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Wood burial is currently the only fast and feasible method of carbon sequestration

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Abstract

This study analyzed and compared several major methods of carbon sequestration based on the first principles, namely energy use efficiency and elemental stoichiometry. This study suggested that wood burial is the only currently feasible carbon sequestration method because it can be implemented immediately on a large scale, is low cost, efficient, has a long sequestration time, has low technical requirements, and has relatively little impact on agriculture.

Keywords: Carbon sequestration, Elemental stoichiometry, Energy use efficiency, First principle.

1 Background

The concentration of atmospheric carbon dioxide (CO_2) has been increasing for more than 100 years due to the burning of fossil fuels to generate energy [1]. From 2010 to 2019, the average annual growth rate of atmospheric carbon has reached about 5×10^{15} g [2]. CO_2 is one of the most important greenhouse gases and is the main control target for carbon neutrality (net-zero emissions). To date, most countries have set a clear plan to achieve carbon neutrality, for example, the top three emitters China, the United States, and India have deadlines of 2060, 2050 and 2070, respectively. There are two pathways to reach net-zero emissions: carbon emission reduction and carbon sequestration. Carbon emission reduction is aimed to reduce the use of fossil fuels and replace with new energy sources. However, new energy sources such as solar energy, wind energy and nuclear energy still have many drawbacks and limitations, which lead to fossil fuels being the world's main energy source at present and in the coming decades. So, there is an urgent need for feasible carbon sequestration programs to save time for the development of new energy technologies.

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A feasible carbon sequestration program contains two steps, first is the large-scale conversion of gaseous CO_2 into other types of inorganic or organic carbon, second is the long-term sequestration. Although we lack a definition on the long-term, carbon neutrality means that the sequestrated carbon should not return to the atmosphere at least ~30 to 50 years (the time left for the plan of carbon neutrality). If the contribution of a program is two orders of magnitude lower than the growth rate of atmospheric carbon, it is of little practical significance; if it is three orders of magnitude lower, it is almost meaningless; if the contribution can reach about 10%, it is highly feasible. Therefore, a viable carbon sequestration program is essentially in long-term competition with the industrial capacity of human civilization.

Several carbon sequestration methods have been proposed based on theories from different disciplines. For example, wood burial is a biological carbon sequestration method through the production and long-term storage of dry wood [3]. To find the best one, we analyzed the feasibility of several major methods based on the first principles, namely energy use efficiency and elemental stoichiometry, and compared wood burial with others (FIG. 1).

2 Comparison of carbon sequestration methods

2.1 Inorganic carbon sequestration method

One inorganic carbon sequestration method that appears attractive is to liquefy CO_2 and inject it into the ground. However, after more than 40 years of development, this method remains highly controversial and more than 80% of commercial projects have failed [4]. Of particular note: liquid CO_2 at –20°C and 5 Mpa has a density of 1059 kg/m^3 which is very close to the density of liquid water. A simple calculation shows that the carbon content per cubic meter of liquid CO_2 is about 290 kg, which is very close to that of dry wood. However, the production and sequestration costs of the former are obviously much higher. Of course, sequestration of liquid CO_2 has unique advantages over biological methods, for example, it does not consume nitrogen, phosphorus and potassium nutrients.

CO_2 is a weakly acidic gas, thus alkalizing seawater with the addition of alkaline minerals

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would help it absorb more CO_2, but this approach would require worldwide agreement and concerted action to make it work. Large-scale changes to the marine environment would have a huge impact on marine ecology and would most likely attract a lot of opposition.

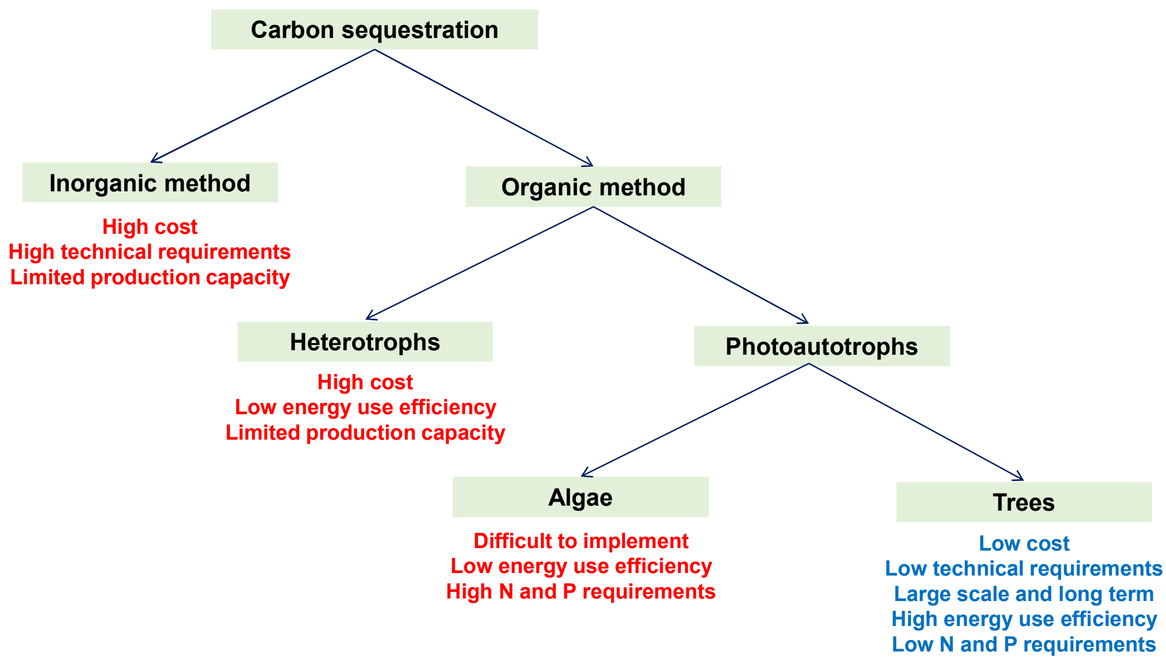

Fig. 1 Comparison of major carbon sequestration methods.

2.2 Organic carbon sequestration method

The industrial synthesis of organic carbon is obviously not yet available for large-scale carbon sequestration. Then, the production of organic carbon through cultivation of organisms is the only way to go at present. Almost all the energy that drives life activities come directly or indirectly from solar energy. The efficiency of energy transfer between two adjacent trophic levels via food is only about 10% [5], suggesting that photoautotrophs have a much higher energy use efficiency in production of organic carbon than heterotrophs.

For almost all living organisms, more than 95% of the biomass is consist of six elements: carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur [1,6]. However, the element composition varies between major photoautotrophs (Table 1), the molar ratio of carbon: nitrogen: phosphorus (C:N:P) of trees is about 1360:8.5:1, much higher than that of marine macroalgae (~550:30:1) and

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microalgae (~106:16:1) [1,7,8]. Thus, cultivation of trees has an advantage over cultivation of other photoautotrophs in terms of nutrient requirement for carbon sequestration. The large-scale cultivation of the latter two photoautotrophs will consume more nitrogen and phosphorus fertilizers, which will impact agricultural production causing food shortages and will cause a new round of intense competition for nutrient resources.

Almost all the organic carbon on the Earth's surface is directly or indirectly derived from photoautotrophs. In this study, sequestered carbon as a percentage of net primary production (NPP) has been used to quantify the efficiency of different carbon sequestration methods. Both marine microalgae and terrestrial plants contribute about half of the global NPP, but the former accounts for only about 0.2% of the biomass of the latter [9]. Microalgae in the open ocean contribute about 80% of the total marine NPP, and macroalgae in coastal waters contribute only about 3% [1,10]. About 80~90% of the marine NPP is decomposed into CO_2 in surface waters, with only about 4% is sequestered in the deep ocean (>1000 m depth) [1]. This is consistent with a recent study that found only about 2.5% of NPP of microalgae in South China Sea is sequestered [11]. These data suggest that the efficiency of carbon sequestration via microalgae cultivation is extremely low. Similar, but much better, about 11% of NPP of marine macroalgae is sequestered [10].

Natural organic matter contains mainly four major classes of macromolecules, among which proteins are rich in nitrogen, nucleic acids and lipids are rich in nitrogen and phosphorus; while carbohydrates are very low in nitrogen and phosphorus. Thus, organisms with low C:N:P ratios rich in proteins, nucleic acids, and lipids, making them the food of choice and a better source of energy and nutrients. This explains why most of the organic carbon produced by macroalgae and microalgae will be rapidly turned back to CO_2.

Regardless of whether the carbon sequestered in the deep ocean is from microalgae or macroalgae, dissolved organic carbon (DOC) is the dominant form of sequestration [1,10]. Because of the carbon amount of marine DOC pool is comparable to that of the atmospheric carbon pool [1], it seems that marine microalgae have great potential for carbon sequestration. However, the focus of carbon sequestration is on the increment rather than the stock.

The plant carbon pool contains mainly terrestrial trees, and about 70% of plant biomass is wood [1,6,12]. Thus, the carbon sequestration efficiency of wood burial can be as high as 70%, which is much higher than that of algae cultivation (Table 1). As the main part of the tree, wood is a solid whose main component is carbohydrates, and these physical and chemical properties make it very easy to sequester carbon for more than 1000 years [3]. The most attractive aspect of wood burial is that even simple and low-cost techniques can significantly increase the time to carbon lockup. In addition, the plant carbon pool is also comparable to the atmospheric carbon pool [1]. Therefore, wood can be preserved on a large scale for a long time.

Table 1 Efficiency and nutrient requirements of biological carbon sequestration methods. The nutrient requirements to achieve carbon neutrality for each method are expressed as a percentage of industrial fertilizer production. To simplify the calculations, this study assumed that all fertilizers added to the ocean cannot be recycled because the turnover times of nitrogen and phosphorus are more than 25 times longer than the time left to achieve carbon neutrality.

Photoautotroph	C:N:P molar ratio		Carbon sequestration efficiency (%)	Nutrient requirement (%)		
	Body	Sequestrated organic matter		N	P	K
Trees	1360:8.5:1	1360:8.5:1	70%	24.3%	27.9%	149.7%
Macroalgae	550:30:1	3511:202:1	11%	212.1%	69.1%	0
Microalgae	106:16:1	3511:202:1	4%	587.0%	358.4%	0

2.3 Disadvantages of carbon sequestration through microalgae cultivation

Marine microalgae mainly distributed in the surface seawater of open oceans, where the concentrations of available nutrients such as nitrogen, phosphorus, iron and silicon are normally very low [13]. Fertilization could increase the biomass of microalgae, which in turn may increase the size of DOC pool in the ocean. This is the core assumption of carbon sequestration via microalgae cultivation. However, this method has several disadvantages:

(1) Difficulties in fertilization. First, short of fertilizer. We don't have enough fertilizer to maintain high nutrient concentrations in the surface water to meet the requirements of microalgae

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cultivation. In particular, we human are facing very short supply of phosphorus resources [1,6,14]. In addition, the ocean is too deep and too wide, and the diffusion effect causes fertilization to increase the nutrient concentration of surface seawater only for a short time. Second, the turnover times of nitrogen (about 2000 years) and phosphorus (> 25,000 years) in the oceans are much longer than the time left to achieve carbon neutrality [1]. Thus, sinking microalgae will lose large (relative to humans, but very small to the ocean) amounts of valuable nitrogen and phosphorus to the deep ocean. Third, we humans are still unable to recycle nutrients from the ocean on a large scale. Fourth, the number of microalgae per unit volume is very low due to nutrient limitation, sinking losses and predator pressure. Thus, fertilization concentration cannot be too high, otherwise a lot of fertilizer will be wasted. Overall, fertilizing the oceans is costly and technically difficult.

(2) It takes years to test and confirm the effect of fertilization.

(3) Lack of general support from the society. Fertilization in the open ocean requires a global consensus and is likely to be ecologically and environmentally controversial.

(4) Low carbon sequestration efficiency. Because most of the carbon fixed by photosynthesis of marine microalgae will be quickly turned back to CO_2 [1], the carbon sequestration efficiency of this method is very low and cannot be implemented on a large scale.

(5) Low energy use efficiency. Under the participation of bacteria, virus, and grazers, only a small amount of microalgal biomass is eventually sequestered as dissolved organic matter (DOM) in the deep ocean, accompanied by a dramatic increase in the C:N:P molar ratio (Table 1) [1,15-17]. Therefore, the energy use efficiency of this method is also very low.

As a result, carbon sequestration via microalgae cultivation in the oceans is not only difficult to implement, but also small-scale, inefficient, and has a high agricultural impact. The same applies to carbon sequestration via macroalgae cultivation.

2.4 Advantages of carbon sequestration via wood burial

Zeng [3] summarized four advantages of wood burial:

(1) The plant carbon pool is comparable to the atmospheric carbon pool, thus wood can be

preserved on a large scale.

(2) Wood burial has the advantages of long-term sequestration, low technical requirements, low cost and easy management.

(3) Burying old or dead trees and planting young trees can improve the efficiency of carbon sequestration because CO_2 emission from decomposition will be decreased and terrestrial NPP will be increased.

(4) By scientific management of global forests and wood production, forest fires can be reduced, which then reduces carbon emissions.

Here, based on previous studies [1,12,18,19], we given five additional advantages of wood burial compared with other biological carbon sequestration methods from the perspective of elemental stoichiometry and energy use efficiency:

(1) The dry wood has a high carbon content, about 45% by weight.

(2) Compared with cultivation of other photoautotrophs, the production of wood consumes less nitrogen and phosphorus nutrients (Table 1) and then has less impact on agricultural production.

(3) About 70% of plant biomass is wood, which indicates the carbon sequestration efficiency can be as high as 70%.

(4) The contribution of wood burial to carbon neutrality can be easily calculated.

(5) High energy use efficiency. Trees are photoautotrophs which can directly utilize solar energy.

These advantages make wood burial the only feasible carbon sequestration method at present. The implementation of wood burial will require management of global forests due to the huge amount of CO_2 emission, and therefore will have an impact on forest ecosystems [3]. In total, humans have emitted 350×10^{15} g carbon (C) into the atmosphere, about two-thirds of which comes from the burning of fossil fuels (origin from ancient plants) and one-third from tropical deforestation [4]. Wood burial can return carbon to its original form.

3 Wood burial program

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Zeng [3] discussed many technical details of wood burial, and here we would like to discuss the feasibility in terms of nutrient requirements. The average density of dry wood is about 650 kg per cubic meter, with a carbon content of about 45% by weight [18,19]. From 2010 to 2019, the average annual growth rate of atmospheric carbon has reached about 5 $\times 10^{15}$ g [2], equivalent to the carbon content in 17 billion cubic meters of dry wood. In addition to nitrogen and phosphorus, trees also have a high demand for potassium (K), with a C:N:K:P molar ratio of about 1360:8.5:4:1 [1,18]. USGS data show that global annual industrial productions of nitrogen, phosphorus and potassium fertilizers are about 150 $\times 10^{12}$ g, 34 $\times 10^{12}$ g and 32 $\times 10^{12}$ g, respectively [1]. Assuming that the nutrients absorbed by trees are fully used for wood production, then at least 24.3%, 27.9%, and 149.7% of the industrial nitrogen, phosphorus, and potassium fertilizer produced globally each year, respectively, would need to be used for tree planting to achieve carbon neutrality (Table 1). Knowledge about the nutrient content in different tree species and the nutrient distribution of trees is limited and more research is needed to provide theoretical guidance for reducing the nutrient requirements of wood burial.

Based on C:N:P molar ratio, the nitrogen and phosphorus requirements for wood burial are significantly lower than for other biological carbon sequestration methods (Table 1). Even so, a conflict between carbon neutrality and agriculture is already inevitable, and the world will face a severe shortage of nitrogen, phosphorus and potassium resources. Nutrients such as nitrogen, phosphorus and potassium are mainly enriched in the soft (active growth) parts, such as, leaves and shoots, thus these parts need to be recycled for wood production. We can also use the nutrient-rich non-agricultural land with net carbon emissions for tree planting. The organic carbon pool of soil is about twice as large as the atmospheric carbon pool, and soil contain much more nitrogen and phosphorus contents than wood [1,6,20], so its potential for use in wood production is very high.

The industrial potassium fertilizer cannot meet the requirement for carbon neutrality through wood burial (Table 1), so we need to use other sources of potassium. Fortunately, based on the data of literature [1], the amount of dissolved potassium in the ocean is about 2 $\times 10^7$ times the annual potassium requirement for carbon neutrality through wood burial. Potassium can be extracted from

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seawater by biological (e.g., farming macroalgae, seagrasses, mangroves, etc.) or chemical methods.

4 Summary

The key to achieving carbon neutrality is low cost, large scale and long implementation time. In this study, we analyzed the feasibility of various carbon sequestration methods from the perspective of energy use efficiency and elemental stoichiometry, and found that wood burial is the only fast and feasible carbon sequestration method at present. Wood burial can be implemented immediately and on a large scale, with long sequestration time, low cost and technical requirements, and relatively little impact on agriculture. It is important to emphasize that the implementation of carbon sequestration requires a globally integrated management of resources.

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Competing interests

The author reports no potential conflicts of interest.

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