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REVIEW PAPER

Potential role of microorganisms in atmospheric carbon sequestration and global climate mitigation

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ABSTRACT

Increasing concentration of atmospheric CO_2 due to anthropogenic carbon dioxide emission has led to serious threat to global climate. Carbon sequestration is the process of transferring atmospheric CO_2 into other more sustainable global pools such as the ocean, terrestrial ecosystem and earth crust to reduce the concentration of CO_2 in atmosphere. Microorganisms inhabiting the ocean play a key role in the biological pump and microbial carbon pump. Soil microbes also have potential to capture anthropogenic CO_2 and convert it to more sustainable form. The fungal: bacterial ratio in soils has been associated with C sequestration potential with greater fungal abundance being related to greater C storage. These microorganisms might be useful as in mitigation of global climate due to their ability of carbon sequestration.

Keywords: - *Carbon sequestration, Microbial carbon pump, Dissolved organic matter (DOM), Recalcitrant DOM, Microbial inoculants.*

1. INTRODUCTION

Fluoxetine Development of human civilization over the past hundred years has resulted to a huge increase in fossil fuel consumption and CO_2 emissions. This has caused a dramatic increase in atmospheric CO_2 concentration. CO_2 emissions from the industries, mainly from the use of coal, oil and natural gas, and from the production of cement, contribute about 8 Gt C (29 Gt CO_2) per year. The concentration of carbon dioxide that was around 280 parts per million (ppm) in pre-industrial times has now increased to around 400 ppm and by the end of the century it is expected to reach 600–800 ppm. Constant increase in anthropogenic CO_2 in the atmosphere has led to climate change crisis and so efforts have been made to mitigate global climate. Carbon sequestration is one of the options for mitigation of anthropogenic CO_2 in the atmosphere. [1,2]

Carbon sequestration is the process of transferring atmospheric CO_2 into other more sustainable global pools such as the ocean, terrestrial ecosystem, and earth crust to reduce the concentration of CO_2 in atmosphere. [3] Terrestrial as well as ocean

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ecosystem have proved to be major carbon sinks. Ocean carbon sequestration means capturing inorganic and organic carbon within the ocean such that it remains unavailable for the exchange with atmospheric CO_2. There are two important mechanisms for biological carbon sequestration in the ocean, the biological pump (BP) and the microbial carbon pump (MCP). [4] Microorganisms were originally thought to only assimilate or utilize dissolved organic matter (DOM) from the ocean but the recent studies in research suggest that they play a much broader and more important role in the biological pump as well as microbial carbon pump. Bacteria and archeae are the inhabitants of the ocean that create DOM and also refractory DOM (RDOM) which is a persistent form of DOM that cannot be biologically degraded. [5] Soil carbon sequestration is the transfer of carbon dioxide from the atmosphere into the soil in a form that is not immediately lost. Terrestrial ecosystems are considered as major sinks for CO_2 emissions in the atmosphere and are important as a research interest because of their potential to mitigate atmospheric CO_2. [6] A major role is played by microbial communities in the capture and storage of soil carbon. According to some estimation, if management of agriculture activities and degraded soils is done judiciously, it could capture an additional of 0.4–1.2 Gt C/year, which is equivalent to 5–15% of global fossil fuel emissions. [7] Along with being an potential method for partially mitigating anthropogenic CO_2 emissions it also provides a numerous other ecosystem advantages such as soil fertility, water quality, resistance to erosion, and climate mitigation. [7] This review will discuss the role played by microorganisms in sequestration of carbon in oceans and terrestrial ecosystem

2. OCEAN CARBON SEQUESTRATION

2.1. Microbe driven carbon fixation

Oceans take up about 25% of annual anthropogenic carbon emissions and so are considered to play an important part in regulation of atmospheric CO_2 concentrations. [8] Microorganisms play a significant role in shaping the marine ecosystem and they also drive the biochemical cycles in the ocean. [9] Microbial communities regulate the efficiency of carbon sequestration in biological carbon pump (BCP) as well as microbial carbon pump (MCP). [10] The BCP is a process of transfer and capture of biogenic particles from surface water to deeper water which is based on various biological processes such as phytoplanktonic CO_2 fixation, consumption, transport, sedimentation, and decomposition. The MCP is a process that involves the generation of recalcitrant dissolved organic matter (RDOM) and long-term carbon storage (more than five thousand years). It is mainly driven by microbial metabolism. [11, 12] This happens when a large fraction of photosynthetically produced organic matter undergoes by various physiological mechanisms and forms dissolved organic matter (DOM). [13] Microbes drive carbon sequestration through a series of metabolic activities and form a huge marine organic carbon pool, of which about 97% exists in the form of DOC. [12] The microbes produce refractory dissolved organic carbon (RDOC) by rapidly utilizing and absorbing the labile organic carbon. The labile organic carbon undergoes a series of metabolic and transformational processes to form refractory dissolved organic carbon (RDOC). The RDOC pool with its long-term carbon storage capacity is an important fraction of the blue carbon, and microbes are the main contributors to the formation of the RDOC pool. The RDOC can be stored in seawater for as long as thousands of years. [14, 15] Most of the marine DOC pool is converted to RDOC that is not bio-available. The key formation processes of carbon sequestration include microbial-driven carbon fixation and generation or release of RDOC. [12] Mainly picoeukaryotic primary producers, and unicellular cyanobacteria such as *Prochlorococcus* and *Synechococcus* are reported to fix CO_2 into biomass in the oligotrophic gyres where there is low level of nutrients. [16] Subsequently labile DOM is released into the surrounding waters through sloppy feeding and grazing by zooplankton (mainly micro zooplankton in the case of *Synechococcus* and Prochlo- rococcus), excretion from primary producers and viral lysis. [17] Upon its release, heterotrophic microorganisms transform and breakdown labile DOM and in turn release nitrogen and phosphorus which are recycled in the oceanic gyres and sustain up to 85% of primary production in these oligotrophic regions. [18] Nearly 10% of the ocean uptake of atmospheric CO_2 each year is the annual production of RDOC in the MCP of ~0.2 Pg carbon. [19]

2.2. Autotrophic and heterotrophic microbes' role in generation of RDOC

There are several biotic processes that may lead to RDOC. This includes the direct exudation of DOC from phytoplankton, the production of liposome-like colloids via micro zooplankton grazing, the release of metabolites by microbes, the preferential removal of specific sugars and amino acids by bacteria, [20] the viral lysis of picocyanobacteria, autotrophic eukaryotic plankton, and bacteria in the euphotic zone, [11,21] the generation of microenvironmental conditions (e.g. chemical gradients and oxygen depletion) around microbial cells, [11] and the possible de novo production of RDOC by metabolic activities of phytoplankton or bacteria. The latter process is mechanistically distinct from bacteria successively transforming labile into refractory organic carbon. [22]

Phytoplanktons sometimes directly exude RDOC. [20, 22] However, the most frequently cited mechanism related to phytoplankton exudation is bacterial transformation into RDOC of some more labile DOC exuded by phytoplankton and other organisms. [23, 22, 24] Bacteria consume most of the DOC exuded by phytoplankton and other organisms, and part of the DOC that is not respired is transformed into RDOC. [23] Eichinger et al. (2011) [25] proposed that bacterial RDOC production could be a stress response to low availability LDOC, on the basis of a model that reproduced the results of a 10-day laboratory experiment. Additionally, bacteria produce exopolymers and capsular material, either as part of their normal life strategy or under stress conditions, e.g. nutrient limitation when they take up much more carbon than needed. [26] Also, bacteria hydrolyze POC in the euphotic zone or during its downward transit, using their ectoenzymes, and consume most of the resulting DOC; some by-products of this hydrolytic activity could be resistant to further utilization by microbe that is RDOC. Grazing and egestion by protists have been cited as possibly contributing to the production of RDOC. [11] However, most of these mechanisms are still largely hypothetical, and the evidence for biotic long-lived DOC production is most compelling for the direct excretion by heterotrophic bacteria of compounds that are recalcitrant on timescales of several months to a year. [23]

3. SOIL CARBON SEQUESTRATION

3.1. Unicellular Microbial CO_2 fixation

Soil represents an abundant stock of potentially volatile C and act as a buffer against atmospheric CO_2 increase and also as a potential sink for additional C. It depends on the balance between photosynthesis, the respiration of decomposer organisms, and stabilization of C in soils. [27, 28] Soils contain carbon in both organic and inorganic forms. SOC (Soil organic carbon) is composed of a mixture of dead plant and animal residues, its decomposed product, the microbial products synthesized from the decayed products and the microbial and animal biomass of soil. [29] Soil biospheric C sequestration can significantly contribute to the mitigation approaches and may offset a significant fraction of diffuse CO_2 sources for which direct capture is not yet feasible. In particular it has been estimated that through judicious management, the world agriculture and degraded soils could sequester an additional 0.4–1.2 Gt C/year, which is equivalent to 5–15% of global fossil fuel emissions. [28] In terrestrial ecosystems, the uptake of CO_2 from the atmosphere by net primary production (NPP) is dominated by higher plants, but microorganisms modify the nutrient availability and influence the c turnover and retention in soil and thus contribute greatly to ecosystem C budgets through their roles as detritivores, plant symbionts, or pathogens. [7]

Soil structure is an important regulator of C storage or decomposition that is mediated by microorganisms. According to some reports the terrestrial ecosystems can potentially be manipulated through land management practices for the generation of distinct microbial communities that may help in C sequestration. Formation and stabilization of microaggregates are facilitated by various groups of microbes. Soil organic matter (SOM) is preferentially conserved in these microaggregate fractions and aggregate stability increases linearly with input of carbon content. [30] Based on the C mineralization potential and growth rates, bacteria inhabiting the soil can be classified into two ecological functional categories, copiotrophs (r-strategists) and oligotrophs (k-strategists) . Members of phyla Actinobacteria and Acidobacteria and class Deltaproteobacteria are considered as oligotrophs whereas phylum Bacteroidetes and classa and Proteobacteria are considered copiotrophs. [32] It has also been postulated that soils dominated by oligotrophs may have low C turnover and, consequently, low CO_2 emissions and thus higher C sequestration. [33] Microbial inoculants could be used to increase the level of carbon inputs and decrease the levels of carbon outputs in the soils. Microbial communities in soil play role in carbon sequestrations and soil carbon emission. In order to increase carbon sequestration in soils, right choice of microorganisms can be very important in order to increase carbon sequestration in soils. Due to the ability of soil microorganisms to regulate multiple pathways input and loss of soil carbon, changes in microbial communities greatly affect the soil organic matter cycling and storage. [31]

3.2. Multi cellular microbial CO_2 fixation

One of the factors that has been associated with C sequestration potential is the fungal: bacterial ratio in soils. The greater fungal abundance is related to greater C storage. [34] There is evidence to suggest that the relative abundance of fungi and bacteria may be important, with more stable carbon being formed in soils with high fungal/bacterial biomass ratios. Fungi have higher C use efficiency than bacteria and therefore form more biomass per unit of C utilised and also a biomass of a more recalcitrant nature are the suggested mechanisms for the greater accumulation of fungal SOM, although both these mechanisms require further study. [35] Bacterial-dominated microbial communities are associated with higher rates of CO_2 respiration, [35] thus have low C assimilation efficiency as compared to fungi-dominated microbial communities. The most abundant component of the fungal community in most agricultural soils is the Arbuscular mycorrhizal (AM) fungi. In some systems, mycorrhizal networks is one of the predominant ways in which carbon enters the SOM pool, potentially exceeding the input via leaf litter, root leachate and fine root turnover. Moreover, fungal cell walls contain polymers of chitin and melanin which are resistant to degradation whereas the main components of bacterial cell wall membrane phospholipids are energy rich, readily decomposable substrates available to a wide range of soil microorganisms. The storage of C is expected to be more persistent when mediated by fungal biomass and more labile when mediated by bacterial biomass. Thus the ecosystems with fungal-dominated soil communities may have higher C retention than soil communities dominated by bacteria. [36] A study was done using high-throughput sequencing combined with stable isotope analysis that has shown that in boreal forests fungi are responsible for stabilizing C and retaining it in soils. [37] In particular, glomalin, a glycoprotein produced by the hyphae of AMF, has been found to have a potential role in stabilisation of microaggregates. Similarly, other hydrophobic proteins produced by mycorrhizal fungi and filamentous bacteria, such as hydrophobins and chaplins, have been associated with microaggregate formation and stabilisation. [38]

4. ROLE OF AUTOTROPHIC MICROORGANISMS FROM SOIL

Autotrophic microorganisms are known to contribute significantly to CO_2 assimilation in aquatic systems but have not generally been thought to play a key role in CO_2 fixation and sequestration in soils. Recently there are some evidences on the basis of which microbial autotrophy could account for up to 4% of the total CO_2 fixed by terrestrial ecosystems each year. [39] The diversity and abundance of autotrophic bacterial community in soil and the SOC content are correlated. It suggests that soil management and cropping regime might be manipulated to enhance soil C sequestration by the growth of autotrophic bacteria. [40] The data presented by Xiaohong Wu & Tida Ge et.al suggest that paddy soils can potentially be used to enhance carbon sequestration through increased numbers and activities of autotrophic bacteria. [41] The work reported by Hongzhao Yuan, Tida Ge et.al shows that the diversity of bacterial and chromophytic algal cbbL genes encoding RubisCO in soils offers significant potential for the microbial assimilation of atmospheric CO_2. In a study conducted by Hongzhao Yuan, Tida Ge, et.al they determined whether $14CO_2$ incorporation was mediated by autotrophic microorganisms. Phylogenetic analysis showed that the dominant ribulose 1,5-bisphosphate carboxylase/oxygenase (RubisCO) gene (cbbL)-containing bacteria were Azospirillum lipoferum, Rhodopseudomonas palustris, Bradyrhizobium japonicum, Ralstonia eutropha, and cbbL-containing chromophytic algae of the genera Xanthophyta and Bacillariophyta. [39] Recent advances have showed the possibility of transformation of heterotrophic microorganisms into hemiautotrophic microorganisms and delves further into fully autotrophic microorganisms (artificial autotrophy) by use of synthetic biological tools and strategies. Rapid developments in artificial autotrophy have laid a solid foundation for the development of efficient carbon fixation cell factories. [42]

5. FUTURE IMPLICATIONS OF MICROBIAL INOCULANTS TO ENHANCE CARBON SEQUESTRATION

Using microbial inoculants in agricultural practices could help to achieve desirable characteristics in soil. Bio-sequestration is the process that includes the natural capture and storage of CO_2 by photosynthetic organisms as well as soil microbes. [43] Microbial inoculants could be used to increase the level of carbon inputs and decrease the levels of carbon outputs in the soils. Soil microbial communities have important roles in carbon sequestration and soil carbon emission. [44] Choosing the right microorganism with the right mechanism for a specific land is very important in order to increase carbon sequestration in soils. Changes in microbial communities affect the soil organic matter cycling and storage due to the ability of soil microorganisms to regulate multiple pathways input and loss of soil carbon. [45] The difference in microbial biomass contents and physiological characteristics between microbial communities can lead to different mechanisms and pathways in sequestering carbon into soils. [31] This indicates that bacteria could contribute to carbon sequestration through different pathways and metabolic activities. Pseudomonas fluorescence is a plant growth-promoting bacterium that could be a useful tool for carbon sequestration and climate change mitigating. [46] The results from this study indicate that this microbial inoculants increased plant productivity as well as having potential to mitigate high atmospheric CO_2 levels by increasing terrestrial carbon sequestration, particularly in high- CO_2 ecosystems. These findings could draw attention to the use of plant growth-promoting bacteria as microbial inoculants to sequester atmospheric CO_2. [31]

6. CONCLUSION

There is consensus among scientists that global climate change is happening and that the increases in global average temperatures since 1900 can be largely attributed to human activities. However, there remains much uncertainty about predictions of future greenhouse gas emissions and the response of these emissions to further changes in the global climate and atmospheric composition. To help tackle this uncertainty, there is a need to better understand the role of microorganisms in carbon sequestration. There is an urgent need to improve the mechanistic understanding of microbial control of greenhouse gas emissions and the interactions between the different abiotic and biotic components that regulate them. Although natural terrestrial and oceanic sinks are presently absorbing approximately 60% of the 8.6 Pg C yrK1 emitted, natural sink capacity and rate are not large enough to assimilate all the projected anthropogenic CO_2 emitted during the twenty-first century or until the C-neutral energy sources take effect. The sink capacity of managed ecosystems (e.g. forest, soils and wetlands) can be enhanced through conversion to a judicious land use and adoption of RMPs of forestry, agricultural crops and pastures. Purposeful manipulation of biological processes can accelerate the CO_2 sequestration process with adoption of regulatory measures and identification of policy incentives. However, for these management systems to be effective there is a strong need for an integrated systems approach. The emerging field of global change microbial ecology will generate systematic, open access datasets that can be used for probing the morphological and molecular makeup, diversity, evolution, and ecology of soil microbial communities as well as their impacts on C sequestration. The MCP provides a formalized focus on the importance of microbial processes in carbon storage in the RDOM pool as well as a framework for testing hypotheses regarding the sources and sinks of DOM and the underlying biogeochemical mechanisms. Our proposal that microbial processes underlie the long-term carbon storage in RDOM underscores the proposition that the part that the ocean plays in structuring the earth's climate is largely driven by microorganisms84. Microbial community of soil aids storage of carbon that has beneficial effects in terms of soil fertility, clean water, increased biodiversity and higher productivity. However, realizing this potential requires much more detailed knowledge regarding the concerned microbe and its mechanisms of C storage.

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