria and protozoa. These microorganisms also contribute greatly to the breakdown of organic matter and conversion of nutrients to forms that are easily absorbed by plants. They facilitate absorption and cycling of nutrients through mineralization, solubilization, chelation and oxidation/reduction [41]. Microbial communities are quite important in biogeochemical processes of carbon, nitrogen and phosphorus, in (Table 2). As an illustration, nitrogen-fixing bacteria establish symbiotic associations with plants whereby they convert nitrogen in the atmosphere to ammonia, which plants can use [42]. Mycorrhizal fungi also establish mutualistic interactions with plant roots and enhance the uptake of phosphorus in exchange for plant carbon. Heterotrophic microbial communities regulate the breakdown and build-up of organic material in terrestrial ecosystems, which is facilitated by their growth, activity, and turnover [43]. Microbial communities are organized by the supply of nutrients such as phosphorus and nitrogen to form a nutrient cycling process in nutrient-poor soils [44]. The microbial processes are essential in the

conduction of nutrient availability, and the microbes decompose the organic matter to release nitrogen, phosphorus, and carbon compounds to the soil. This is a complex microbial process that maintains the growth of plants and manages the loss of nutrients [45].

The importance of Soil organic matter (SOM) to the functioning and fertility of soil is a direct supply of the elements available to plants and indirectly through interactions with nutrient cycling (Figure 3). SOM is a source of essential macro and micronutrients, as well as a primary food source of soil microbes [3, 20, 46]. It improves ion exchange, water retention capabilities, and infiltration, and also increases the formation of soil aggregates, which are also beneficial in ecosystem health and productivity. The strong linkage between SOM and nitrogen can be seen in the biochemical processes that predominate the nitrogen cycle, whereby SOM is the major source of nitrogen within the natural ecosystems [47, 46]. SOM availability and quality have a strong impact on microbial nitrogen immobilization and mineralization, which can have a short-term impact on the nitrogen availability of plants, but will also limit nutrient loss during low plant uptake. Warmer temperatures in changing climates may increase the rate of decomposition of SOM and cause the loss of carbon, which may affect soil fertility. On the other hand, one of the effective measures of climate change in the agricultural sector is to increase the content of SOM as it helps to mitigate climate change by capturing CO₂ in the atmosphere and enhances the water retention and soil structure. The SOM should be maintained and developed by using such practices as regular soil testing, which is crucial to sustainable agriculture [47].

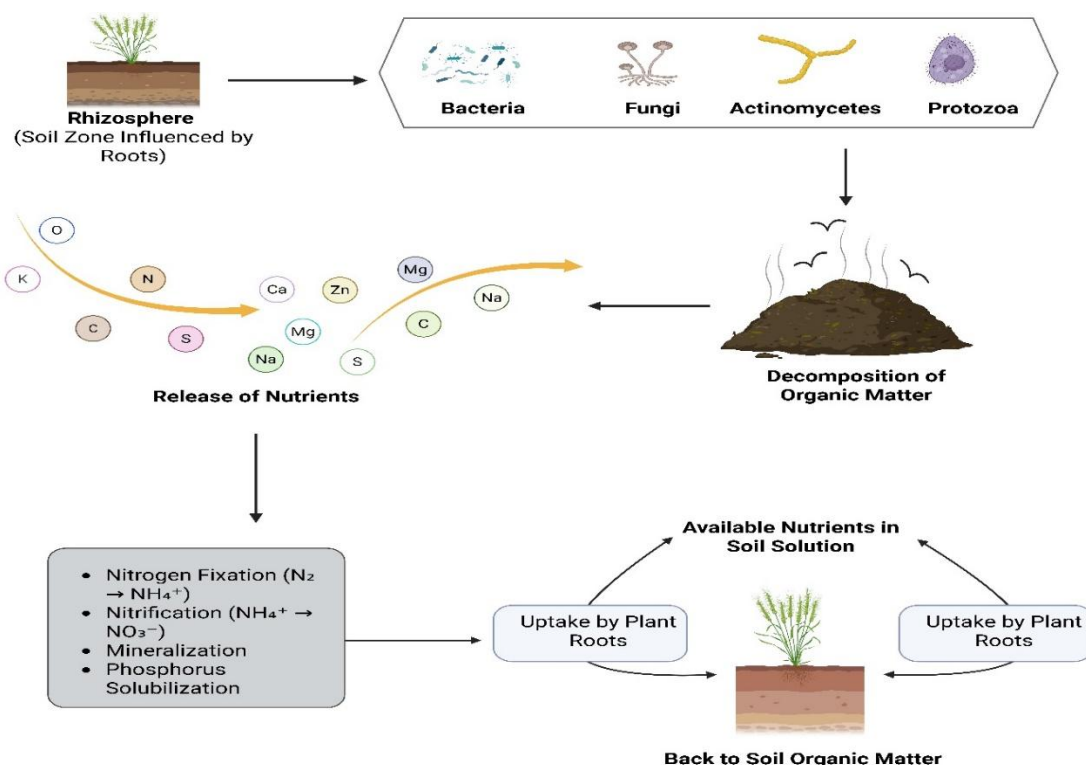


Figure 3. The functions of the Soil Microorganisms in the nutrient cycling and intake of nutrients by plants [1, 35, 41, 43, 45].

Table 2. Major microbial processes involved in soil nutrient transformations affecting crop growth.

Microbial Process	Nutrient Affected	Process Description	Microorganisms Involved	Increases biologically available N and can reduce dependence on external N inputs, particularly in effective symbiotic associations	References
Nitrogen Fixation	Nitrogen (N)	Microbial reduction of atmospheric N ₂ to NH ₃ /NH ₄ ⁺ through nitrogenase-mediated biological N fixation.	Rhizobium, Azotobacter, Cyanobacteria	Provides nitrogen, which enhances growth.	[113]
Nitrification	Nitrogen (N)	Aerobic microbial oxidation of ammonia/ammonium to nitrite, followed by oxidation of nitrite to nitrate (NH ₃ /NH ₄ ⁺ → NO ₂ ⁻ → NO ₃ ⁻).	<i>Nitrosomonas</i> , <i>Nitrobacter</i>	Produces nitrate (NO ₃ ⁻), a plant-available form of nitrogen that can be directly absorbed by roots but may also be lost through leaching or denitrification.	[48]
Denitrification	Nitrogen (N)	Stepwise microbial reduction of nitrate through the pathway NO ₃ ⁻ → NO ₂ ⁻ → NO → N ₂ O → N ₂ , predominantly under oxygen-limited conditions	<i>Pseudomonas</i> , <i>Clostridium</i>	Removes reactive N from soil and can reduce N availability to crops; incomplete denitrification also releases N ₂ O, a potent greenhouse gas	[115]
Mineralization	Organic nutrients	Inorganic production of nutrients by the breakdown of organic substances.	Heterotrophic fungi	Breaks down nutrients in vegetable forms of availability.	[49]
Ammonification	Nitrogen (N)	Microbial conversion of organic nitrogen compounds into ammonia (NH ₃), which predominantly occurs as ammonium (NH ₄ ⁺) under typical agricultural soil conditions.	Heterotrophic bacteria and fungi	Releases ammonium (NH ₄ ⁺), which can be directly absorbed by plant roots, immobilized by microorganisms, or converted to nitrate through nitrification.	[50]
Phosphorus Solubilization	Phosphorus (P)	Dissolves phosphates that are not soluble (H ₂ PO ₄ ⁻)	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Aspergillus</i>	Increases phosphorus levels in plants.	[78]
Sulfur Oxidation	Sulfur (S)	To obtain the sulfate, sulfur compounds can be oxidized to sulfate (SO ₄ ²⁻).	<i>Thiobacillus</i> spp.	Avails sulfate form to the plants.	[12]

4. Climate Change Effects on Soil Biogeochemical Cycle

4.1. Effects of warming

Climate change also has a major effect on soil biogeochemical cycling by modifying the temperatures, precipitation patterns and extreme weather patterns (**Figure 4**), which affects the cyclic movement of vital elements such as carbon, nitrogen, phosphorus, sulfur and silicon. Research has shown that soil carbon turnover is more sensitive to temperature change in colder climates than warmer climates. As an example, decadently cycling Soil Organic Carbon (SOC), which is a significant portion of the entire soil carbon store, is much more temperature sensitive to decomposition than the more rapidly cycling SOC [51]. The feedback between climate

change and the global carbon cycle is extremely vital as the carbon response of soil in response to an increase in temperature [41]. Although cumulative soil respiration tends to rise with temperature, it is usually greater in cold than in warm biomes. This warming microbial effect and soil respiration have the potential to result in a reduction of carbon storage in soil [52]. It is, however, not clear the extent of carbon loss that occurs in the soils of the tropical areas since non-climatic variables such as the input chemistry of plants, nutrient availability and the composition of the decomposer community also affect the flux to changing temperatures [53]. Communities of microbes display an adaptation to their environmental temperatures, whereby in warmer environments, we have warm-shifted relationships, whereas in colder environments, we have cold-shifted relationships.

The temperature dependence of soil respiration (Q10),

that is the rate at which CO₂ is emitted per 10 degrees C increase in temperature, is a critical value in assessing the strength of feedback between soil carbon efflux and global warming [54, 53]. Q₁₀S are usually large at low temperatures (e.g., 5-15 °C) and usually decrease with an increase in temperature. This is a negative correlation between Q₁₀ and temperature, which is found in numerous empirical studies. The dynamics of temperature sensitivity of both microbial growth and respiration are interconnected in a variety of biomes with different soil properties and different climates [55]. The alterations in precipitation patterns have great effects on soil nitrogen cycling, which mainly affects the diffusion of nitrogen and uptake by plants and microbes. Precipitation has a direct impact on the cycling of nitrogen by changing the availability of soil water, soil erosion, and soil leaching and an indirect impact by changing the activity of the microbes or plant nutrient uptake [56]. Raised precipitation has the potential to facilitate mineralization and enhance soil nutrient availability, which consequently boosts plant net primary productivity (NPP), which is a limiting factor to nutrient uptake in plant soils. But excess rain may also cause a rise in the amount of nutrients run off and washed away, and this lowers the nutrients in the soil [57].

4.2. Effects of elevated atmospheric CO₂

Alterations in precipitation and runoffs may also favor the release and dissolution of nutrients from soils, particularly during rainy seasons that are mostly accompanied by an increase in temperature. High levels of CO₂ in the atmosphere (eCO₂) form one of the key contributors to climate change, which affects the activities of soil microbes and carbon and nitrogen levels. Prolonged eCO₂ can play an important role in enhancing microbial biomass carbon (MBC) and nitrogen (MBN) in rhizospheric soil [58]. The number of fungal internal transcribed spacer (ITS) sequences would tend to grow under eCO₂, whereas the amount of 16S rRNA in rhizospheric soil could decrease. The imbalance between carbon and nitrogen in crops, which are basic to their growth and nutrient content, may also be caused by high CO₂ [59].

The plants grow, and the water in the soil is absorbed by the plants, providing the plants with nutrients like iron and manganese. Even though high CO₂ has a tendency to increase the rate of growth of plants as well as increase the general amount of nutrients in plants (**Table 3**). Their concentrations in plant tissues may decrease because of biomass dilution and hence may decrease the amount of nutrients. It has been evident that eCO₂ can enhance nitrogen fixation by a considerable percentage (as much as 73 per cent) and enhance grain yield (10-11 percent) [60]. Additionally, the eCO₂ is capable of enhancing root development, thus allowing the roots to search in a more significant soil and hasten the obtaining of nutrients. High CO₂ may also impact the soil microbial mineralization and nutrient recycling, possibly changing soil pH to acidic, and enzyme activity such as amylase and urease [61, 62]. The net effect of the high CO₂ concentration of soil organic carbon and nutrient cycles is complicated, with research indicating that the high plant

productivity and greater carbon input into soils may lead to SOC storage, although there is an increase in the decomposition of the ancient carbon, hence, alleviating climate change. Nevertheless, how the carbon of soil is going to respond to eCO₂ is a significant uncertainty in climate scenarios [63].

4.3. Effects of excessive soil moisture and waterlogging

Excessive soil moisture and waterlogging affect biogeochemical cycling differently from drought because saturation restricts oxygen diffusion and lowers soil redox potential. Under oxygen-limited conditions, aerobic decomposition and nitrification generally decline, whereas denitrification and methanogenesis can increase, potentially enhancing N₂ O or CH₄ losses depending on redox conditions and available substrates [64, 65]. Prolonged saturation can also alter Fe- and Mn-mediated P retention, increasing dissolved P availability or loss in some soils. Responses vary strongly with texture, drainage, organic-carbon availability, temperature, pH, duration of inundation, and microbial community composition. Thus, greater precipitation cannot be assumed to improve nutrient availability uniformly; moderate increases in soil moisture may stimulate mineralization, whereas prolonged saturation can shift nutrient pathways toward gaseous or hydrological losses [66, 65].

5. Soil-Crop-Environment Dynamics in Agroecosystems

Soil-crop-environment interactions are governed by feedbacks among nutrient transformations, root acquisition, microbial activity, and pathways of nutrient loss. Mineralization and biological N fixation increase pools of plant available nutrients, whereas immobilization, sorption, precipitation, leaching, volatilization, and denitrification determine how much of those nutrients remains accessible to crops [65]. Plants modify these processes through nutrient uptake, rhizodeposition, root-induced changes in pH and redox conditions, and associations with rhizobia, arbuscular mycorrhizal fungi, and other rhizosphere microorganisms. In turn, nutrient availability regulates photosynthesis, biomass production, root development, and the quantity and biochemical composition of residues returned to soil [69]. This creates a feedback loop in which crop growth modifies subsequent soil C and nutrient cycling. When nutrient supply exceeds crop demand, however, the same cycles can generate environmental costs through nitrate leaching, P runoff, NH₃ volatilization, N₂ O emissions, and eutrophication. Therefore, synchronizing nutrient release with crop demand is the key mechanistic link between productive and environmentally efficient agroecosystems [64, 65].

The health of soils is central to supporting crop yield and suppressing environmental effects in agroecosystems [70]. This is through complex interactions between plants and soil, which, when managed adequately, will help minimize greenhouse gases and loss of nutrients [71].

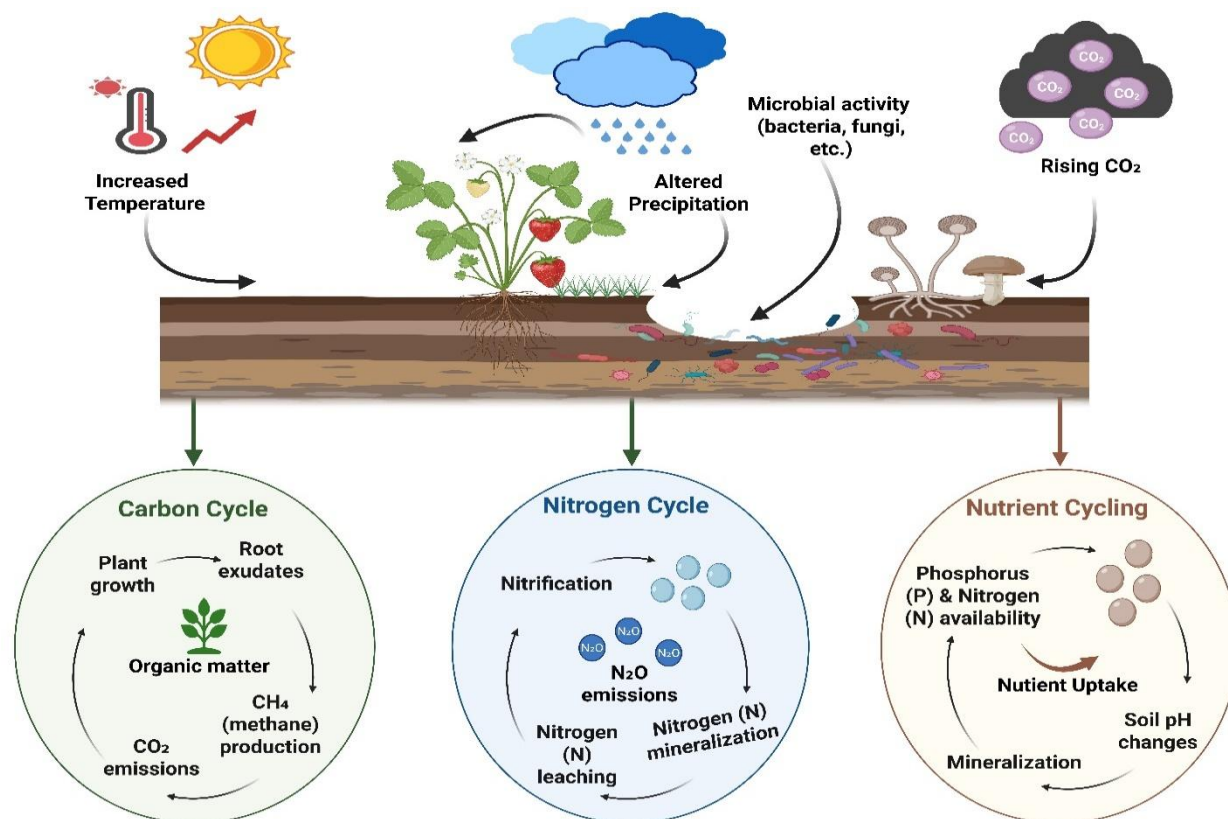


Figure 4. Biogeochemical Cycles (Carbon, Nitrogen and Nutrient Dynamics) of Soil Drivers of Climatic Change [51, 52, 55, 58, 60].

Table 3. Effects of Climate Change Drivers on Soil Nutrient Cycling and Crop Productivity.

Climate Change Driver	Effect on Soil Nutrient Cycling	Effect on Crop Productivity	References
Elevated CO ₂	Typically, does not have an effect on the status of soil nutrients; may elevate soil levels of P.	Increases yield and biomass production of certain crops, although it may decrease nitrogen and phosphorus levels in plants (dilution effect).	[111]
Warming/Heat Stress	Stimulates the mineralization and nitrification of nitrogen in soil, though it may also inhibit the activity of the microbes as well as the mineralization of the nutrients in dry soils.	Decreases the overall plant growth, uptake of nutrients by the roots and crop harvesting; reduces the levels of nutrient (N, P, K) content of plant structures.	[67]
Drought	Reduces the metabolism of the microbes and nutrient recycling, resulting in poor nutrient supply.	Decreases the biomass and growth rate of plants, crop productivity and nutrient (N, P) levels in plant tissues.	[68]
Excessive soil moisture/waterlogging	Restricts oxygen diffusion and lowers soil redox potential, suppressing aerobic decomposition and nitrification while potentially enhancing denitrification, methanogenesis, and N ₂ O or CH ₄ emissions. May alter Fe- and Mn-mediated phosphorus retention and increase nutrient losses.	Reduces root aeration, nutrient acquisition, and growth; prolonged waterlogging may decrease biomass and yield. Responses depend on crop tolerance, soil properties, and duration of saturation.	[64–66]

Soil is a vital natural resource which contributes water, nutrients, and mechanical support to the development of plants. In an agroecosystem, the process of soil manipulation by continuous addition of inputs, microbial extraction,

alteration of water balance and microbial life affects soil characteristics. Soil health is an integrative aspect that portrays the ability of the soil to react to agricultural interventions so that agricultural production can be

maintained and other ecosystem services provided [72]. Physical, chemical, and biological health of soil is an important factor that needs to be maintained to ensure soil is healthy, and this can be done through several agronomic methods. Some of the essential processes that are promoted by healthy soil include nutrient cycling, microbial activities, soil structure integrity and pest control [73]. Healthy soil is also associated with growing healthy food, human health and the quality of the environment.

The recommendation of management methods aimed at soil health can provide a promising solution to environmental effects and even higher economic gain [74]. Plant-Soil feedback (PSF) refers to the mutual interactions in which the properties of the soil are modified by plants and, consequently, these properties affect the performance of plants in the future [75]. These processes entail the response of plants to the environment of the soil and actively transform the rhizosphere by exuding carbon compounds through roots, developing particular microbial species, and changing the soil itself [62].

The scale of operation of PSFs ranges between short-term interactions and long-term legacies [76]. Nutrient Cycling Plants can also have a major impact on the nutrient cycle in soil by rhizodeposition, nutrient absorption, litter chemistry, and mycorrhizal associations. The timing of the supply of nutrients and their demand by plants in the soil is the key to productivity and sustainability. Low synchrony may result in surplus soluble nutrients, nutrient loss and environmental contamination, or nutrient deficiencies restricting plant growth [10]. Soil microbial communities are also important components of PSF, and site-to-site differences as well as PSFs influence plant community composition and ecosystem functioning. The key to such feedback effects is specific microbial functional groups, including Arbuscular Mycorrhizal Fungi (AMF) and rhizobia. Plant diversity may facilitate synchrony through functional complementarity between organisms, as legumes fix nitrogen and various groups of microorganisms degrade organic matter [77]. Diversity among plants and microbes contributes to the stabilization of mutualistic interactions, including those between plants and their fungal or bacterial symbionts. This stabilization plays a vital part in synchrony systems such as Sync-Free OM, Sync-Inorganic and Sync-Market, which are based on resource exchanges. In an example, plants can redistribute energy to microbial companions that regulate nutrient uptake routes, equalizing the provision of various nutrients [78]. The agricultural systems also make their own marked contributions to environmental degradation in terms of climate change and other biodiversity losses in the form of Greenhouse Gas (GHG) emissions and leaks [79]. The food demand has led to greater releases of GHGs to the soils owing to the strengthening of the high-input farming practices [71]. N_2O and CH_4 are major agricultural greenhouse gases. On a 100-year time horizon, IPCC AR6 assigns a global warming potential (GWP₁₀₀) of 273 to N_2O and 27.0 to biogenic CH_4 relative to CO_2 (= 1); the corresponding value for fossil fugitive and process CH_4 is 29.8 [80].

The most common sources of the anthropogenic emission

of N_2O and CH_4 are agricultural soils [81]. Soil type, climate, intensive agriculture, the use of synthetic fertilizers, and management of crop residues are natural and anthropogenic drivers of GHG emissions, respectively [3, 25]. Greater rates of residue and nutrient application raise the levels of NO_3-N and NH_4-N , which may improve the fertility of the soil but result in greater GHG emissions. The most important aspect of regulating the level of emissions is the influence of the Soil Type, which is defined by physical and chemical properties of the soil, including texture, content of organic matter, pH, cation exchange capacity etc. [82]. As an example, clay soils are more prone to an anaerobic environment, which allows N_2O and CH_4 production, whereas sandy soils, because of more aeration, are more prone to produce more CO_2 and less N_2O and CH_4 . Eutrophication is due to the loss of nutrients in agricultural systems, especially nitrogen and phosphorus, which have eutrophic effects on the terrestrial and aquatic environments with great impacts on biodiversity, human health and economic activities [83]. Over 40 per cent of the world's food supply depends on synthetic N fertilizers, but their efficiency of use ranges between 20 per cent and 80 percent, indicating that a high percentage of N applied goes to waste. Such losses could be linked to shortcomings of existing strategies and the challenge of farmers accessing the knowledge and technologies required. Unsustainable management of soil can intensify soil erosion, culminating in acidification of soil and soil pollution. Ecosystems may become a source of CO_2 through loss of soil organic matter caused by processes such as ongoing nutrient losses, which eventually cause decline in the ecosystem in the long term [84].

6. Sustainable Soil Management Strategies

The application of conservation agriculture and the application of organic amendments, biofertilizers and microbial-based soil management practices are very crucial in improving the soil biogeochemical cycling under changing climatic conditions (Figure 5), and crop productivity of the soil [85]. These practices have been linked to a healthier soil, higher carbon sequestration rate and climate resilience, and that is why sustainable agricultural systems are in great need of these practices [18, 86]. Conservation Agriculture (CA) is defined as a mainstream practice of sustainable agriculture that emphasizes low disturbance of soil, in (Table 4), permanent soil cover, and diversified plant species. The system is designed to heal soil health and ecosystem resilience, decrease the cost of farming and enhance soil security across many climates and soils [87]. There are many advantages associated with CA practices, such as no-tillage, crop rotation, and keeping crop residue cover, which are beneficial to soils, crop yield, and the environment [25, 88]. One of the key practices of CA is no-tillage, which comprises the absence of ploughing in the traditional way, which ensures soil integrity and consumes less fuel due to the minimum use of machinery. This is done to aid in the preservation of soil cover, which is significant in the enhancement of the advantages of the below-ground food webs of food processes.

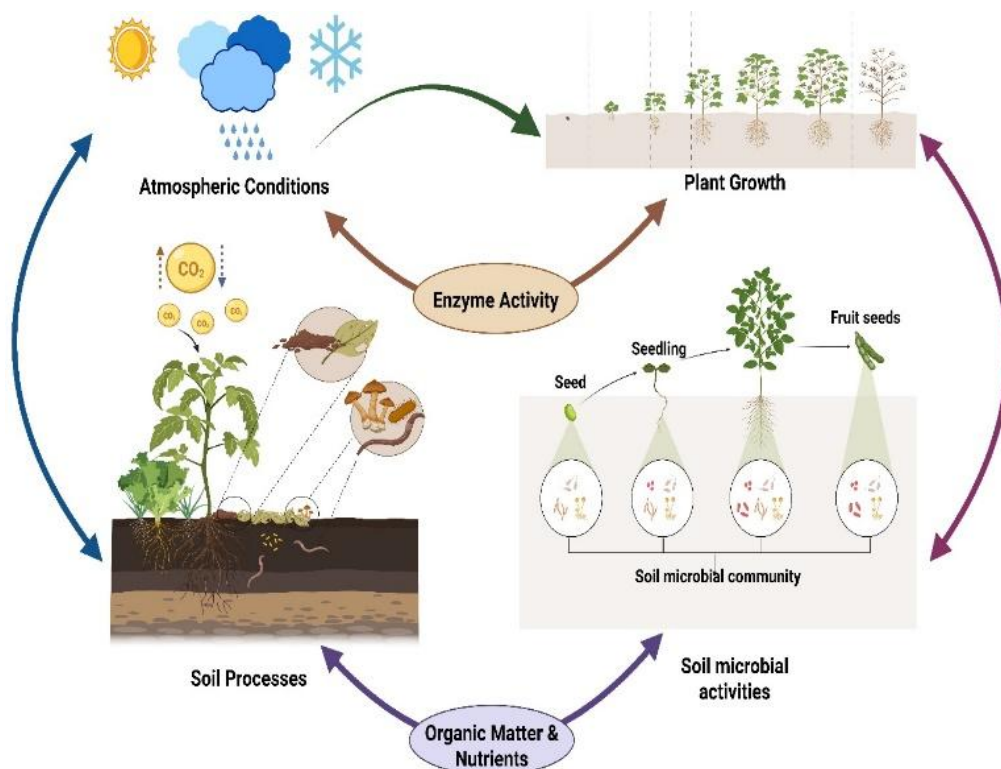


Figure 5. Climate Change Drivers and their energetics on Soil Biogeochemical Cycles (Carbon, Nitrogen and Nutrient Dynamics) [15, 40, 55, 63, 71]

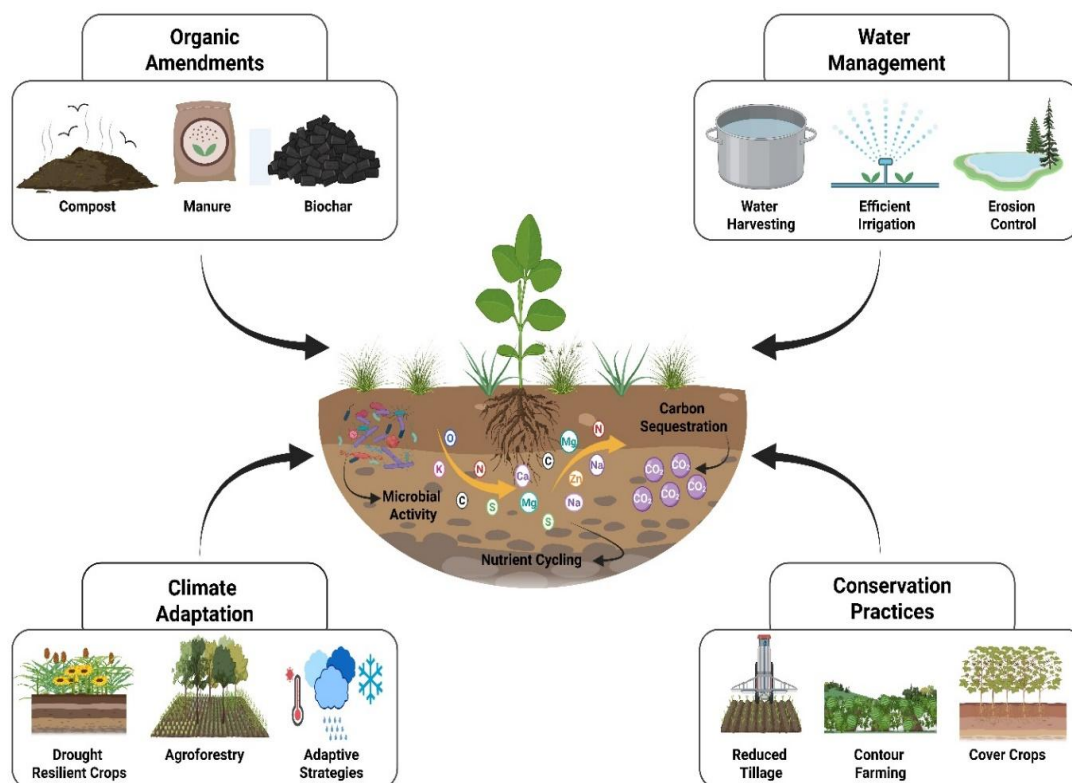


Figure 6. Sustainability of Society in Soil Management Practices to Enhance Biogeochemical Cycling and Health of Soil in Climate Change [85, 89, 91, 92, 100].

Table 4. Sustainable soil management methods to enhance soil biogeochemical flows and crop productivity.

Practice of Sustainable Soil Management	Description	Impact on Biogeochemical Cycling and Crop Productivity	Key Benefits	References
Conservation tillage practices	Minimize or eliminate tillage or no-tillage processes that can be defined by the existence of crop residues on the soil surface.	Reduces soil erosion, increases (SOC), enhances microbial health and activity, increases physical properties of soil (e.g. water-holding capacity, infiltration, aggregation), contributes nutrients in decomposing residues and has a positive impact on chemical soil properties (e.g. pH buffering, nutrient retention). Minimizes greenhouse gas emissions and can enhance long-term carbon storage of soil.	Improves carbon uptake, minimizes soil erosion and runoff, improves soil structure and water ability, and minimizes application of synthetic manure.	[3, 114]
Carbon Farming and Control of Soil Organic Carbon (SOC).	Strategies to enhance the quantity of carbon back in agricultural soils, which is largely achieved by increasing the storage of the soil organic matter.	Increases the water retention and fertility of soils, improves the soil structure and helps to curb climate change as it lowers the amount of atmospheric CO ₂ . Provides silicon to plants and reduces the need for plants for nitrogen fertilizers.	Enhances soil health and resilience, works to reduce climate change and increases nutrient cycling.	[114]
Crop Rotation	Planting alternatively dissimilar types of crops in the same region in sequenced seasons.	Helps control soil fertility, decreases soil erosion, enhances the health of the soil, augments the nutrient level in crops, and alters the cycles of pests and diseases. Planting deep-rooted crops aids in the recycling of nutrients in the soil.	Increases the fertility of soils, cycling of nutrients, minimizes the use of chemicals (pesticides, fertilizers), increases the biodiversity and improves water retention.	[110]
Organic Amendments	Organic substances added to the soil, including compost, manure or plant remains.	Anciently improves the fertility, soil structure, water-holding potential, growth of the plants, and alters the communities of the bacteria within the soil, thereby increasing nutrient cycling and nutrient availability.	Enhances the fixation of organic carbon in the soil, soil biological activity and microbial biomass and reduces the application of artificial fertilizer.	[100]
Soil Amendments	Treatment of soil to enhance either chemical, physical or biological properties.	Has the capacity to improve phosphorus availability and accessibility, promote soil structure, reduce soil pH, and stabilize soil organic carbon.	Fills in particular deficiencies of the soil, supplements the supply of nutrients and improves the overall health of the soil.	[101]

Cover crops, when planted in orchards, are also a good soil management practice to cover the soil surface against erosion as well as to conserve the environment. The rotation of crops with the use of legumes increases the spatial and temporal diversity of crops, increasing the abundance and diversity of the soil biota. The pest and pathogen growth is also mitigated through this diversification, thus reducing the use of chemical pesticides and fungicides. Moreover, crop rotation has been observed to alter the pest cycles and consequently, decrease the weed pressure as well as increase the general soil health [89]. Although the impact of CA on Soil Organic Carbon (SOC) varies across the world, with some situations recording growth and others reducing it, it can increase SOC levels relative to those under traditional management in desirable soil and climate conditions. Increased SOC is usually accompanied by better soil structure, water infiltration, soil water retention, plant nutrients, microbial biomass, diversity and yield [90]. An international study shows that CA can be of particular use in arid countries, where it has provided improved carbon capture and greater harvests. Conservation agriculture leads to a mean 21% improvement in soil health and can sustain the same level of crop production following

long-term practices [91]. But in some conditions, such as cold and wet climates, when the soil is poorly drained or where CA does not perform well in the local environment, it may not be an effective management system [92].

Organic amendments and biofertilizers are a part of sustainable soil management, which is essential in enhancing soil health (**Figure 6**), nutrient cycle and crop yield [85]. These methods are progressively known to be environmentally friendly and a source of sustainability and biodiversity [93]. Organic amendments consist of crop residues, compost, and green manure, which results in a rise of the content of Soil Organic Matter (SOM), thus improving the organization of soil, its aggregation, and water retention. Such shifts favor a more abundant microbial community, which is significant in the cycling of nutrients and soil structure. It was found out that organic matter-treated soil contains more carbon, and it also sustains a higher number of communities. When organic soil amendments are applied, the soil will capture more carbon compared to synthetic fertilizers. Another way to improve the water holding capacity and infiltration of soils can also be organic amendments, which make it possible to resist the problems associated with the

climate [94].

The benefits of these practices are nevertheless context dependent and should not be interpreted as universal. Conservation tillage may increase surface SOC and reduce erosion, but responses of whole-profile SOC and crop yield depend on climate, soil texture, drainage, residue availability, and duration of management; cool or poorly drained soils may show delayed warming and restricted crop establishment [97]. Biochar can improve nutrient retention, pH buffering, water-holding capacity, and carbon persistence, but its effectiveness varies with feedstock, pyrolysis temperature, application rate, soil properties, and crop type. High-pH or nutrient-rich biochars may be unsuitable for some soils, and poorly characterized materials can introduce salts, metals, or organic contaminants [98]. Likewise, microbial inoculants such as PGPR and AMF frequently perform well under controlled conditions but may establish inconsistently in the field because of competition with native microbiota, soil pH, moisture, temperature, crop genotype, and management history. Their agronomic value therefore needs to be evaluated against costs, persistence, yield stability, nutrient losses, and greenhouse-gas responses rather than short-term plant growth alone [99].

7. Knowledge Gaps and Future Research Directions

The existing body of work on soil biogeochemical cycles and their effects on crop-environment interactions is limited, but recent developments in technologies and future research agendas seek to overcome these limitations in shifting climates. An integrated discussion of interrelated biogeochemical cycles in terrestrial ecosystems, specifically an agro-plant-soil ecosystem, examines the underlying processes and interactions to extract the implications for ecosystem dynamics and services [102]. Existing studies in soil biogeochemical cycles have several limitations, especially regarding how cycles interact with each other and how they respond to global change. A major knowledge gap is the paucity of a full grasp of the impact of imbalances in one biogeochemical cycle on others, particularly when changes in climate and land-use occur [103]. Most Earth system models do not mechanistically describe soil processes, but instead represent them in some way as a black box. Moreover, available process knowledge of biogeochemical cycling in soils is heavily biased towards temperate latitudes, and cannot be broadly applied to low-latitude (tropics) or high-latitude (boreal/subpolar) climates with substantially different soil properties and developmental histories [104].

Major uncertainties remain in predicting how soil biogeochemical cycles will respond to increasingly variable climates. Four priorities deserve particular attention. First, interactions among C, N, P, S, and Si cycles need to be quantified simultaneously rather than inferred from single-element studies. Changes in one cycle can constrain or amplify others, yet such coupling remains poorly represented in many ecosystem models [105]. Second, responses to compound and sequential climate extremes require substantially greater attention. The consequences of drought

followed by intense rainfall, recurrent heat-drought events, and prolonged waterlogging may differ markedly from responses to isolated stresses because of microbial mortality, substrate pulses, altered redox conditions, and nutrient-loss events [35]. Third, the mechanisms through which plant traits, root exudation, microbial communities, and mineral surfaces regulate long-term soil organic-matter stabilization and nutrient availability remain insufficiently resolved, particularly in tropical, subtropical, dryland, and high-latitude agroecosystems [106]. Fourth, management recommendations require stronger evidence of transferability across soils, crops, and climates. Long-term, multi-site experiments should therefore compare conservation tillage, organic amendments, biochar, diversified rotations, and microbial inoculants using common measurements of crop productivity, nutrient-use efficiency, SOC stocks, greenhouse-gas emissions, and nutrient losses [107]. Future progress will require integration of isotope tracing, metagenomics and other molecular tools, continuous soil sensors, remote sensing, artificial intelligence, and process-based modelling. These approaches should be used not only to improve prediction but also to identify measurable thresholds at which soil-crop systems shift from nutrient retention to nutrient loss. Linking these biophysical advances with economic feasibility and locally relevant management constraints will be essential for translating biogeochemical knowledge into climate-resilient agricultural practice [108].

The development of technology provides hopeful solutions to the study and control of the biogeochemical cycles. AI algorithms can be used on different scales. This is a future trend in the field of soil monitoring; by making use of remote and flexible field sensors, digital soil mapping is being implemented. New Generation Soil Biogeochemical Models [109]. These are models that are being formulated to explicitly capture many eco-biogeochemical processes. Future developments of soil monitoring are high-resolution images, sensors, and localized and specific laboratory analysis, could be used to determine the products of photosynthesis, i.e. sugars, just deposited in the soil and can give information on the nutrient exchange in soil microsites.

The future research directions need to focus on a multidisciplinary approach to the complexity of the soil biogeochemical cycles. It is necessary to couple the study of biogeochemical processes with ecosystem models, socio-economic and policy studies to come up with holistic sustainable management schemes. More studies on natural resources in the future should address areas like close element cycles in agricultural Plant-Soil systems, the exploitation of the potential of adapted soil microorganisms, as well as cultivars of plants and the implementation of soil conservation techniques [16]. To have better predictions of the ecological and biogeochemical responses of soils to climate change, there is more need to understand the role played by the microbes in decomposition. Transdisciplinary methods of combining various fields of study into soil research are important in learning soil processes and their significance to humanity. The critical issue is properly considered to be effective soil conservation strategies. The fact that microplastics are a new possible pollutant, as well as the

creation of green technologies to restore the soil, are also significant [16].

8. Conclusion

Soil C, N, P, S, and Si cycles are interconnected components of agroecosystem functioning and jointly regulate nutrient availability, soil organic-matter dynamics, crop productivity, greenhouse-gas exchange, and nutrient losses. Climate change can disrupt these processes through warming, drought, excessive soil moisture, altered precipitation, and elevated atmospheric CO₂, but the magnitude and direction of responses depend strongly on soil properties, microbial communities, crop characteristics, and management. Consequently, no single soil-management practice can provide a universally effective response. Conservation agriculture, organic amendments, biochar, diversified cropping, and microbial inoculants can improve nutrient retention and resilience when matched appropriately to local soil and climatic conditions, but their trade-offs and long-term effects must also be considered. Future research should prioritize interactions among elemental cycles, responses to compound climate extremes, mechanisms of microbial and mineral stabilization of soil C and nutrients, and long-term multi-environment evaluation of management interventions. Integrating these processes into monitoring and predictive models will be essential for improving nutrient-use efficiency, limiting environmental losses, and designing productive and climate-resilient agroecosystems.

Author contributions

Tasnim Tahara: Writing – original draft, reviewing and editing, conceptualization, data curation, figure making, and visualization; Md. Nahid Mahmud: Writing, reviewing and editing, conceptualization, data curation, figure making, visualization, resources, software, formal analysis, and investigation; Nafiza Tasnim: Writing, reviewing and editing, conceptualization, and data curation; Muhammad Khizar Hayat: Reviewing and editing, conceptualization, data curation, and visualization; Jarif Billah: Writing, reviewing and editing, conceptualization, and data curation; Khorshed Hasan Abir: Writing, reviewing and editing, conceptualization, and data curation; Rida Batool: Writing, reviewing and editing, conceptualization, and data curation; Abdullah Al Kafi: Writing, reviewing and editing, and conceptualization; Rajesh Gudihalli Munivenkatappa: Writing, reviewing and editing, and supervision; Ayomide Emmanuel Fadiji: Writing, reviewing and editing, conceptualization, supervision, and investigation; Md. Minhajul Abedin: Writing, reviewing, and data curation; Tohfa A Mashruba: Writing, reviewing, and data curation. All authors have reviewed and approved the final version of the manuscript for publication.

Ethical approval

Not applicable.

Conflicts of Interest

The authors report no conflicts of interest.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used AI-assisted tools (specifically GPT-5) in order to polish the English language and enhance clarity. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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