Short Note

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Wood Burial May Be a Leading Candidate for Carbon Sequestration

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Short Note

Wood Burial May Be a Leading Candidate for Carbon Sequestration

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Abstract: Although several carbon sequestration methods have been proposed according to theories from various disciplines, it is not known which method is the best. This study evaluated and summarized the advantage and disadvantages of several major carbon sequestration methods, including carbon capture and sequestration, ocean alkalinization, algal cultivation, and wood burial, based on the first principles, namely, sequestration scale and time, elemental stoichiometry, and energy use efficiency. This study suggested that, at present, wood burial may be a leading candidate for carbon sequestration 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. This study also discussed the implementation of wood burial from the perspective of nutrient requirements. To achieve carbon neutrality by 2050, the present study proposed a 25-year project starting in 2025 with an average sequestration rate of 3 Pg C per year, which includes burying 1.5 Pg of dead wood carbon and the creation of 9.7×10^6 ha woodland.

Keywords: Carbon sequestration; Elemental stoichiometry; Energy use efficiency; First principles; Sequestration scale; Sequestration time

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1. Introduction

The burning of fossil fuels to generate energy has greatly increased the concentration of atmospheric carbon dioxide (CO_2) for the past 100 years (Schlesinger & Bernhardt 2020). The rate of atmospheric carbon increase between 2010 and 2019 was approximately 5 Pg per year (Friedlingstein et al. 2020). CO_2 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, the top three carbon emitter countries, China, the United States, and India 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 (Halkos & Gkampoura 2020). For example, the power generation from renewable energy technologies is inconstant because it largely depends on weather conditions, which poses a challenge to grid stability. A recent study predicted that capacity credits will be saturated when the proportion of solar and wind energy in Japan's power grids reaches 25% and 60%, respectively (Xu et al. 2022). The growth potential of hydropower is very limited, as it can only increase by about 30% from the present until 2050 (Holechek et al. 2022). In addition, different renewable energy projects have different requirements for land use (Ioannidis & Koutsoyiannis 2020), which may lead to different conflicts with agriculture and forest-based carbon sequestration.

In 2020, fossil fuels accounted for 83% of global energy consumption (Holechek et al. 2022). Even if the future global energy roadmap follows the Net-Zero Emissions Scenario, fossil fuels will remain the world's main energy source for the next two or three decades, accounting for about 20% by 2050 (IEA 2021). It is worth noting that world energy consumption in 2050 is projected to be 50% higher than the 2018 level (US-EIA 2019). Currently, the global carbon emission rate is about two times the natural carbon sequestration rate (Friedlingstein et al. 2020). In addition, we know little about the potential for natural carbon sequestration under a changing climate. Therefore, there is an urgent need to identify and implement large-scale and low-cost carbon sequestration programs that not only serve to decrease net carbon emissions, but also buy time to upgrade renewable energy technologies.

A feasible carbon sequestration program contains two steps: (1) the large-scale conversion of gaseous CO_2 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 sequestrated 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. As the world's energy consumption and industrialization increase, a feasible large-scale and long-term carbon sequestration program is critical to achieving carbon neutrality.

Based on theories from various disciplines, several carbon sequestration methods have been proposed that are considered to have great potential. For example, wood burial is a method of biological carbon sequestration through the production and long-term sequestration of organic matter in the form of wood (Zeng 2008). To find the best carbon sequestration method, this study investigated the feasibility of several major methods, including carbon capture and sequestration (CCS), ocean alkalinization, algae cultivation, and wood burial, based on the first principles, namely, sequestration scale and time, energy use efficiency, and elemental stoichiometry (Figure 1).

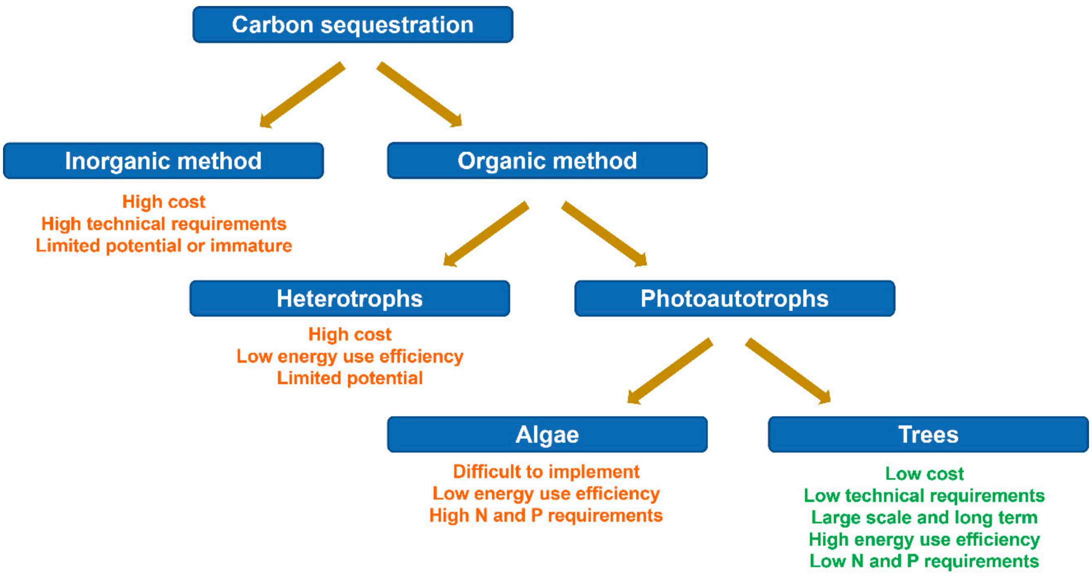

Figure 1. Comparison of major carbon sequestration methods.

2. Comparison of carbon sequestration methods

2.1. Inorganic carbon sequestration method

An inorganic carbon sequestration method that appears attractive is to capture and compress CO_2 into a supercritical fluid or liquid state and then inject it into the ground at a selected location for permanent geological sequestration (Boot-Handford et al. 2014). This method is commonly referred to as CCS, and it is the leading candidate for directly capturing CO_2 from industrial sources, such as fossil fuel power plants, iron and steel plants, and cement manufacturing plants. Carbon sequestration via CCS is predicted to rise to 2.1 Pg C per year by 2050 (IEA 2021). However, this method remains contentious after 40 years of development, and more than 80% of commercial projects based on this method have failed (Abdulla et al. 2021).

This study uses carbon content per unit volume as an indicator to briefly compare the cost of CCS and wood burial. At –20°C and 5 Mpa, liquid CO_2 can reach a relatively high density of 1059 kg/m^3, which is very close to the density of liquid water. Here, this density is used to compare the carbon content per volume of liquid CO_2 with that of dry wood. The average density of dry wood is about 645 kg/m^3 (Chave et al. 2006) with a carbon content of about 47% by weight (Martin et al. 2021). A simple calculation shows that the carbon content per cubic meter of liquid CO_2 (at –20°C and 5 MPa) and dry wood is 289 and 303 kg, respectively. CO_2 becomes a supercritical fluid above its critical temperature of 31.1 °C and critical pressure of 7.4 MPa. Liquid CO_2 and CO_2 supercritical fluid typically have densities below 1059 kg/m^3, indicating that they have a lower carbon content per unit volume than dry wood. However, the production, transport, and sequestration costs of CO_2 supercritical fluid or liquid CO_2 are obviously higher than those of the wood. Of course, the inorganic carbon sequestration method 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, the addition of alkaline minerals to seawater allows the ocean to absorb more CO_2. The advantage of this approach is that it has a high carbon sequestration potential with a small impact on the global ocean and can also help mitigate the effects of ocean acidification caused by rising atmospheric CO_2 concentrations (Renforth & Henderson 2017). Ocean alkalinization can sequester carbon for several thousands of years (Ilyina et al. 2013). A modelling study by Feng et al. (2017) suggested that ocean alkalinization has the potential to remove atmospheric carbon by more than 265 Pg by 2100. However, this approach would require a global agreement and concerted action to make it work. In addition, further studies are needed to make this approach mature and operational, and the technical uncertainties and limitations of this approach have been discussed in detail in a previous study (Feng et al. 2017).

2.2. Organic carbon sequestration method

The industrial synthesis of organic carbon using CO_2 as a building block is not yet available for large-scale carbon sequestration (Dabral & Schaub 2019). Thus, the production of organic carbon through the cultivation of organisms is likely to be a better method 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% (Barneche et al. 2021), 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 (Schlesinger & Bernhardt 2020). 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 (Schlesinger & Bernhardt 2020), which is higher than that of marine macroalgae (~550:30:1) (Atkinson & Smith 1983) and microalgae (~106:16:1) (Falkowski 2000). 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 will consume 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 biological 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 (Field et al. 1998). The disproportionate contribution of microalgae to global NPP gives them a very high potential for use in carbon sequestration, such as in the famous Iron Hypothesis proposed by John Martin (Stoll 2020).

Microalgae in the open ocean contribute approximately 80% of the total marine NPP (Schlesinger & Bernhardt 2020), while macroalgae in coastal waters contribute approximately 3%

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(Duarte et al. 2022). Carbon sequestration via algal cultivation has already attracted much attention (Gao et al. 2022), but the sequestration rate and potential of this method have not yet been carefully evaluated. Approximately 80–90% of marine NPP is decomposed into CO_2 in surface waters, with approximately 4% sequestered in the deep ocean (>1000 m depth) (Schlesinger & Bernhardt 2020). This percentage is consistent with a recent study that showed that approximately 2.5% of NPP of microalgae in the South China Sea was sequestered (Ma et al. 2021). These data show that the efficiency of carbon sequestration via microalgal cultivation is extremely low. However, approximately 11% of NPP of marine macroalgae is sequestered (Krause-Jensen & Duarte 2016), 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_2.

The dominant form of sequestration for both microalgae (Schlesinger & Bernhardt 2020) and macroalgae (Krause-Jensen & Duarte 2016) is the dissolved organic carbon (DOC) in deep ocean. Because the carbon amount of marine DOC pool is comparable to that of the atmospheric carbon pool (Schlesinger & Bernhardt 2020), 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.

Table 1. Efficiency of biological carbon sequestration methods and nutrient requirements to produce 1.5 Pg biogenic carbon.

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%	7.3%	8.4%	44.9%
Macroalgae	550:30:1	3511:202:1	11%	63.6%	20.7%	0
Microalgae	106:16:1	3511:202:1	4%	176.1%	107.5%	0

The nutrient requirements are expressed as a percentage of industrial fertilizer production. To simplify the calculations, this study assumes that all fertilizers added to the ocean cannot be recycled because the mean residence times of nitrogen and phosphorus in the ocean are more than 60 times the time left to achieve carbon neutrality by 2050.

The plant carbon pool contains mainly terrestrial trees, and about 70% of plant biomass is wood (Bar-On et al. 2018). Since there is no statistical difference between the ratio of biomass production to gross primary production (GPP) and the ratio of NPP to GPP of forests (Collalti et al. 2020), biomass production can be considered to be 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 an ideal form for carbon sequestration on land (Zeng 2008) or under water (Zeng & Hausmann 2022) for more than 1000 years. 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 (Schlesinger & Bernhardt 2020). Therefore, wood has the potential to be sequestered on a large scale for a long time.

Biochar, a carbon-rich material generally produced from the combustion of waste organic material with limited oxygen, has received increasing attention because of its potential for carbon sequestration as a source of carbon adsorbents (Karimi et al. 2022). Since biochar can be made from wood, it may be a better option for carbon sequestration than wood burial if its cost is competitive.

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However, biochar carbon sequestration has not yet been tested and evaluated on a large scale (Karimi et al. 2022), and further studies are needed to further develop this approach and make it operational.

2.3. Carbon sequestration through microalgae cultivation

The core mechanism of carbon sequestration via algal cultivation is that for the organic matter exported to the deep ocean, its carbon can be considered to be sequestered on the time scale of climate change because the residence time of deep waters is generally longer than 100 years (Zhang et al. 2018). 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 (Moore et al. 2013). 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 (Cordell & White 2015). Second, the mean residence times of nitrogen (~2000 years) and phosphorus (>25,000 years) in the ocean are much longer than the time required to achieve carbon neutrality (Schlesinger & Bernhardt 2020). 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 large amount 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 factors such as ocean circulation and storms can bring large amounts of organic carbon from the deep ocean to surface waters, where it can then be converted to CO_2 through photo-enhanced biodegradation (Shen & Benner 2018). A recent study suggested that ocean circulation is accelerating (Hu et al. 2020), 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 CO_2 (Schlesinger & Bernhardt 2020); 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 (Legendre et al. 2015), while the C: N: P molar ratio increases dramatically (Table 1) (Hopkinson & Vallino 2005). 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. Carbon sequestration via wood burial

Zeng (2008) 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.

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(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 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, six additional advantages of wood burial compared with other biological carbon sequestration methods based on elemental stoichiometry and energy efficiency were given:

(1) Dry wood has a high carbon content of approximately 47% by weight (Martin et al. 2021).

(2) Compared with the cultivation of other photoautotrophs, wood production consumes less nitrogen and phosphorus nutrients (Table 1) (Schlesinger & Bernhardt 2020), which has less impact on agriculture.

(3) Wood accounts for approximately 70% of plant biomass (Bar-On et al. 2018), 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.

(6) Some simple and low-cost methods, such as surface carbonization (Kymäläinen et al. 2022), could significantly extend the sequestration time of wood and fit into a large-scale carbon sequestration project.

The estimated total cost for land-based wood burial includes equipment, buildings, land purchase, transportation, and management is about $110 USD per ton of carbon (Zeng & Hausmann 2022), which is much lower than the assumed carbon price in advanced economies and several major developing economies in 2025 and beyond (IEA 2021). Notably, burying wood in the deep ocean should be less costly in terms of buildings, land purchases, transportation, and management than on land. These advantages make wood burial the leading candidate for carbon sequestration at present. In total, humans emit 350 Pg of carbon into the atmosphere, approximately two-thirds generated from the burning of fossil fuels (origin from ancient plants) and one-third from tropical deforestation (Schlesinger & Bernhardt 2020). Wood burial can return carbon to its original form.

The implementation of wood burial will require the proper management of global forests, which can impact forest ecosystems (Zeng 2008). However, knowledge is limited on this issue. Another technological uncertainty is the methane emissions from wood burial, which is of course common to all biological carbon sequestration methods. Degradation of organic material by methanogenic *Archaea* under anaerobic conditions is one of the major sources of global methane emissions (Saunois et al. 2020). Although wood and wood products generally decompose slowly and their methane yield is relatively low among many organic wastes (IPCC 2019), the methane issue still requires attention because the radiative forcing of methane is 27.9 times that of CO_2 over 100 years (Masson-Delmotte et al. 2021). In addition, methane yield varies considerably among different wood products under anaerobic conditions (Wang et al. 2011), suggesting the potential for improvement in wood burial technology.

3. Wood burial

3.1. Wood sources and timeline

Most of the forest are threatened by climate change and require adaptative forest management (Jandl et al. 2019). Dead wood is very sensitive to wildfires, and global warming makes the situation even worse (Zhuang et al. 2021). Notably, the total estimated economic cost of the California wildfires in 2018 was $148.5 billion USD (Wang et al. 2020). Therefore, sequestering dead wood can be considered an adaptive forest management that not only helps to decrease atmospheric CO_2 but also increases the primary production of forests (Pugh et al. 2019) and reduces forest fire emissions and associated economic losses.

According to the Net-Zero Emissions Scenario by 2050 (IEA 2021), the net carbon emission rate should be decreased from about 5 Pg per year to zero (Friedlingstein et al. 2020). Assuming the rate will decrease linearly, then the accumulation of atmospheric carbon from 2020 to 2050 should be approximately 75 Pg. This number is almost equal to the carbon pool in global dead wood (Pan et al. 2011) and about one-third of the potential of global tree restoration (Bastin et al. 2019). Thus, both the global dead wood and the global tree restoration potential could satisfy the wood requirement for achieving carbon neutrality through wood burial by 2050.

To reduce the nutrient requirement and ecological impact, the present study briefly suggests obtaining half of the sequestered carbon from dead wood, with the other half being temporarily stored in newly created woodlands and used as a future source of wood burial. The area of global forests is 3.9 billion ha, with a carbon stock of 861 Pg C (Pan et al. 2011), and wood accounts for 70% of the biomass of trees (Bar-On et al. 2018); the average wood carbon per ha forest is about 154.6×10^6 g C. The present study proposes a 25-year project starting in 2025 with an average sequestration rate of 3 Pg C per year, which includes burying 1.5 Pg of dead wood carbon and the creation of 9.7×10^6 ha woodland. The global wood production in 2020 was about 5 billion cubic meters (FAO 2021), and the wood carbon content is 303 kg per cubic meters according to the calculation in section 2.1, which indicates global wood production contains 1.5 Pg C. Therefore, wood industry has the potential to implement wood burial, but needs to quickly double its production. Considering the contribution of dead wood removal to primary production and the use of fast-growing forest species, this project is feasible and should fit the Net-Zero Emissions Scenario by 2050. The wood used for sequestration after 2050 could be taken entirely from newly created woodlands in the 25-year project.

3.2. Nutrient requirements of wood burial

Zeng and Hausmann (2022) discussed many technical details of wood burial. Here, the present study discusses the feasibility in terms of nutrient requirements. In addition to nitrogen and phosphorus (Schlesinger & Bernhardt 2020), trees require a large amount of potassium (K) at planting (Taiz & Zeiger 2010), as they have a C: N: K: P molar ratio of about 1360:8.5:4:1. The United States Geological Survey data show that, in 2018, the global annual industrial production of nitrogen, phosphorus, and potassium fertilizers was approximately 150 Tg, 34 Tg, and 32 Tg, respectively (Schlesinger & Bernhardt 2020). Assuming that the nutrients absorbed by trees are fully used for the production of 1.5 Pg wood carbon, then at least 7.3%, 8.4%, and 44.9% of the industrial nitrogen, phosphorus, and potassium produced each year globally, respectively, would need to be used for tree planting (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, other sources of potassium need to be explored. According to literature data (Schlesinger & Bernhardt 2020), the amount of dissolved potassium in the ocean is approximately 6.7×10^7 times the annual potassium requirement for the production of 1.5 Pg wood carbon. Potassium can be extracted from seawater by biological (e.g., farming high-potassium macroalgae, seagrasses, and salt-tolerant plants) 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 (Schlesinger & Bernhardt 2020), and soil contains more nitrogen and phosphorus contents than wood (Cleveland & Liptzin 2007). Therefore, the soil has great application potential in wood production.

The above analyzation suggests that, if carbon sequestration via wood burial is carried out in the future, the world will face more serious shortages of nitrogen, phosphorus, and potassium resources.

4. Conclusions

The key to achieving carbon neutrality is methods that are low in cost, large in scale, and have a long implementation time. This study evaluated the feasibility of several carbon sequestration methods from the perspective of sequestration scale and time, energy use efficiency, and elemental stoichiometry (Figure 1), and found that wood burial may be the most competitive method of carbon sequestration. Wood burial features low cost and low technical requirement, 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 a wood burial project requires a globally integrated management of nutrients and forest resources.

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Data availability: All derived data are included in the tables and text.

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