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Comprehensive Analysis on Soil Keystone Species and Climate Resilience from the Perspectives of Biogeochemical Cycles

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Abstract. A keystone species is an organism that significantly impacts its ecosystem due to its essential role in maintaining biodiversity on top of other organisms. Keystone species have a crucial influence on the stability of the environment and require people's key protection. Soil keystone species specifically require more studies and protection. Soil contains the chemical elements essential for the growth and development of life, and soil keystone species, specifically soil microbial communities, transfer these chemical elements to living organisms and non-living environments through biogeochemical cycles. In the carbon cycle, soil microbial communities aggravate global warming by releasing CO_2 into the atmosphere through microbial respiration. Soil microbial communities also absorb and store carbon in the soil through decomposition, which increases SOC, promoting plant growth and stabilizing the ecosystem. In the nutrient cycle, specifically the nitrogen cycle, soil microbial communities can convert N_2 into usable forms for plants and reduce the amount of N_2O in the atmosphere through nitrogen fixation and nitrification. Still, their denitrification releases N_2O into the atmosphere and aggravates climate change. In the water cycle, soil microbial communities improve soil water-holding capacity and purify water. At the same time, they release and absorb water vapor in the atmosphere, affecting the climate. In this way, soil microbial communities positively and negatively affect the climate and ecosystem, creating a delicate balance system that may cause drastic effects if any minor changes occur. Therefore, more studies are needed to understand the net impact of soil microbial communities on the environment and climate.

Keywords: soil keystone species, ecosystem science, global warming, biogeochemical cycle

1. Introduction

A keystone species is an organism that has a significant impact on its ecosystem due to its essential role in maintaining biodiversity on top of other organisms. Losing those organisms in an ecosystem often leads to biodiversity decline and sometimes ecological collapse [1]. As a result, keystone species have a crucial influence on the stability of the environment and, therefore, require people's key protection. However, data from the research has shown that soil keystone species specifically

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receive less attention than other keystone species, even though they have a critical impact on soil ecology and even the climate on a global scale. Soil contains the chemical elements that are essential for the growth and development of life. Organisms obtain those essential elements from soil directly or indirectly and release them into the atmosphere. These chemical elements are transferred through living organisms and non-living environments, and the pathways they create are known as the biogeochemical cycles [2]. During the cycle, some chemicals react and form greenhouse gases such as CO_2, CH_4, and N_2O. These gases are released and accumulate in the atmosphere, which traps heat and increases the global temperature. The rising temperature not only increases human health risks but also negatively impacts soil keystone species, further disrupting the ecosystem [3].

As the main factors affecting soil's ability in those processes, soil keystone species also play a pivotal role in the global biogeochemical cycles. There are different types of soil keystone species, and we are going to focus on soil microbial communities in this study. Soil microbial communities are systems of microorganisms, including bacteria and fungi. They break down organic matter through decomposition, store nutrients in the soil by nutrient fixation, and release chemical elements through respiration. Those functions cause even the most minor changes in these organisms to have a significant impact on the entire ecosystem [4]. Therefore, it is abundantly clear that a nuanced understanding of the soil keystone species is critical for limiting global warming and maintaining the ecosystem.

However, the relationship between soil microbial communities, climate resilience, and the local ecosystem has not yet been fully understood. In current literature, soil microbial communities are shown to affect climate and local biota through their role in the carbon cycle. Soil microbial communities release carbon through their respiration process, which has been repeatedly shown to aggravate global warming. Their presence also plays a vital role in soil carbon storage, affecting other organisms' growth and the local ecosystem as a whole [5]. Still, the impact of soil microbial communities on climate and the biota is far more than that. There is still some gap in our understanding of the effect of soil microbial communities on climate and the ecosystem through the nitrogen and water cycles. N_2O and water vapor are also dominant greenhouse gases and occupy a large portion of the atmosphere; changes in nutrients and water in the soil also affect life's growth [6]. Therefore, the impact of the product from soil microbial communities in nutrient and water cycles should be studied more.

We believe soil microbial communities play a significant role in climate resilience and ecosystem dynamics. Hence, in this study, we collected data from several existing studies and systematically analyzed them to understand how soil keystone species affect climate and local biota through their roles in the biogeochemical cycles, specifically the carbon, nutrient, and water cycles.

2. Carbon cycle

Soil can act as both a carbon sink and a carbon source depending on its condition, which makes it a critical regulator of the global carbon cycle if it is managed properly. As soil keystone species, soil microbial communities affect soil carbon storage and, therefore, play a vital role in the carbon cycle. Soil microbial communities affect the carbon cycle mainly through two processes: microbial respiration and the decomposition of the organic matter.

2.1 Soil microbial respiration and carbon dynamics

Soil microbial communities directly affect the global carbon cycle by releasing about 60 petagrams of carbon into the atmosphere through yearly microbial respiration [7]. They respire by breaking

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down organic matter and releasing carbon into the atmosphere in the form of CO_2. CO_2, as one of the most important greenhouse gases, concentrates in the atmosphere and traps heat, accelerating climate change. The change of climate includes the rising temperature and the increasing rainfall. Pre-existing studies have shown that higher soil moisture can cause soil microbial communities to be more active and speed up soil respiration. For example, increased soil moisture level due to the increased precipitation, on average, stimulated microbial respiration by 26.1%, whereas decreased soil moisture level due to the decreasing precipitation suppressed mean microbial respiration by 49.9% [8]. With this effect, like how figure 1 shows, soil microbial communities release CO_2 which exacerbates climate change and raises the global temperature. Higher temperature accelerates microbial activity and increases CO_2 emissions, further aggravating climatechange.

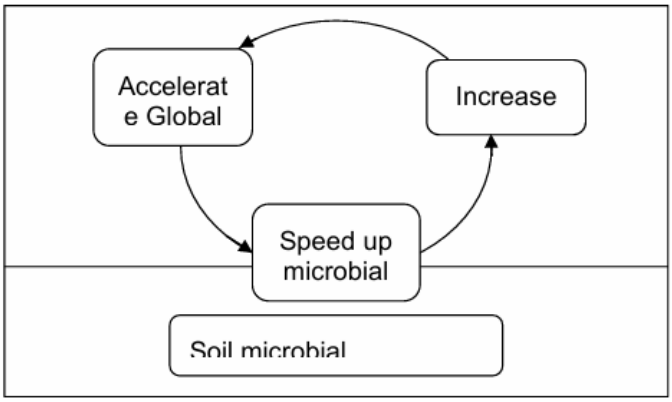

Figure 1: Soil microbial communities and climate change create a positive feedback loop triggered by soil microbial respiration, harming the environment [9].

2.2 Soil organic matter decomposition and carbon dynamics

However, microbial respiration is not the only way soil microbial communities affect the climate and local biota. As a carbon sink, soil also absorbs carbon to regulate the ecosystem, and soil microbial communities help this process by storing carbon through decomposition. The products of soil microbial decomposition are carbon-rich soil organic matter (SOM), which is essential for plant growth and the maintenance of the whole ecosystem. Some chemoheterotroph microbes like bacteria (Nitrosomonadales, Thermoanaerobacterales [10], etc.) and fungi (Arbuscular mycorrhizal fungi [11], etc.) break down once-living organisms and litter, which allows the carbon in the SOM to reenter the carbon cycle and make it available for other organisms to use. There are also chemoautotroph microbes such as Azospirillum lipoferum and Rhodopseudomonas palustris, which directly use CO_2 from the atmosphere to produce energy. In this way, soil microbial communities achieve carbon sequestration by storing atmospheric carbon back into the soil and completing the carbon cycle [12]. Based on current literature, microbial decomposition rate is partly determined by climate factors such as temperature and soil moisture level. Higher temperatures and moisture levels accelerate soil microbial decomposition, which increases soil organic carbon (SOC) production. Increasing SOC promotes plant growth, improving soil health and enhancing biodiversity. More active soil microbial communities also capture more CO_2 from the atmosphere, reducing climate change and stabilizing the ecosystem.

In general, soil microbial respiration and decomposition do not exist independently. Instead, they are highly affected by the climate and other factors. As global temperature and precipitation

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increase, soil microbial communities become more active, speeding up decomposition and respiration. Although soil microbial communities aggravate climate change through the positive feedback loop from their respiration, the benefit from their decomposition process is not ignorable. However, it is clear that more diverse soil microbial communities are needed to maintain a healthy ecosystem. However, the net effect of soil microbial communities on the global ecosystem is yet to be determined.

3. Nutrient cycle

Soil is a primary source of nutrients needed by organisms for growth. The three primary nutrients are nitrogen, phosphorus, and potassium. These nutrients are crucial for plant growth and development and can indirectly impact the ecosystem. Among all the plant nutrients, nitrogen has been proven to have the most critical impact on plant growth [13]. Soil microbial communities play a vital role in transforming nitrogen into a usable form for plants through nitrogen fixation and nitrification. At the same time, soil microbial communities reduce the amount of nitrous oxide in the atmosphere through denitrification, mitigating climate change.

3.1 Soil microbial nitrogen fixation, nitrification, and ecosystem

Soil microbial communities affect the amount of nutrients in soil for plant growth, directly influencing the local ecosystem. Nitrogen is the main component of chlorophyll, which determines the photosynthetic rate. More nitrogen forms more chlorophyll, which increases the rate of photosynthesis [14]. Faster photosynthesis means more energy is produced for plant growth and development, resulting in a more healthy and diverse ecosystem.

Nitrogen is essential to plants and the ecosystem, yet only about 1% of it is stored in the soil. Instead, about 78 to 79% of nitrogen is available in the atmosphere as N_2, which is unusable for plants [15]. However, soil microbial nitrogen fixation and nitrification can fix atmospheric nitrogen into forms that are usable by plants. During nitrogen fixation, nitrogen-fixing microbial organisms reduce N_2 and convert it into ammonia.

Nitrogen fixation: $N_2 + 8H^+ + 8e^- \rightarrow 2NH_3 + H_2$

Ammonia is later oxidized and converted into nitrite and then nitrate, which can be used for plants.

Ammonia oxidation: $NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$

Nitrite oxidation: $NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$

Plants with more nitrate available grow healthier and establish a sustainable ecosystem [16].

3.2 Soil microbial denitrification and climate change

Moreover, nitrogen is a significant component of the atmosphere, making up about 78% of it in the form of N_2 [17]. Although N_2 does not contribute to climate change, nitrogen compounds, like nitrous oxide, are greenhouse gases that hugely impact climate. N_2 can be converted into N_2O through denitrification of microbial communities. Soil microbes, essentially aerobic bacteria, reduce nitrate into N_2O and then N_2 during the denitrification [18]. So, N_2O will be formed as a byproduct if the process is incomplete. Soil microbial communities use the nitrate they formed from nitrification and convert it back into N_2O, contributing to the atmosphere. Although soil microbial denitrification completes and balances the nitrogen cycle, the effect of its N_2O formation can not be

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ignored. N_2O, as a greenhouse gas with 300 times the heat-trapping capacity of CO_2, not only traps heat in the atmosphere, accelerating climate change, but also depletes the ozone layer, causing health problems for plants and humans [19].

3.3 Soil microbial communities and eutrophication

Soil microbial communities play a significant role in eutrophication, which is the overload of nutrients in the water bodies, through its role in nutrient cycling. In nitrification, bacteria and fungi convert ammonia into nitrite and then nitrate. Nitrate can be used for plant growth but can also leach into water bodies and cause eutrophication [20]. However, studies have shown that denitrifying microbes convert nitrate back to nitrogen gas and reduce the amount of nitrogen for eutrophication [21]. Some soil microbial communities, such as mycorrhizal fungi, can also enhance plant nutrient uptake, which prevents the nutrients from leaching into the water, reducing the risk of eutrophication [22]. Generally speaking, ammonia-oxidizing bacteria release nitrogen into the aquatic system, promoting eutrophication; denitrifying bacteria remove nitrogen from water bodies, inhibiting eutrophication. With this said soil microbial communities can simultaneously increase and reduce the risk of eutrophication. Therefore, more studies are needed to determine the effect of soil microbes on eutrophication in different situations.

Overall, soil microbial communities play a crucial role in the global nutrient cycle and can influence the ecosystem both positively and negatively. Its nitrogen fixation and nitrification process can not only convert N_2 into usable forms for plant use but also reduce the amount of N_2O in the atmosphere, stabilizing the biota and mitigating climate change. However, its denitrification process releases more N_2O into the atmosphere and exacerbates climate change at the same time. Soil microbial denitrification reduces the amount of nitrogen in soil, inhibiting eutrophication, but its ammonia oxidation process releases nitrogen into water bodies, promoting eutrophication. It is hard to say which of these functions of soil microbial communities have a more significant effect on the environment. Still, its role in completing the nutrient cycle has made it indispensable to the ecosystem. More work is required to understand the net effect of soil microbial communities on biota and climate change.

4. Water cycle

Water is the fundamental ingredient for life on Earth; no life can live without it. It is vital for the growth and development of all living organisms. Especially for plants, the presence of water facilitates essential processes such as photosynthesis and transpiration. These processes generate energy not only for plants but also for the ecosystem as a whole. As a key factor of soil moisture, soil microbial communities store water in the soil with their unique structure. Some soil microbes can also clean the water through bioremediation, which can prevent eutrophication. In this way, soil microbial communities can affect the ecosystem through water availability. Moreover, soil microbial respiration also releases water vapor into the atmosphere as a byproduct, which is a greenhouse gas that will affect the climate.

4.1 Soil microbial communities, bioremediation and water availability

Water is one of the most essential parts of the soil system that supports the growth and development of many organisms. Plants under limited water conditions will experience a decrease in their growth due to the reduction of photosynthetic rates. Based on current studies, soil microbial communities

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can affect the soil's water-holding capacity. Soil microbes like bacteria produce a layer of polysaccharides or glycoproteins to form biofilms [23]. These substances bind soil particles together, forming microaggregates that improve soil structure. These microaggregates can also be formed by fungal hyphae [24]. Microaggregates are small compound soil structures that create pore space in the soil. More pores can hold more water and prevent it from draining too quickly, increasing the total water-holding capacity of the soil [25]. Overall, soil microbial communities improve soil structure and increase the water-holding capacity of the soil, providing more water for plants to use. However, this is not the only way soil microbial communities affect water in the soil; they can also affect water quality through Bioremediation [26]. Soil microbial communities can degrade pollutants such as oil and heavy metals, converting them into less harmful substances. In this way, soil microbial communities clean the water source as a filter, which increases the water quality, benefiting the ecosystem.

4.2 Soil microbial respiration and climate change

Soil microbial communities not only affect the water availability in soil but also affect the climate through its respiration process. As one of the greenhouse gasses, water vapor traps the infrared radiation inside the planet, contributing to the global temperature increase [27]. Soil microbial communities, although not directly producing it, release some amount of water vapor into the atmosphere as a byproduct of its respiration process. These water vapors accumulate in the atmosphere, aggravating climate change. However, as was said in section 4.1, studies have shown that soil microbial communities can increase soil water-holding capacity by forming aggregates. Higher water-holding capacity reduces evaporation from the surface of the soil, decreasing the water vapor released into the atmosphere, which slows down climate change. In most circumstances, these two processes happen simultaneously, so it is hard to say whether soil microbial communities accelerate or mitigate climate change. Therefore, more studies are needed to investigate the net effect of soil microbial communities on climate change.

Generally, soil microbial communities impact the water cycle through water movement and quality. They can improve soil structure by forming aggregates, which increases soil water-holding capacity. They can also break down pollutants, which improves water quality. Having sufficient and clean water supports the growth of plants and other organisms, increasing the biodiversity and sustainability of the ecosystem. Additionally, soil microbial communities regulate the flow of water vapor, which still needs more study to determine its net effect on climate change.

5. Conclusion

Through the research, soil keystone species, especially soil microbial communities, have been proven to play a crucial role in the biogeochemical cycles, affecting global climate and the ecosystem. In the carbon cycle, soil microbial communities aggravate global warming by releasing CO_2 into the atmosphere through soil microbial respiration. Higher temperatures speed up microbial reparation and increase the amount of CO_2 released in the atmosphere, which creates a positive feedback loop, further exacerbating climate change. However, soil microbial communities absorb and store carbon in the soil through its decomposition process. This process increases SOC, which promotes plant growth and stabilizes the ecosystem. Soil microbial communities have been found to positively and negatively affect the climate and ecosystem. This contradictory effect can be found not only in carbon cycles but also in nutrient and water cycles. In the nutrient cycle, specifically the

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nitrogen cycle, soil microbial communities can convert N_2 into usable forms for plants and reduce the amount of N_2O in the atmosphere through nitrogen fixation and nitrification. Still, their denitrification process can release N_2O into the atmosphere and aggravate climate change. Soil microbial denitrification reduces the amount of nitrogen in soil, inhibiting eutrophication, but its ammonia oxidation process releases nitrogen into water bodies, promoting eutrophication. In the water cycle, soil microbial communities can improve soil structure to hold more water and break down pollutants to purify water. At the same time, soil microbial communities release and absorb water vapor in the atmosphere, affecting the climate. As what was shown in figure 2, this system is maintained in a delicate balance, any minor changes might cause some drastic effects that adversely impact the environment and climate pattern. Human activities, such as fossil fuel combustion and deforestation, disrupt the balance, negatively affect the climate and environment. Interpreting these impacts in context, soil microbial communities benefit the ecosystem in different ways, but their adverse effect on climate change is not ignorable.

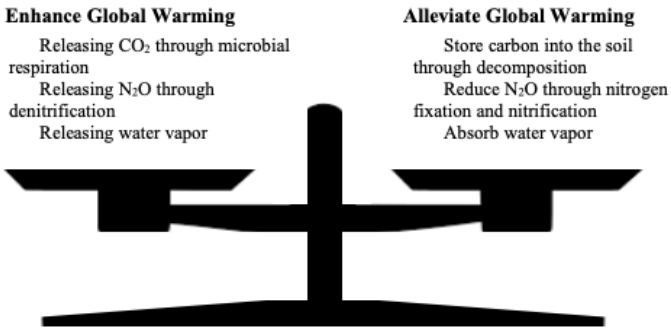

Figure 2: Factors that might enhance global warming vs factors that might alleviate global warming.

This research offers a more comprehensive perspective on the relationship between soil microbial communities, global ecosystems, and climate change. It integrates findings of the effect of soil microbial communities on the environment from different currently available literature. Moreover, this research focuses on the interaction between different influences of soil microbial communities, which makes it unique from other research. However, there remains much work to be done to fully understand the extent of soil microbial influence on the ecosystem and climate. More studies on the net effect of the contradictory influences of soil microbial communities are needed.

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