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Progress of Research on Soil Organic Carbon Stock And Influencing Factors in the Process of Restoration of Karst Desertification Vegetation Cover

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Abstract

Karst areas are vast and harbor a large amount of organic carbon, which plays an important role in the soil carbon sink effect of terrestrial ecosystems. Vegetation restoration has led to a significant increase in soil carbon sequestration, and the karst soil carbon sink effect will continue to increase in the new era. In view of this, this paper firstly summarizes the research progress on soil organic carbon content in the process of karst vegetation restoration, then reviews the current status, progress and uncertainty of the research on soil carbon stock and sequestration effect in karst region, and summarizes the driving factors of soil organic carbon stock; finally, it provides an outlook on the possible problems and challenges of soil carbon sink effect in the process of karst vegetation restoration, so as to provide important references for the karst region's soil carbon sink Finally, it provides an outlook on the possible problems and challenges of the soil carbon sink effect in the process of karst vegetation restoration, which will provide an important reference for the enhancement of soil carbon sink function and ecological benefits in karst areas.

Keywords: soil organic carbon, vegetation restoration, rocky desertification

1. Introduction

Karst mainly refers to the geological action of water on soluble rocks that is mainly chemical and supplemented by the mechanical action of flowing water such as erosion, subduction and collapse, and the general term of the phenomena caused by these actions [1]. China's karst is mainly distributed in the southwest region centered on Guizhou Province, with an area of about 540,000 km2, which is one of the three major karst concentration distribution areas in the world [2]. Soil formation in karst areas is slow, and it takes at least 40,000 years to form a 1-cm-thick soil [3]. Karst areas are mainly dominated by soluble rocks (carbonate rocks, sulfate rocks, and chloride salts), which have poor water-fixing capacity and a thin layer of soil, and thus are prone to surface drought and fragile ecosystem environments, and together with deserts, cold deserts, and loesses, they constitute four major ecologically fragile zones in China [3]. Under the condition of strong dissolution and erosion, underground caves develop in karst areas, forming a dichotomous structure above and below the ground, and the permeability is strong, and soil and water are easy to be lost. Southwest karst and its development, carbonate rock outcrop area as high as 12.8 × 104 km2 [4-6], in the tropical, subtropical humid, semi-humid climatic conditions and human activities, surface vegetation suffered damage, soil erosion is serious, bedrock exposed large areas, land degradation, the formation of a poor environment, rocky desertification phenomenon.

The process of karst ecological restoration is complex, including aboveground ecological vegetation and belowground soil ecological restoration, and the soil and vegetation are interrelated [7]. Various techniques have been used for karst ecological restoration, including vegetation restoration [8], biological crust [9], fertilizer application [10], biochar and biochar-based fertilizer application [11], biological mulching [12-13], soil water retention agent application [14], and engineered water-saving restoration [14]. Among them, vegetation restoration is the main way of ecological restoration of karst desertification, which can effectively increase soil organic carbon storage [16], accelerate the accumulation of organic matter in karst ecosystems, and also improve the soil water-holding capacity, which is an effective measure to enhance the soil-fixing capacity of karst areas and improve the quality of soil [17]. In the process of natural succession recovery of karst vegetation, plant roots and microbial species in soil ecosystems gradually increase, soil particles coalesce into large aggregates, soil porosity increases, bulk density decreases, water infiltration is enhanced, soil water-holding capacity improves, and the natural water content and field water-holding capacity increase [18]. However, geospatially, there are significant differences in climate and vegetation types, and vegetation restoration measures do not always show an increasing trend in carbon [19]. Due to the high spatial heterogeneity of karst regions, the effect of their vegetation restoration on soil organic carbon remains uncertain. Therefore, it is necessary to evaluate the SOC in karst areas to provide a reliable basis for further analyzing the effects of karst soil use type, vegetation type, restoration time and other factors.

Soil is the largest carbon sink in the global terrestrial ecosystem and the most active part of the global carbon cycle, with its organic carbon stock accounting for two-thirds of the carbon sink in the entire terrestrial ecosystem [20]. Small fluctuations in soil carbon pools influence the global carbon cycle process [21]. As an essential element of soil physical and chemical properties, soil organic carbon (SOC) plays an important role in mitigating the release of greenhouse gases (GHGs) and is an important indicator for assessing changes in soil quality in degraded ecosystems [22]. Therefore, improving SOC stocks is one of the important ways to achieve global carbon neutrality [23]. The global terrestrial vegetation carbon pool is about 550 Pg, accounting for 17% of the carbon stock of the whole ecosystem, and the sequestration rate can be up to 2.5 Pg-a-1; in the 0-100 cm soil layer, the soil organic carbon stock is 1,400-1,500 Pg, accounting for 75% of the carbon stock of the whole ecosystem, of which the global soil carbon sequestration potential is about 0.5-0.9 Pg-a-1 [24]. The soil organic carbon pool in China is about 69-92 Pg [25], and the annual soil carbon sequestration is about 0.12-0.17 Pg [26-27]. Soil in karst area is the surface vegetation cover, the material basis of the ecological environment, and stabilizing the surface vegetation by improving soil quality is one of the important measures for current karst ecological restoration. Due to the fragility of the ecosystem in karst areas, the restoration of degraded soils in karst areas and the ecological restoration of rocky desertification areas are particularly challenging. Therefore, it is of great significance to study the effects of different karst ecological restoration measures on soil for the current karst ecological restoration Figure 1.

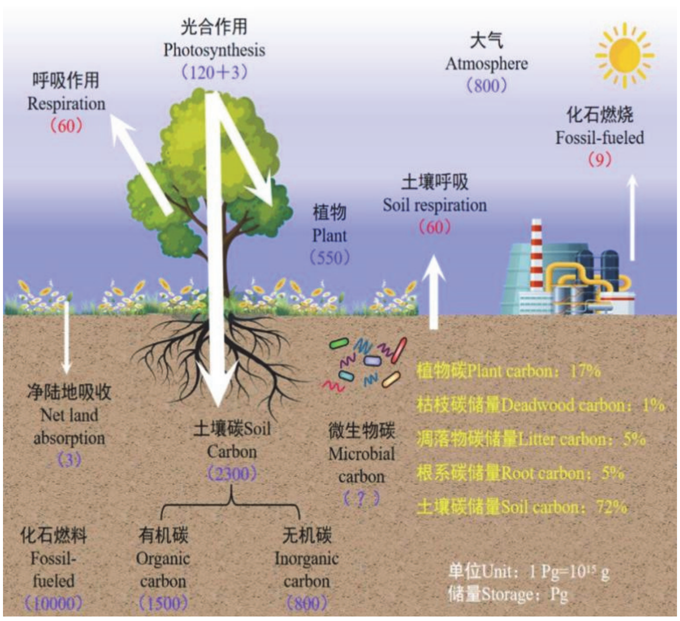

Figure 1. Schematic representation of global terrestrial ecosystem carbon stocks and allocation (IPCC 2021)

2. Progress of Research on Soil Organic Carbon Content in the Process of Karst Desertification Vegetation Restoration

The fixation of soil organic carbon in karst area is a long-term process. During the process of vegetation restoration, soil accumulation makes the decomposition of organic matter such as apoptosis and plant and animal residues slow, and soil organic matter is continuously inputted into the underground ecosystem, which leads to the enhancement of soil quality and the large accumulation of organic carbon. However, long-term human activities have resulted in the degradation of a large amount of natural vegetation, frequent soil erosion, and the loss of a large amount of surface soil due to erosion with rainfall. Scholars estimated that the soil organic carbon stock in the 0-20 cm soil layer of Southwest Karst is about 4.39 Pg [28].

Soil organic carbon in karst area shows the highest content of soil organic carbon in the surface layer, and the content of each layer has a significant positive correlation between the vertical distribution characteristics, with each other having the characteristics of mutual dependence on each other to pass from top to bottom, and the difference in the horizontal direction is significant [31]. This is due to the fragmentation and discontinuity of habitats in karst areas, and the prevalence of large spatial differences in characteristics. The SOC storage in the till layer of dolomitic karst soil decreases gradually with the increase of soil depth, which is the same as the distribution characteristics of organic carbon and nutrient mass fraction, i.e., organic carbon and nutrient mass fraction in each layer of the soil are positively correlated with the storage [34].

Karst soil organic carbon stock is deeply affected by soil depth, and the organic carbon stocks in 0-20 cm, 0-50 cm and 0-100 cm soil layers are 1.7 Pg, 3.5 Pg and 5.3 Pg, respectively; the carbon stock in 0-20 cm soil layer accounts for 32% of the 0-100 cm layer, and the carbon stock in 0-50 cm accounts for 65% of the 0-100 cm layer, which contributes about two-thirds to the formation, transformation and root decomposition of the vegetation biomass at the surface of soil. The formation and transformation of surface vegetation biomass and the decomposition of the root system are mostly gathered in the soil surface layer, so the contribution of 0-50 cm soil organic carbon stock reaches about 2/3. The organic carbon reserves of swampy soils, gray desert soils and alkaline soils in the karst area are low, while the yellow loam and limestone soils, which are larger in area, are the main distribution areas of organic carbon. For different land use types, there are differences in soil organic carbon content in karst areas. Based on the sampling depth of 20 cm, the soil organic carbon contents of arable land, grassland, lianas, shrubs and trees were 8.7653, 6.8476, 17.3466, 14.4144 and 14.5794 mg/hm2, respectively.Soil organic carbon stock not only decreased sharply with the intensification of rocky desertification, but also concentrated in the top layer of the soil, so that any event that caused top soil erosion will result in a significant decrease in soil organic carbon stocks [70].

With the increase of vegetation restoration years, the layer of dead branches and leaves on the surface was thickened, the decomposition of apoptotic materials released nutrients continuously, and the content of organic carbon and total nitrogen in the soil increased gradually. Peng Jiajia et al. found that fencing planted red willow made the soil organic matter (SOM) and nitrogen (TN) content increase with the extension of restoration years, and the SOM and TN content was highly significant higher than that of the un-restored area at 8 years of restoration ($P< 0.01$) [68]. Ma Xinyu et al. found that the SOC and TP contents of trees and herbs increased significantly after restoration, but the combined effect values showed that SOC was higher than TP, which significantly increased soil C:P. This indicated that the accumulation of soil organic matter increased after the restoration of trees and herbs, but the mineralization capacity of phosphorus in the soil was weak, and it was not easy to be converted into an effective state for plant uptake and utilization [69].

Soil organic carbon content varies between restoration modes. Compared with artificial restoration, the natural restoration mode had higher soil organic carbon content. For example, after 15 years of vegetation restoration in karst peaked depressions in northwest Gui, the SOC content of natural restoration mode (scrub) was significantly higher than that of artificial forest [29].Zhang et al. investigated the effect of vegetation restoration on the soil quality of karst degraded ecosystems, and found that the SOC and TN contents of the restored vegetation showed the characteristics of shrubs＞artificial forest＞artificial grassland [30]. The results of a large number of studies show that there are significant differences in the content and distribution of SOC under different land use modes, and the SOC of agricultural land is low compared to the SOC storage of natural vegetation [71-74]. The decrease of SOC storage was more obvious after the land use mode was changed from natural vegetation to agricultural production land, especially from forest to agricultural land. For example, Wu Chongshu et al. found that the conversion of arboreal forest land to dryland also caused a significant decrease in the soil carbon pool management index, with dryland SOC decreasing by 16.1%-47.0% compared to the corresponding arboreal forest land, with an average decrease of 28.8% [75].

For a long time, the SOC content in karst ecosystems has been significantly smaller than in other ecosystems due to the poor soil of karst rock desertification ecosystems, however, it was found that karst SOC content was significantly higher than that in non-karst areas [76]. The SOC content of each soil layer in karst landscapes was higher than that of non-karst landscapes, and the phenomenon of higher values of SOC content was observed in different karst landscapes with a higher degree of rock outcrop [77]. In karst landscapes, the presentation of this spatial distribution characteristic may be due to the higher rock outcrop, which leads to soil aggregation in localized depressions [39]. In the subsoil layer, the SOC values of karst landforms are also higher than those of non-karst landforms, which may be a result of the fact that the caves and holes underneath the karst areas can promote the movement of organic matter in each soil layer [79].

3. Factors Affecting The Organic Carbon Stock in Karst Rocky Desertification Soils

China's southwestern karst region has strong topographic cuts, longitudinal and horizontal development of gullies and valleys, and complex and diverse land use types, forming a typical aboveground-underground dichotomous structure [32]. The SOC distributed in the depth of 0-100 cm is highly susceptible to the disturbance of anthropogenic activities and the influence of climate change, and at the same time, various factors such as land use change, soil type, soil-forming parent material, and soil physicochemical properties will also change the spatial distribution of SOC [33].

3.1 Geographic and Topographic Factors

The rocky contiguous and complex topography of the karst region divides the soil into different microhabitats, and factors such as elevation, latitude and longitude, slope direction, and slope gradient all affect soil temperature and humidity [34]. The SOC content in the soil layer does not simply decrease directly with the increase of soil thickness, but shows a coupling relationship that first increases and then decreases in an upper approximation of an arc [31]. Elevation determines the atmospheric temperature and rainfall and other hydrothermal conditions, as the temperature decreases with higher elevation, while lower temperatures inhibit soil microbial activity and decrease decomposition capacity, favoring the accumulation of organic matter and ultimately affecting the accumulation of soil organic carbon [35]. Slope and slope orientation alter the intensity and dimension of solar radiation to a large extent, mainly due to the creation of localized microclimates on different slopes and slopes, affecting processes such as precipitation evapotranspiration and rainwater infiltration, which in turn change the input and output of soil carbon. In particular, calcium carbonate in soils on shady slopes carries away large amounts of organic carbon by leaching losses. Therefore, in general, the soil organic carbon content of shady slopes is significantly lower than that of sunny slopes [36]. Some studies have found that the surface micro-morphology of the karst rocky desertification area in southern China has a trapping and enriching effect on SOC, and the SOC content increases with the increase of rocky desertification degree to a certain extent [37], which is contrary to the high rocky desertification degree and low soil organic carbon content. However, studies have shown that slope, soil depth and bare rock rate only have correlation with soil organic carbon storage, which is not an important influence factor of soil organic carbon storage [38].

The distribution of geomorphologic units is controlled by tectonic movements, climate, hydrology, and other factors, and different geomorphologic units are distinguished by their geology, hydrodynamics, climate, vegetation, and soil cover. Different geomorphologic units have formed soil covers with different thicknesses, nutrients and textures under the long-term joint effects of hydrodynamics, climate, vegetation and soil types, which led to the spatial differentiation of SOC under different geomorphologic units. Taking SOC density as an example, there is great spatial heterogeneity in the SOC density of surface soil (0-20 cm depth) in different geomorphic units. Study shows that the SOC density of surface soils of different geomorphologic units is manifested as karst plateau basin > karst fracture basin > karst plateau > karst trough > crested depression > karst canyon. The SOC density in karst basins was significantly higher than that in other landform types, which may be related to the fact that the basin landform unit is more favorable for the convergence of organic matter, thus giving the SOC a "clustered surface effect" [39]. It was found that in the karst canyon area, soil thickness had the greatest effect on organic carbon content and land use type had the least effect, while soil thickness directly affected SOC input, degradation rate and accumulation rate. Rock desertification in karst canyons is more serious than in other landscapes, resulting in higher SOC content in karst canyon soils [78].

3.2 Biological Factors

The carbon sequestration capacity and organic carbon stability of the soils in the karst mountains of southwestern Guizhou under different vegetation types are weak, and the shallow soil layers are susceptible to organic carbon loss due to anthropogenic disturbances, which may lead to the risk of soil quality decline or degradation. In the process of vegetation restoration, the quantity and quality of carbon inputs (e.g., lignin content or carbon to nitrogen ratio) have a direct impact on soil organic carbon stocks [41]. Agricultural activities in karst areas are mainly reclamation and cultivation, and land use changes such as returning farmland to forest and grassland. Changes in land use lead to different rates of soil microbial decomposition, which in turn leads to soil organic carbon content and storage [42]. The large amount of reclamation and tillage in karst areas can lead to a large amount of organic carbon depletion, mainly due to the fact that reclamation and tillage methods on the one hand make the soil organic matter exposed to the air unprotected, resulting in a large amount of organic matter mineralization and decomposition; on the other hand, changing the soil porosity, the change of temperature and humidity conditions in the soil changes soil microbial activity, which leads to the acceleration of the decomposition and mineralization of soil organic matter [43,44]. In addition, afforestation does not always increase soil organic carbon content, and the effect of afforestation on soil organic carbon depends on background soil carbon content [45].

Vegetation type is the main factor influencing the spatial distribution characteristics of soil organic carbon [46]. There are differences in the organic matter content of different vegetation itself, and its input of organic matter to the soil and other changes affect the soil microbial community and soil carbon pool. Specifically, the promotion of soil organic carbon by apomictic additions indicates that, although aboveground apomictic inputs can accelerate the decomposition of soil organic matter through the excitation effect, they are generally favorable to the sequestration of soil organic carbon [47]. Differences in the amount and composition of apoplastic litter produced by different vegetation types directly affect exogenous carbon inputs, and the processes of carbon input and carbon loss largely control the dynamics of SOC accumulation and decomposition [48]. Vegetation in karst areas is more susceptible to the influence of bedrock chemical characteristics, which is manifested in the fact that bedrock chemical characteristics lead to a decrease in the water storage capacity of the weathered layers in karst areas, making the vegetation in karst areas more susceptible to intermittent drought disturbances, which affects the productivity of the vegetation [49]. However, it was found that there was no significant correlation between apoplastic biomass, apoplastic C content and soil SOC storage after vegetation restoration [50], which may be related to soil stabilization capacity [51] and exchangeable calcium in soil [47]. When the soil stabilization capacity is weak, the C input from the apoplastic matter will be lost, while when the soil exchangeable calcium is high, the multivalent cations can act as bond bridges between the clay minerals and humic substances to form a stable organo-mineral complex, enhance the stability of carbon, and sequester the carbon in the soil.

Bacteria and fungi promote the accumulation of soil organic carbon by decomposing the soil surface apoplastic material and thus obtaining nutrients. Studies have shown that soil microbial abundance increased significantly after vegetation restoration, which showed a significant positive correlation with soil organic carbon row two, and further studies found that higher soil microbial abundance was found under natural vegetation restoration compared to artificial vegetation restoration [52]. This was attributed to higher species richness under natural restoration compared to artificial vegetation restoration, which in turn influenced soil microbial abundance. Under natural conditions, the main sources of carbon in the soil are the downward migration of organic carbon in the surface layer and the plant root system and microbial population, the surface soil as the main receiving layer of vegetation dead leaves and leaves and the microbial population is the largest, the organic matter is in the period of rapid turnover, the decomposition rate is the fastest, so the content of carbon in the surface layer of the soil is higher than in the other layers of the soil, as the depth of the soil layer continues to increase, the number of microorganisms in the soil will decreasing, the turnover rate of organic matter in the soil will become slow, and the organic matter content enters a slowly decreasing level, as the depth continues to increase, the source of organic matter gradually decreases, while the amount of decomposition loss is increasing, and the deeper layers of the organic matter content, although lower, is mainly a stable component of the organic matter, and the content of soil organic carbon tends to be stabilized.

3.3 Climatic Factors

Differences in conditions such as average annual temperature and precipitation in karst areas lead to changes in soil temperature and humidity, and the rate of soil organic carbon accumulation and decomposition [53]. Climate also constrains the vegetation type, ecosystem productivity, thus determining the amount of organic carbon input into the soil; secondly, during the output of soil organic carbon, microorganisms produce a series of hydrolytic and oxidative enzymes to decompose apoplastic material and thus increase soil organic matter, which plays an important role in accelerating organic matter decomposition and soil nutrient cycling [54]. A large number of studies have shown that in the rainy season, with the increase in precipitation and the rise in temperature, the growth rate of vegetation will be much greater than that in the dry season, and the large input of vegetation apomixis and roots will not only increase the net primary productivity, but also enhance the microbial activity in the soil, so it has a strong effect on the decomposition of organic carbon in the soil; in the dry season, with the lowering of the temperature and the decrease in precipitation, the rate of apomixis decomposition is slowed down, and the decomposition rate of soil organic carbon is also slowed down. In the dry season, with the decrease of temperature and precipitation, the decomposition rate of apomictic material slows down, and the decomposition rate of soil organic carbon also slows down accordingly, and the content of soil organic carbon also decreases accordingly.

Changes in conditions such as temperature affect microbial decomposition and conversion of organic carbon [55]. Soil moisture conditions affect the mineralization and decomposition of intrinsic soil organic carbon and the degradation of exogenous organic carbon by influencing soil aeration, which in turn affects the organic carbon content of soil holdings [56]. When the soil moisture is sufficient, the permeability is poor, the original organic carbon is not easy to mineralize, exogenous organic residues are easy to decay and degrade into small molecule organic matter under the action of moisture, stored in the soil, thus conducive to the improvement of soil organic carbon content; when the moisture is insufficient, the porosity of the soil will become larger, which is more favorable for the mineralization and decomposition of organic carbon, and unfavorable for the accumulation of soil organic carbon [57]. A large number of studies have shown that an increase in temperature will not only increase the net primary productivity of vegetation, but also promote the decomposition of organic carbon in soil, and the relative sensitivity of the two to temperature will largely determine the source/sink role of soil organic carbon to atmospheric CO2 under global warming [57,58].

3.4 Soil Physical and Chemical Factors

Changes in soil organic carbon content are largely regulated by soil physicochemical properties [58], and changes in soil organic carbon content also have an important regulating effect on soil physicochemical properties [59], and the magnitude of this regulating effect can usually be expressed by the correlation between soil organic carbon content and soil physicochemical properties, where the larger the correlation coefficient is, the stronger the correlation is between the two [60]. Many studies have shown that soil organic carbon content is correlated with soil physicochemical factors such as soil bulk weight, soil water content, soil pH, and total porosity [61-63].

Soil bulk weight and porosity can reflect the looseness of the soil and affect soil aeration; the smaller the bulk weight and the larger the porosity, the looser the soil is, the more microorganisms and apoplastic matter enter the soil layer, resulting in an increase in organic carbon content; on the contrary, it affects the activity of microorganisms and the entry of organic matter, and the content of organic carbon decreases [64]. In karst areas, soil bulk weight shows a spatial distribution trend of rapid increase and then slow decrease with the increase of soil depth, with rapid increase in the upper soil layer and little change in the lower soil layer [65]. Therefore, soil organic carbon content in karst areas decreases with increasing soil depth.

Changes in soil water content reflect the quality of soil to a certain extent, and play a crucial role in the conservation and transfer of soil nutrients and organic matter. Differences in soil water content affect the changes in SOC to a certain extent, especially in karst areas, where soil water-holding capacity is relatively poor and water content is generally low, thus becoming an important factor affecting SOC.

Soil properties directly affect soil organic carbon storage. Studies have shown that soil clay particles show a positive correlation with soil organic carbon content [64]. Clay minerals can protect organic matter from decomposition, and the distribution of SOC in soils of different textures also directly affects the distribution of SOC due to differences in water-holding capacity, clay-grain content and other characteristics [48]. Soil gravel content influences soil water content, which indirectly affects soil organic carbon content. When the soil gravel content gradually increased, the corresponding SOC content also increased, but the density of SOC content distribution decreased significantly. This reveals that when the stone content in the soil is too high, although it can also increase the value of SOC content to a certain extent, it may not be a very favorable environmental condition for promoting SOC. Meanwhile, the stone grain content in rocky desertification soils was larger and decreased with the gradual increase of soil layer depth. Soil pH further affects the distribution of soil organic carbon content by influencing the activity of microorganisms in the soil as well as enzyme activity, which makes the intensity of organic matter mineralization different [65]. The SOC content of soils with different grain size particles in karst areas varies significantly, showing sand > silt > clay [66, 67].

4. Conclusion and Prospect

4.1 Carbon Sink Function of Karst Ecosystem is a Long-Term Process

Karst area is characterized by the development of aboveground and belowground binary system, and the soil has developed vertical joints and strong uprightness; however, the soil is weak to the resistance of flowing water and prone to erosion, and once the vegetation on the soil surface suffers from damage, the soil erosion phenomenon will spread rapidly, and a large amount of organic carbon will be lost. With the continuous progress of vegetation restoration, the soil and vegetation can re-absorb and fix a large amount of carbon, which in turn increases the ecosystem carbon stock. In the current form, the restoration of vegetation on the Loess Plateau is only the beginning, and from a long-term perspective, the Loess Plateau ecosystem still has a great potential for carbon sequestration; therefore, the function of carbon sinks in the Loess Plateau ecosystem is a long-term process.

4.2 Enhancing Soil Carbon Sequestration Under Natural Vegetation Succession

Current indications show that: karst areas are dominated by artificial vegetation restoration measures, followed by the transition to the natural restoration stage, and carbon sequestration effect is also in a relatively stable state; the vegetation restoration method has shifted from the importance of planting trees and forests and planting grasses in the past to emphasize the self-repair of vegetation, and tends to favor natural restoration measures. It can be seen that following the law of vegetation restoration and focusing on natural succession, supplemented by human activities, is an effective way to accelerate vegetation restoration and maximize the effect and function of soil carbon sinks in ecosystems.

4.3 Main Research Methods and Future Challenges of Current Soil Carbon Stock in Karst

Karst has a complex natural environment, which is affected by climate change and human activities, and the soil carbon stock in the region is under dynamic change, which leads to further increase in the uncertainty of carbon stock assessment, and increases the bias in the assessment of the overall carbon balance in China. Currently, more studies have been carried out on karst soil carbon stock, mainly through data inventory, sample point survey for small-scale estimation, and modeling and other methods for large-scale estimation. The results of modeling are slightly lower than the measured values of data inventory and sample point survey, which may be due to the precision of parameter setting of the model; in addition, the results of data inventory and sample point survey also show a big difference, which may be due to the different sampling methods and means. For model estimation, if the vegetation type or soil type is used as the base map, the higher the accuracy of the base map, the higher the accuracy of the estimation results; while when using the unitary model and the hierarchical model for estimation, the results of the different models are more different. For the estimation of data inventory and sample point survey, it is necessary to standardize the sampling method and standard, and expand the scale survey and soil depth; therefore, in the future, it is necessary to combine the carbon cycle model with multiple pathways, and at the same time, assist in the validation of the model with the measured values, in order to improve the accuracy of the estimation of the carbon stock.

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