

## Carbon sequestration via wood burial: the only fast and feasible method

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### Abstract

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

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

### 1 Background

The burning of fossil fuels to generate energy has greatly increased the concentration of atmospheric carbon dioxide (CO<sub>2</sub>) for the past 100 years<sup>1</sup>. The increasing rate of atmospheric carbon between 2010 and 2019 was approximately  $5 \times 10^{15}$  g per year<sup>2</sup>. CO<sub>2</sub> is one of the most important greenhouse gases and the main control target for carbon neutrality (net-zero emissions). Currently, most countries have set a clear plan to achieve carbon neutrality. For example, China, the United States, and India (the top three carbon emitter countries) have fixed 2060, 2050, and 2070 deadlines, respectively, to achieve carbon neutrality. Net-zero carbon emissions can be achieved through carbon emission reduction and carbon sequestration. Carbon emission reduction can be achieved by reducing the use of fossil fuels and replacing them with renewable energy sources. However, renewable energy sources, such as solar energy, wind energy, and hydropower, are characterized by several drawbacks and limitations, making fossil fuels remain the world's

main energy source at present and in the coming decades. Therefore, effective and time-efficient carbon sequestration programs for developing renewable energy technologies are needed.

A feasible carbon sequestration program contains two steps: (1) the large-scale conversion of gaseous CO<sub>2</sub> into other types of inorganic or organic carbon and (2) the long-term sequestration of carbon. Although we lack a strict definition for long-term sequestration, the sequestered carbon should not return to the atmosphere for at least ~30 to 50 years (the time left for the plan of carbon neutrality). Considering the huge growth rate of atmospheric carbon, the program feasibility can be measured as follows: if the program contribution of the program is two orders of magnitude lower than the increasing rate of atmospheric carbon, it is of little practical significance; if its contribution is lower than the increasing rate of atmospheric carbon by three orders of magnitude, it is insignificant; and if its contribution can reach approximately 10%, it is of high feasibility. Therefore, a feasible large-scale and long-term carbon sequestration program is essential to achieve carbon neutrality with the increase in industrialization.

Several carbon sequestration methods have been proposed according to theories from various disciplines. For example, wood burial is a biological carbon sequestration method through the production and long-term storage of dry wood<sup>3</sup>. To find the best carbon sequestration method, we investigated 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).

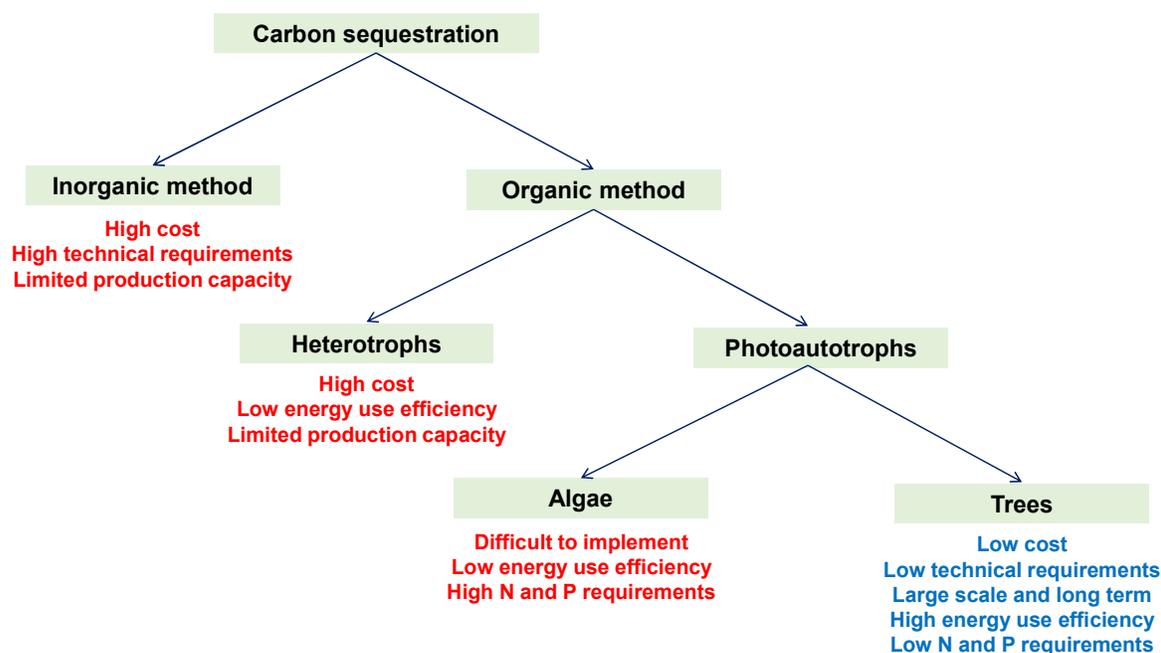
## **2 Comparison of carbon sequestration methods**

### ***2.1 Inorganic carbon sequestration method***

An inorganic carbon sequestration method that appears attractive is to liquefy CO<sub>2</sub> and inject it into the ground. However, this method remains contentious after 40 years of development, and more than 80% of commercial projects based on this method have failed<sup>4</sup>. Notably, liquid CO<sub>2</sub> at -20°C and 5 Mpa has a density of 1059 kg per cubic meter, which is very close to the density of liquid water. The average density of dry wood is about 650 kg per cubic meter, with a carbon

content of about 45% by weight <sup>5,6</sup>. A simple calculation shows that the carbon content per cubic meter of both liquid CO<sub>2</sub> and dry wood is about 290 kg. However, the production and sequestration costs of the former are considerably higher than those of the latter. Of course, sequestration of liquid CO<sub>2</sub> has unique advantages over biological methods; for example, it does not consume nitrogen, phosphorus, and potassium nutrients.

CO<sub>2</sub> is a weakly acidic gas. Thus, the addition of alkaline minerals to seawater allows the ocean to absorb more CO<sub>2</sub>. However, this approach would require global agreement and concerted action to make it work. The large-scale application of the approach will greatly impact marine ecosystems, which might attract much opposition from environmental regulatory bodies.



**Figure 1:** Comparison of major carbon sequestration methods.

## 2.2 Organic carbon sequestration method

The industrial synthesis of organic carbon is not yet available for large-scale carbon sequestration. Thus, the production of organic carbon through the cultivation of organisms is the only way to go at present. Almost all the energies that drive life activities come directly or indirectly from solar energy. The efficiency of energy transfer between two adjacent trophic levels via food is

approximately 10% <sup>7</sup>, suggesting that photoautotrophs have a much higher energy use efficiency in the production of organic carbon than heterotrophs.

For almost all living organisms, more than 95% of the biomass consists of six elements: carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur <sup>1,8</sup>. However, the element composition varies among photoautotrophs (Table 1), and the molar ratio of carbon: nitrogen: phosphorus (C: N: P) of trees is approximately 1360:8.5:1, which is higher than that of marine macroalgae (~550:30:1) and microalgae (~106:16:1) <sup>1,9,10</sup>. Thus, the cultivation of trees has an advantage over the cultivation of other photoautotrophs in terms of the nutrient requirements for carbon sequestration. The large-scale cultivation of macroalgae and microalgae consumes more nitrogen and phosphorus fertilizers, impacting agricultural production and causing food shortages.

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) was used to quantify the efficiency of different carbon sequestration methods. Both marine microalgae and terrestrial plants contribute approximately 50% of the global NPP; however, marine microalgae account for approximately 0.2% of the biomass of terrestrial plants <sup>11</sup>. Microalgae in the open ocean contribute approximately 80% of the total marine NPP, while macroalgae in coastal waters contribute approximately 3% <sup>1,12</sup>. Approximately 80–90% of the marine NPP is decomposed into CO<sub>2</sub> in surface waters, with approximately 4% sequestered in the deep ocean (>1000 m depth) <sup>1</sup>. This percentage is consistent with that of a recent study, which only showed that approximately 2.5% of NPP of microalgae in the South China Sea was sequestered <sup>13</sup>. These data show that the efficiency of carbon sequestration via microalgae cultivation is extremely low. However, approximately 11% of NPP of marine macroalgae was sequestered<sup>12</sup>, which is higher than that of microalgae.

Natural organic matter contains mainly four major classes of macromolecules, including proteins (rich in nitrogen), nucleic acids and lipids (rich in nitrogen and phosphorus), and carbohydrates (rich in carbon and low in nitrogen and phosphorus). Thus, organisms with low C: N: P ratios are rich in proteins, nucleic acids, and lipids, making them a better source of energy

and nutrients. This phenomenon explains why most organic carbon produced by macroalgae and microalgae will be rapidly turned back to CO<sub>2</sub>.

The dominant form of sequestration for both microalgae and macroalgae is the dissolved organic carbon (DOC) in deep ocean <sup>1,12</sup>. Because the carbon amount of marine DOC pool is comparable to that of the atmospheric carbon pool <sup>1</sup>, marine algae might have great potential for carbon sequestration. However, our above analysis suggests that the growth rate of marine DOC pool is very low due to the low carbon sequestration efficiency of marine algae, and this study will give more limitations of this method in the next section.

Plant carbon pool contains mainly terrestrial trees, and about 70% of plant biomass is wood <sup>1,8,14</sup>. Since there is no statistical difference between biomass production and NPP of forest <sup>15</sup>, biomass can be considered as a proxy for NPP. Thus, the carbon sequestration efficiency of wood burial can be as high as 70%, which is higher than that of algae cultivation (Table 1). The main component of wood is carbohydrates, and the physical and chemical properties of carbohydrates make wood very easy to sequester carbon in for more than 1000 years <sup>3</sup>. The most attractive aspect of wood burial is that even simple and low-cost techniques can significantly increase the time the carbon is locked up. Additionally, the plant carbon pool is comparable to the atmospheric carbon pool <sup>1</sup>. Therefore, wood can be preserved on a large scale for a long time.

**Table 1** Efficiency and nutrient requirements of biological carbon sequestration methods.

Photoautotroph	C:N:P molar ratio		Carbon sequestration efficiency (%)	Nutrient requirement (%)		
	Body	Sequestered 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

The nutrient requirements for achieving carbon neutrality for each method are expressed in the percentage of industrial fertilizer production. To simplify the calculations, this study assumes that all fertilizers added to the ocean cannot be recycled because the turnover durations of nitrogen

and phosphorus are 25 times the time left to achieve carbon neutrality.

### ***2.3 Disadvantages of carbon sequestration through microalgae cultivation***

Marine microalgae are mainly distributed in the surface seawater of open oceans, where the concentrations of available nutrients, such as nitrogen, phosphorus, iron, and silicon, are relatively low<sup>16</sup>. Fertilization could increase the biomass of microalgae, which 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 limitations:

(1) Difficulties in fertilization. First, because of the deepness and wideness of the ocean, we lack adequate supplies of fertilizer to maintain high nutrient concentrations of the surface seawater to meet the requirements of microalgae cultivation. In particular, humans are facing inadequate supplies of phosphorus resources<sup>1,8,17</sup>. Second, the turnover times of nitrogen (~2000 years) and phosphorus (>25,000 years) in the oceans are longer than the time required to achieve carbon neutrality<sup>1</sup>. 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, humans are currently unable to recycle nutrients from the ocean on a large scale. Fourth, the number of microalgae per unit volume is relatively low due to nutrient shortage, sinking losses, and predator pressure. Thus, fertilization of the ocean cannot be too high; otherwise, a great deal of fertilizer will be wasted. Hence, fertilizing the oceans is costly and technically difficult.

(2) It takes years to test and confirm the effect of the fertilization. Even if the DOC pool increases in the coming decades through fertilization, the future at the centennial or millennial scale still faces great uncertainty. The marine environment is changing and will probably change even more in the future. Large-scale water movements caused by many factors such as ocean circulation and storms can bring large amounts of organic carbon from deep ocean to surface waters, where it can then be converted to CO<sub>2</sub> through photo-enhanced biodegradation<sup>18,19</sup>. A recent study suggested that ocean circulation is accelerating<sup>20</sup>, and if it does in the future, then the worst consequence will be the decreasing size of marine organic carbon pool.

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

(4) Low carbon sequestration efficiency. Most of the carbons fixed by photosynthesis of marine microalgae are rapidly converted to  $\text{CO}_2$ <sup>1</sup>; as a result, the carbon sequestration efficiency of this method is considerably low. Hence, this method cannot be implemented on a large scale.

(5) Low energy use efficiency. Under the activities of bacteria, viruses, and grazers, only a small amount of microalgal biomass can be sequestered as dissolved organic matter in the deep ocean, while the C: N: P molar ratio increases dramatically (Table 1)<sup>1,18,19,21</sup>. Therefore, the energy use efficiency of this method is considerably low.

Thus, carbon sequestration via microalgae cultivation in the oceans is difficult, inefficient, and can only be implemented on a small scale; additionally, it has a high agricultural impact. The same applies to carbon sequestration via macroalgae cultivation.

#### ***2.4 Advantages of carbon sequestration via wood burial***

Zeng<sup>3</sup> 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 is characterized by long-term sequestration, low technical requirements, low cost, and easy management.

(3) Burying old or dead trees and planting young trees can improve carbon sequestration efficiency because the former inhibits the decomposition of trees, thus decreasing  $\text{CO}_2$  emissions, while the latter increases terrestrial NPP.

(4) Wood burial improves scientific management of global forests and wood production, reducing forest fires and carbon emissions.

According to previous studies<sup>1,5,6,14</sup>, five additional advantages of wood burial compared with other biological carbon sequestration methods based on elemental stoichiometry and energy efficiency were given:

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

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

(3) Wood comprises approximately 70% of plant biomass, indicating that 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 is achieved due to the photoautotrophic nature of trees.

These advantages make wood burial the only feasible and effective carbon sequestration method at present. The implementation of wood burial will require the proper management of global forests, which can impact forest ecosystems<sup>3</sup>. In total, humans emit  $350 \times 10^{15}$  g of carbon (C) into the atmosphere, approximately two-thirds generated from the burning of fossil fuels (origin from ancient plants) and one-third from tropical deforestation<sup>1</sup>. Wood burial can return carbon to its original form.

### 3 Wood burial program

Zeng<sup>3</sup> discussed many technical details of wood burial, and in this study, we discussed the feasibility in terms of nutrient requirements. Based on previous studies<sup>5,6</sup>, we calculated that the carbon content per cubic meter of dry wood is about 290 kg. The average annual increase in atmospheric carbon from 2010 to 2019 was about  $5 \times 10^{15}$  g<sup>2</sup>, which is equivalent to the carbon content in 17 billion cubic meters of dry wood. The global wood production in 2020 was about 5 billion cubic meters<sup>22</sup>. Therefore, the wood industry has the capacity to implement wood burial.

In addition to nitrogen and phosphorus, tree cultivation requires high potassium (K), with a C: N: K: P molar ratio of about 1360:8.5:4:1<sup>1,5</sup>. The United States Geological Survey data show that global annual industrial productions of nitrogen, phosphorus, and potassium fertilizers are approximately  $150 \times 10^{12}$  g,  $34 \times 10^{12}$  g, and  $32 \times 10^{12}$  g, respectively<sup>1</sup>. 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 produced each year globally,

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; thus, more research is needed to provide theoretical guidance for reducing the nutrient requirements of wood burial.

Based on the C: N: P molar ratio, wood burial requires significantly less nitrogen and phosphorus than carbon sequestration via algae cultivation (Table 1). The industrial potassium fertilizer cannot meet the requirement for carbon neutrality through wood burial (Table 1); thus, we need to use other sources of potassium. According to literature data <sup>1</sup>, the amount of dissolved potassium in the ocean is approximately  $2 \times 10^7$  times the annual potassium requirement for carbon neutrality through wood burial. Potassium can be extracted from seawater by biological (e.g., farming macroalgae, seagrasses, and mangroves) or chemical methods. Nutrients: nitrogen, phosphorus, and potassium are mainly enriched in the soft (active growth) parts of trees, including leaves and shoots. These parts need to be recycled for wood production. The nutrient-rich non-agricultural land with net carbon emissions can be used for tree planting. The organic carbon pool of soil is approximately twice that of the atmospheric carbon pool, and soil contains more nitrogen and phosphorus contents than wood <sup>1,8,23</sup>. Therefore, the soil has great application potential in wood production.

The above analyzation suggests that the world will face a severe shortage of nitrogen, phosphorus, and potassium resources; thus, the conflict between carbon sequestration and agriculture is inevitable if an appropriate measure is not taken.

#### **4 Summary**

The key to achieving carbon neutrality is low cost, large scale, and long implementation time. In this study, we evaluated the feasibility of various carbon sequestration methods from the perspective of energy use efficiency and elemental stoichiometry. Currently, we found that carbon sequestration via wood burial is the only effective and feasible method. Wood burial features low cost and simple technical support, and it can be implemented on a large scale with a

long-sequestration time. Additionally, the method has relatively little impact on agriculture. Finally, 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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