Green Buildings and Materials
Volume 1 Issue 1 No. 3
Published Online July 10 2022

Research progress of carbon sequestration in transportation field

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Abstract In several carbon sequestration projects which were proposed at home and abroad in transportation field, there are two different pathways to sequester carbon, one is the soil carbon sequestration (SCS), the other is the plant biomass carbon sequestration (PBCS). The carbon sequestration mechanism, carbon sequestration ability and corresponding research methods of SCS and PBCS were reviewed in this paper respectively. After a comparative analysis, the reason why they should be coordinated working is given. Finally, we proposed a carbon sequestration management system based on local climate conditions, hoping to provide some technical advice to the implementation of the carbon trading in the field of transportation in the future.

Keywords Carbon sequestration, transportation, highway, management system

1 Introduction

The national carbon trading market is about to open in 2017, to explore the application of carbon trading in various sectors is imminent [1].In 2013, the World Wide Fund for Nature (WWF) released a report “Carbon emission intensity rankings of Non-fossil energy companies in china in 2013”. According to this report, among all the domestic non-fossil energy sectors, transportation industry carried with the largest average carbon intensity, and that number is 119 times that of the financial industry [2] (Table 1). Therefore, it is particularly important to carry out a carbon sequestration research in transportation field.

The carbon sequestration of terrestrial systems can be defined as the capture and storage of carbon in the atmosphere into the carbon pool of organisms or soils that would otherwise be released to or stuck in the atmosphere[3]. The US Federal Highway Administration carried out a pilot program for carbon sequestration of highways in 2008 and achieved remarkable progress [4]. China has also carried out a preliminary study of carbon sequestration on national highway[5].However, their research objects and research methods are quite different, the former is treating soil as a carrier to study carbon sequestration, while the latter is aimed at increasing plant biomass to sequester carbon. In this paper, we first review and compare these two carbon sequestration pathways in the field of transportation, and then explain why they should cooperate instead of separating from each other to sequester carbon. Finally, we propose a "Climate-Soil-Land cover" management system, hoping to provide some technical advice to the implementation of the carbon trading in the field of transportation in the future.

Table1. Industry average carbon emission intensity

Industry	Average carbon emission intensity (tCO_2e/ / Ten thousand yuan)
Financial	0.0183
Telecom/Electronics/Equipment manufacturing industry	0.1133
Automobile manufacturing industry	0.2900
Telecommunication/ computer services	0.3360
Construction industry	0.3486
Transportation	2.1822

Calculation method of average carbon emission intensity:

The listed industry average carbon emission intensity = Total listed industry carbon emission intensity/Number of listed enterprises

2 Soil carbon sequestration

Soil carbon sequestration is the process by which carbon dioxide in the atmosphere is transferred into the soil unit under the action of organic matter (humus: such as plants, plant residues and other organic solids) remaining in the soil [6]. Commonly, soil carbon sequestration refers to soil organic carbon (SOC) sequestration. The carbon sequestered in the soil (terrestrial carbon pool) has a long residence time in the soil, and soil- sequestered carbon can be stored in the soil for centuries or even thousands of years without soil disturbance[7].

2.1 Mechanism

Soil organic carbon (SOC) in an ecosystem is derived from a single natural process: Plant photosynthesis [8]. Through this process, the carbon dioxide in the air is absorbed and transformed into its own organisms by plants, which are present in the soil in a variety of forms (root-secreted serous, plant debris), and these rhizosphere deposits will soon be decomposed into fresh organic residues by the soil microbial (humification). Under normal circumstances, the carbon sequestration process always make the changes in the chemical form of organic matter to realize the resistance to microbial attack, or easier be adsorbed by solid particles and thus more difficult to escape from the soil [9; 10].However, it should be emphasized that the nature of organic matter resistance to microbial decomposition is not inherent of the organic matter itself, but because of the complexity of physical and biochemical environment around, the probability of decomposition of organic matter is reduced, so it shows the characteristics of resistance to microbial decomposition[11]. At the micro scale, under the action of hydrogen bond, Van der Waals force and Coulomb force [12],the organic residues comes from organic matter decomposition are adsorbed and encapsulated by mineral ions in the soil to form organ-mineral complexes, so that the internal organic residues cannot be decomposed, and thus achieve the goal of carbon sequestration[13](Figure 1).The amount of plant residues in the soil and the degree of decomposition of soil organic matter are crucial factors for the formation of stable carbon aggregates, they present a positive correlation [14].

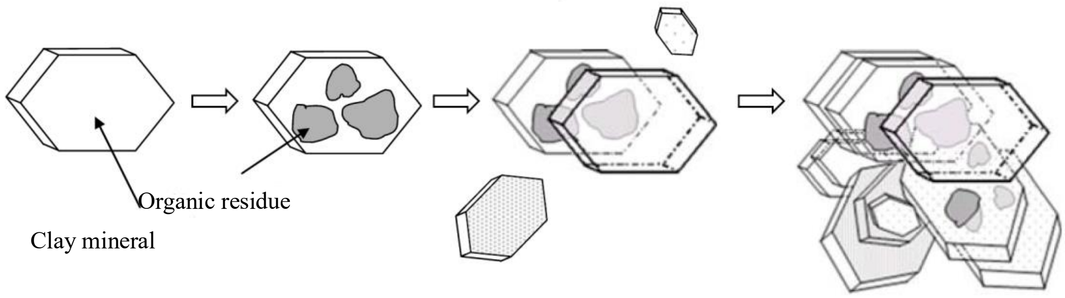

Figure 1. Schematic diagram of soil carbon sequestration mechanism within aggregates [13]

2.2 Carbon sequestration capacity

The study on particle size analysis of soil organic matter showed that, soil organic matter was classified as an active soil carbon pool in sandy soils. However, in silty soils and clay soils, soil organic matter was classified as moderate active carbon pool and inactive carbon pool respectively. This phenomenon has stimulated the scientists to study carbon sequestration ability in different soil types [15] Data shows that, in temperate arable soils, about 50-70% of total organic carbon is associated with soil particles of clay size ($< 2\mu m$) , and about 20-40% is associated with silt size soil particles ($2–63\mu m$), only less than 10% is associated with sand size soil particles ($> 63\mu m$) [16].Further studies have shown that under the action of polyvalent cations, there is a strong connection between organic anions and clay crystals, this connection can prevent the decomposition of organic matter by microorganisms. The strength of bonding forces between inorganic minerals and organic anion depends on the valence of the mineral metals in the soil and is ordered as followed: $Al^{+3} > Fe^{+3} > Ca^{+2} > Na^{+}$[14].The nature and quantity of clay minerals have great influence on the connecting force mentioned above, and the clay minerals with larger specific surface area could be easier adsorbed on the surface of organic residues and form a strong protective effect on the organic substances in clay minerals. In contrast, minerals with low specific surface areas and low charge densities have relatively low overall electrostatic charge levels and therefore cannot form stable carbon aggregates effectively[3](Table 2).This also clearly explains why montmorillonite clay soils can store and protect more soil organic carbon than kaolinite soils and illite clay soils. [17].

Microorganisms and invertebrates also promote the carbon sequestration in soils. Their decomposition activities can directly increase the amount of organic residues in the soil and reduce the volume of organic residues, they can make organic particles more likely to be protected by mineral ion adsorption, thereby enhancing soil carbon sequestration[9; 18; 19].

Table 2. Clay mineral types and their corresponding physicochemical properties

Clay mineral	Particle size (mm)	specific surface area (m^2/g)	Chemical formula
Kaolinite	0.1-5.0	5-20	$Al_2(OH)_4Si_2O_5$
Illite	0.1-2.0	100-200	$K_{00-2}Al_4(Si_{8-6}Al_{0-25})O_{20}(OH)_4$
Montmorillonite	0.01-1.0	700-800	$Al_2(OH)_2Si_4O_{10}$

2.3 Study method

Based on the review of soil carbon sequestration mechanism and carbon sequestration, we can draw the following conclusions.

- Soil carbon sequestration occurs mainly in vegetation-covered areas
- Soil organic carbon data should be expressed as soil organic carbon content per unit area under certain depth in the soil [6]

Assuming that soil organic carbon is evenly distributed along the vertical and horizontal directions within a certain depth below the surface, the total amount of soil carbon sequestration in a certain area can be expressed as:

$$Q_1 = C_{den} \times A$$

Where Q_1 is total amount of carbon sequestration in soils in a study area (kg), C_{den} is the content of organic carbon in soil per unit area (kg/m^2),A is the total soil area covered by vegetation (m^2). This expression is also used by the Federal Highway Administration and the North Carolina Department of Transportation. [20; 21].

In the literature review, we found that many researchers have used different formulas to express the same indicator C_{den}(Table 3),And these formulas are consistent with the definition given by Professor Olson [6].From Table 3, we can see that $2mm$ is a recognized particle size limit, and this size limit is the precisely boundary of soil fine particles (including clay, silt and sand), this size limit separates the fraction of carbon that has been stabilized in the soil from other soil sample.

Table 3 The expression of C_{den} in the historical literature

Author	Formula	Remark
Post et al. (1982)[22]	$C = C_f B_D (1-\delta_{2mm})V$	δ_{2mm} is the proportion of soil with particle size ≤ $2mm$; V is the volume of soil sample under certain depth;
Batjes et al. (1996)[23]	$SOC_d = \sum_{i=1}^{k} \rho_i \times P_i \times D_i \times (1-S_i)$	S_i is the proportion of soil with particle size ≤ $2mm$ in soil sample i; D_i is soil thickness in soil sample i
Pouyat et al. (2009)[24]	$C_{den} = FBD \times d \times \%C$	FBD is the bulk density of soil sample (particle size ≤ $2mm$); d is the sampling depth;

The main method for determining the area A is the use of aerial imaging techniques such as remote sensing and GIS [20; 25; 26].However, the key to identifying the area is the determination of the right of way (ROW) within the study area (the owner of the road has absolute control over all land within the right-of-way boundary and no private land is allowed).For example, a highway right of way includes the entire carriageway, shoulders, adjacent sidewalks, a roadside corridor with public facilities, and a rest area [21].

3 Plant biomass carbon sequestration

Plant biomass carbon sequestration means plant can absorb carbon dioxide in the atmosphere to form their own organisms through photosynthesis, plant biomass carbon sequestration is mainly reflected in net weight increase [27].Since plant carbon fixation and oxygen release capacity can effectively mitigate global warming, the current plant biomass carbon sequestration has evolved into carbon sequestration projects of afforestation across the country [5; 28].Researchers, represented by Prof. Zhou, formulated the *National Guidelines for Measuring and Monitoring Carbon Sequestration in Forestry* in 2011, and conducted nationwide pilot studies [36]. In addition, the plant body can be further processed into biochar, which has been proved a more efficient material in sequestering carbon.

3.1 Mechanism

In the sunny day, green plants can use the energy of sunlight to photosynthesis to obtain the necessary nutrients for growth and development. The key participant in photosynthesis is the chloroplast inside the plant, and the chloroplast is the site for photosynthesis. Under the action of sunlight, chloroplasts can convert the CO_2 absorbed by leaves and water absorbed by roots into glucose, and release oxygen. Photosynthesis of plants can be divided into two steps: light reaction and carbon reaction [30]:

$$12H_2O + \text{Sunlight} \rightarrow 12H_2 + 6O_2 \qquad \text{(Light reaction)}$$

$$12H_2\text{(From light reaction)} + 6CO_2 \rightarrow C_6H_{12}O_6\text{(Glucose)} + 6H_2O \qquad \text{(Carbon reaction)}$$

Photosynthesis achieves the conversion of carbon from inorganic to organic state, and thus participate in the Earth's entire ecosystem carbon cycle.

3.2 Carbon sequestration capacity

From the mechanism of plant biomass carbon sequestration, we can know that any factors that involved in plant photosynthesis will affect its carbon sequestration ability. Using the isotope technique to study the carbon cycle of photosynthesis, C3 plants showed different photosynthetic pathways to C4 plants. Compared with the C3 plants, C4 plants are more adaptable to high temperature, strong light and dry environment. Usually, under high temperature, strong light and dry conditions, the green plant stomata will be closed. At this time, the C4 plants can utilize photosynthesis with very low carbon dioxide content in the intercellular space of the leaves, and its photorespiration intensity is also low. In contrast, C3 plants not only cannot use low concentrations of carbon dioxide between cells for photosynthesis, but also has a high photorespiratory intensity, which is detrimental to the growth of plants. In general, C4 plants have a lower CO_2 compensation point than C3 plants, and have a stronger ability to absorb carbon dioxide, and thus have a greater capacity for carbon sequestration [9; 31; 32].In addition, the morphology of plant leaves is also an important factor to determine their ability to sequester carbon, broad-leaved plants have a larger leaf surface area than coniferous plants, and their leaves can carry more chloroplasts, So broad-leaved plants have stronger photosynthesis intensity and carbon fixation ability [33].

The type of climate, the concentration of CO_2 around the plant, mineral elements and heavy metal elements in soil also have certain influence on plant carbon sequestration, but these are external factors [34-36].

3.3 Study method

There are many achievements in the study of plant biomass carbon sequestration in China, and now it has developed into a nationwide carbon sequestration project of afforestation. According to the various biological morphology that the plant organism may appear before the end of the afforestation project, the amount of total carbon sequestration should be stratified calculated. Based on *The carbon sequestration project Methodology*[37] and the *Guidance on Monitoring Carbon Sequestration for Afforestation Project*, total amount of carbon sequestration of this project can be expressed as:

$$Q_2 = \sum C_i \times A_i$$

Where Q_2 is the total amount of carbon sequestration of this project (kg); C_i is the amount of carbon sequestration in the i morphological layer per unit area (kg/m^2), Among them, morphological layer contains the survival layer, the natural dead layer, the residual layer, the wood product layer, soil carbon layer; A_i is the project area in i morphological layer (m^2).

Assuming that the growth of plant biomass in the project is positively correlated with the time period, the biomass and carbon content of each layer can be used to represent the carbon content of the layer biomass, and then use the molecular weight ratio of CO_2 and C, we can transfer carbon content into carbon dioxide equivalent [37]:

$$C_i = \frac{44}{12}(B_i \times R_i) \div A_i$$

Where $\frac{44}{12}$ is molecular weight ratio of CO_2 and C (Dimensionless),B_i is the plant biomass in i morphological layer (kg),R_i is the carbon content in i morphological layer (Dimensionless),A_i is the project area in i morphological layer (m^2).

The main method for determining the area A_i is the use of aerial imaging techniques such as remote sensing and GIS, the key point, as with soil carbon sequestration, is still the determine of project boundary line.

4 Discussion

In the literature review, we found that soil carbon sequestration and plant biomass carbon sequestration are often separated from each other. Although the *Carbon Sequestration Project Methodology* also includes soil carbon, the methodology suggests that the SOC growth rate is too slow and the increase in the SOC pool is negligible. But according to the summary and induction of this two king of carbon sequestration pathway, we believe that they should not be divided:

1) This two kind of carbon sequestration pathway are derived from the same natural process: photosynthesis

2) The growth of plants will affect the soil carbon input, the factors affecting plant growth will also affect the soil carbon sequestration and plant biomass carbon sequestration

3) The quality of soil texture will affect the growth of plant body, soil mineral elements and heavy metals will promote or inhibit the growth of plants in different degrees

4) The influence effects of local climate conditions, such as light, temperature, humidity, and rainfall, on both soil carbon sequestration and plant biomass carbon sequestration are the same.

Table 4. Comparison of Carbon Sequestration Effects between Different pathway

Carbon sequestration Pathway	Amount	Carbon turnover time	Carbon turnover rate
Soil carbon sequestration	Large	Long (hundreds years)	Slow (Not easy to release back to the atmosphere)
Plant biomass carbon sequestration	Large	Short (limit to plant lifetime)	Fast (Easy to release back to the atmosphere)

In view of the synergistic effects of soils and plants in carbon sequestration, we propose the following "Climate-Soil-Land cover" carbon sequestration management systems:

1) Under certain climatic conditions and certain soil type, the amount of sequestered carbon per unit area of a certain plant species should be a constant with a small fluctuation value. We call this constant the carbon-sequestration index Q_{CSL} for this "climate-soil-land cover" combination. Under the influence of three dimensions, the index Q_{CSL} has an expression similar to the tensor. Assuming C=S=L=3, Q_{CSL} can be expressed as:

$$Q_{CSL} = \begin{matrix} Q_{111}+ & Q_{112}+ & Q_{113} \\ Q_{121}+ & Q_{122}+ & Q_{123} \\ Q_{131}+ & Q_{132}+ & Q_{133} \end{matrix} + \begin{matrix} Q_{211}+ & Q_{212}+ & Q_{213} \\ Q_{221}+ & Q_{222}+ & Q_{223} \\ Q_{231}+ & Q_{232}+ & Q_{233} \end{matrix} + \begin{matrix} Q_{311}+ & Q_{312}+ & Q_{313} \\ Q_{321}+ & Q_{322}+ & Q_{323} \\ Q_{331}+ & Q_{332}+ & Q_{333} \end{matrix}$$

2) Researchers across the country can quantitatively assess the Q_{CSL} index local conditions (Figure 2)

3) In the actual project, the manager can guide the design or adjust the Q_{CSL} index combination based on local carbon emission reduction requirements

4) The Q_{CSL} index combination can provide technical support for calculation of carbon credits in a carbon sequestration project.

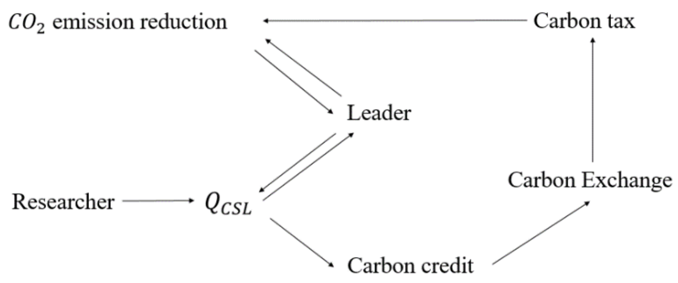

Figure 2. A carbon sequestration management system based on Q_{CSL}

The road area in the transportation field, whether it is urban road or suburban highway, has always been the most important part of green areas to government, but also the largest area of carbon dioxide emissions, how to use the optimal management model to effectively use Roadside soil and vegetation within the ROW to achieve the greatest carbon sequestration effect, will be the most important part for carbon trading in the transportation field in the future.

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