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Review

Review of Managing Soil Organic C Sequestration from Vegetation Restoration on the Loess Plateau

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Abstract: China's Loess Plateau is both the largest and deepest loess deposit in the world, and it has long been one of the most severely eroded areas on Earth. With the implementation of the Grain-for-Green Project in 1999, the Loess Plateau has become the most successful ecological restoration zone, and soil organic carbon (SOC) sequestration has greatly increased. However, little is known about the balance of SOC sequestration and vegetation restoration on the Loess Plateau. Thus, this review focused on the SOC sequestration from vegetation restoration in this region. Firstly, the current situations and principal aspects of vegetation restoration processes were reviewed, and the effects of vegetation restoration on SOC sequestration were summarized. Secondly, based on the new technologies and methods for soil carbon (C) sequestration, the mechanism of soil microbial C sequestration was described from the molecular level of genes, and some management measures for SOC sequestration were summarized. Finally, we pointed out the main directions in C sequestration mechanisms for vegetation restoration depending on the basic process of the C cycle, which should integrate into physics, chemistry, and biology. Overall, this review will help us understand the SOC sequestration function and the ecological benefits of vegetation restoration on the Loess Plateau.

Keywords: microbial C sequestration; physical C sequestration; chemical C sequestration; C sequestration; controlling factors; China's Loess Plateau

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1. Introduction

The Loess Plateau in northern China is located in the catchment of the middle reaches of the Yellow River; it covers an area of 640,000 km^2 (Figure 1a) [1], and, in typical areas, it has a depth of more than 300 m [2,3]. The land use classification includes farmland, forestland, grassland, and desert (Figure 1b) [4]. The average annual precipitation varies from 750 mm in the southeast to 200 mm in the northwest, with 70% in the growing season between May and September. The interannual variability rate of precipitation is high: up to 695 mm in wet years, but only 200 mm in drought years. The rainfall protection rate of 500–550 mm is only 17.7%. The average annual temperature has ranged from 4.3 °C to 14.3 °C during the last 20 years (Figure 1c) [5,6]. Based on the water resources available to the local ecosystem, the Loess Plateau can be divided into a loess hilly area in the southeast, the Muus desert in the north, and the irrigated area (Figure 1a). In this region, loess is a highly erosion-prone soil that is susceptible to the forces of both wind and water [7,8]; as a result, soil erosion rates (3431.8 t/(km^2 a) from 1999 to 2016) on the Loess Plateau are high, and river sediment loads are heavy [9,10]. The erosion is exacerbated by the high-intensity rainstorms and long history of agricultural development. Most of the plateau is in a semiarid zone, according to an aridity index (defined as the ratio of potential evaporation to precipitation) [1,11,12]. This makes the region ecologically vulnerable and sensitive to climate change.

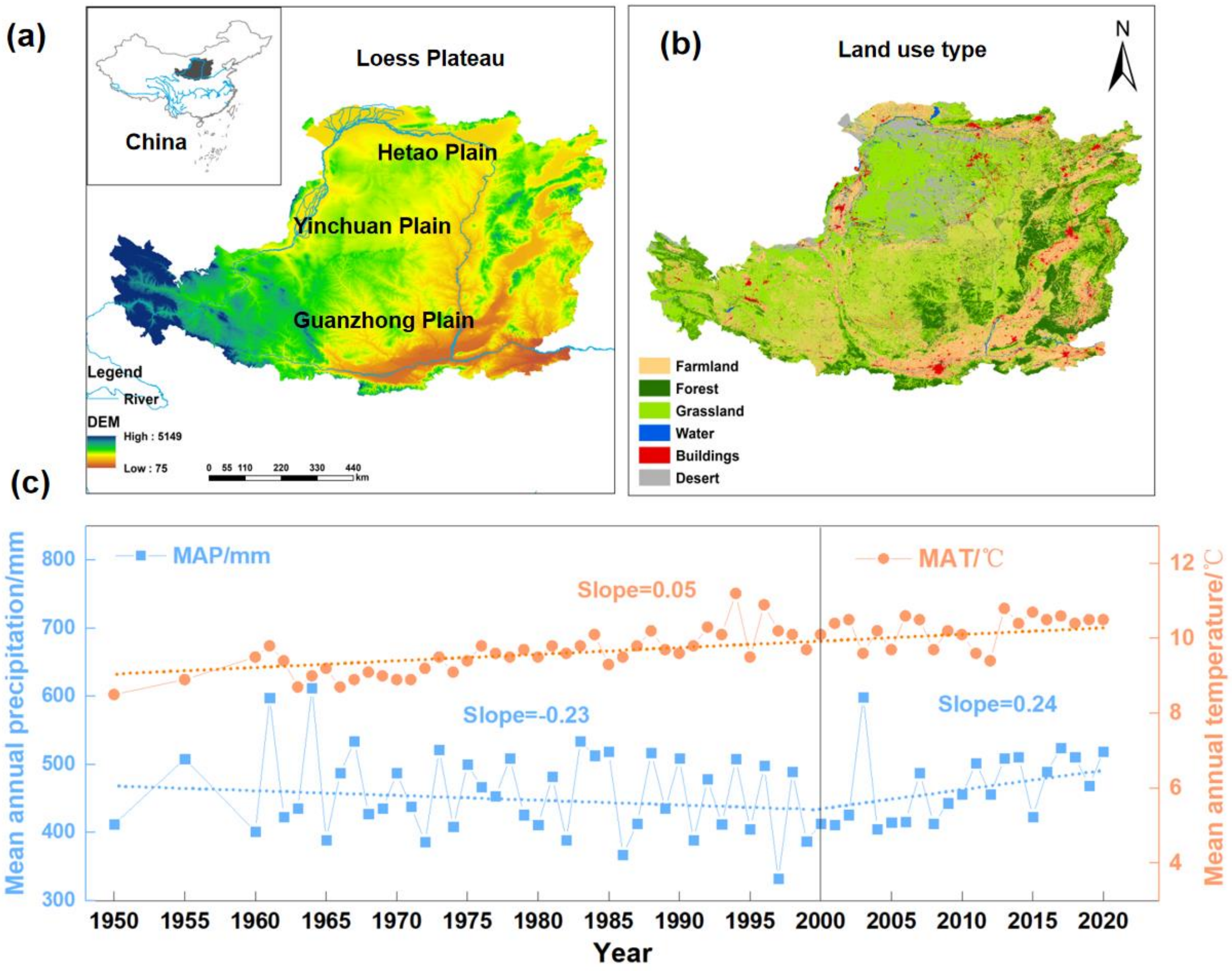

Figure 1. Overview of the Loess Plateau. (**a**) Location of the Loess Plateau, (**b**) land use types (2020), (**c**) the mean annual precipitation and temperature.

Soil organic carbon (SOC) represents the largest pool of terrestrial C, with an average content of 2400 Pg in soil depth of 2 m, which is 3.2 times the atmospheric pool and 4.4 times the biotic pool [13,14]. Due to the size of the SOC pool, even small changes in SOC could significantly affect the concentrations of atmospheric CO_2 [15,16]. Although SOC-positive policies have been enacted during the last decade, much uncertainty remains regarding the effects of long-term land-management policies on SOC sequestration on the Loess Plateau [17,18]. To reduce this uncertainty, we need to understand the links between SOC sequestration and vegetation restoration. Here, we build the conceptual path diagram of SOC sequestration from vegetation restoration on the Loess Plateau (Figure 2), and, thus, this review is focused on SOC sequestration from vegetation restoration on the Loess Plateau. Firstly, the current situations and principal aspects of vegetation restoration processes are reviewed, and the effects of vegetation restoration on SOC sequestration are summarized. Secondly, based on the new technologies and methods (such as light-driven carbon fixation, C fixation by microorganisms and SOC biologic material, and other C capture and storage, or direct air capture of CO_2, or enhanced weathering of minerals, etc.) for C sequestration, the mechanism of soil microbial C sequestration is described from the molecular level of genes. Finally, we point out the main directions in the soil C sequestration mechanism for vegetation restoration depending on the basic process of the C cycle, which should integrate into the physics, chemistry, and biology effects.

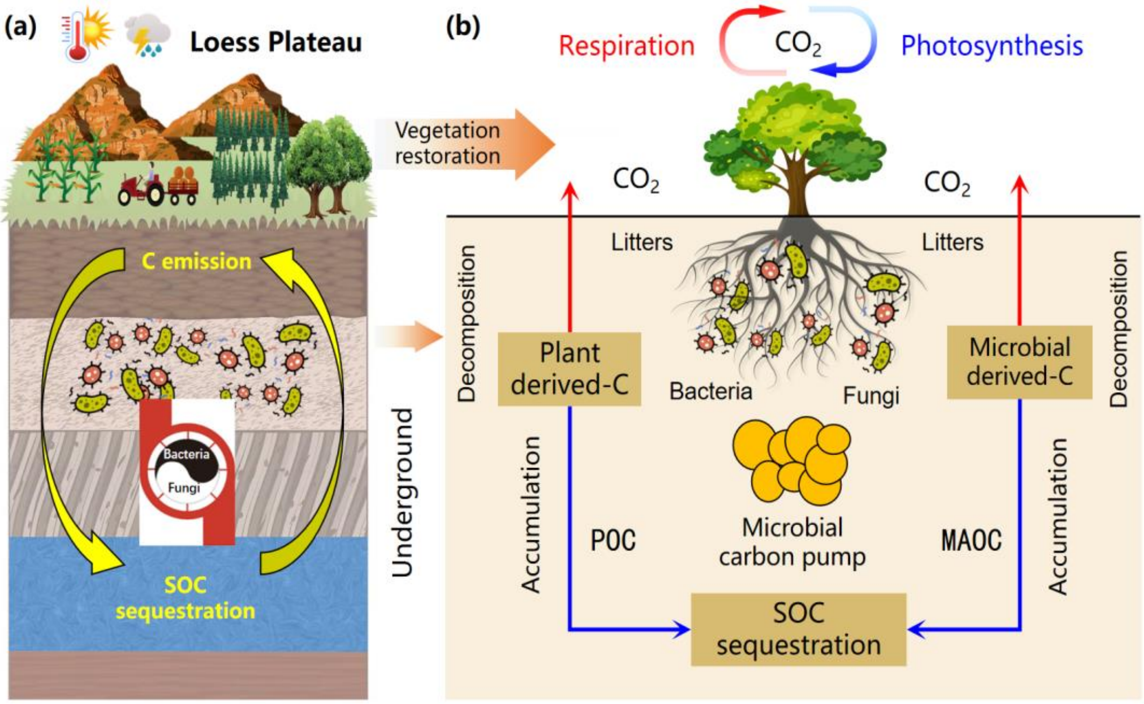

Figure 2. The conceptual path diagram of the C emission and sequestration in vertical (**a**). And the conceptual path diagram of SOC sequestration from vegetation restoration on the Loess Plateau (**b**).

2. SOC Storage Following Vegetation Restoration on the Loess Plateau

The area of unused land gradually decreased, while the area of residential land and forest land continued to increase from 1982 to 2020 (Figure 3). Before the project of returning farmland to forest, the vegetation coverage on the Loess Plateau was dominated by small fluctuations [19–21]. The SOC areas have improved, but most of the region has not changed significantly [22,23]. After 1999, the annual average of the normalized vegetation index increased significantly, and it most contributed to the growth in summer and autumn [24,25]. Vegetation coverage showed a clear regional increase in space, with the most obvious increase in the hilly–gully region of the Loess Plateau [26]. Recently, SOC studies collected remote sensing image data before and after the "Conversion of Cropland to Forest (Grass)" ecological project (1980s, 2001–2013) [27–29]. They divided the entire Loess Plateau into different zones, such as forest restoration areas, forest grasses or shrubs restoration areas, grassland restoration areas, rehabilitated areas of dry scrubs, and natural restoration areas. There is also research showing that (1) the overall restoration of vegetation on the Loess Plateau should be based on returning farmland to grassland, especially for growing grasses and asteraceae; (2) some woody plants can be properly planted, which enhances SOC; (3) it was taken into consideration that appropriate planting of economic plants, such as hazelnuts and walnuts, was conducted in the southeast of the Loess Plateau to keep soil and water conservation and economic development [30,31]. In addition, the vegetation coverage of the Loss Plateau increased from 21% in 1982 to 71% in 2020 (Figure 4). After 1999, the vegetation coverage rapidly increased due to the large Grain-for-Green Project in this region.

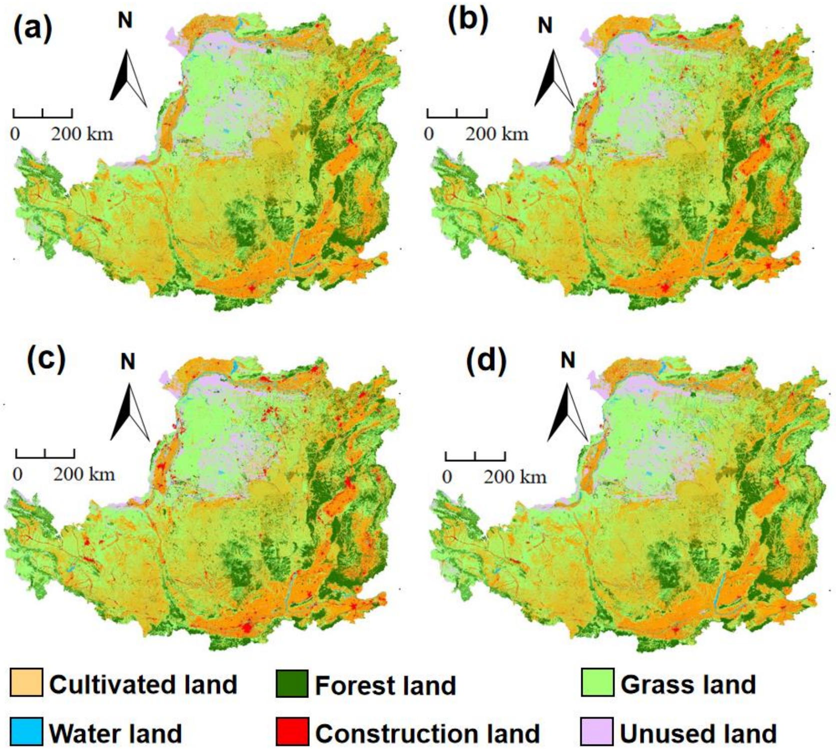

Figure 3. The land use types on the Loss Plateau from 1982 to 2020. (**a**) 1982; (**b**) 1999; (**c**); 2010; (**d**) 2020.

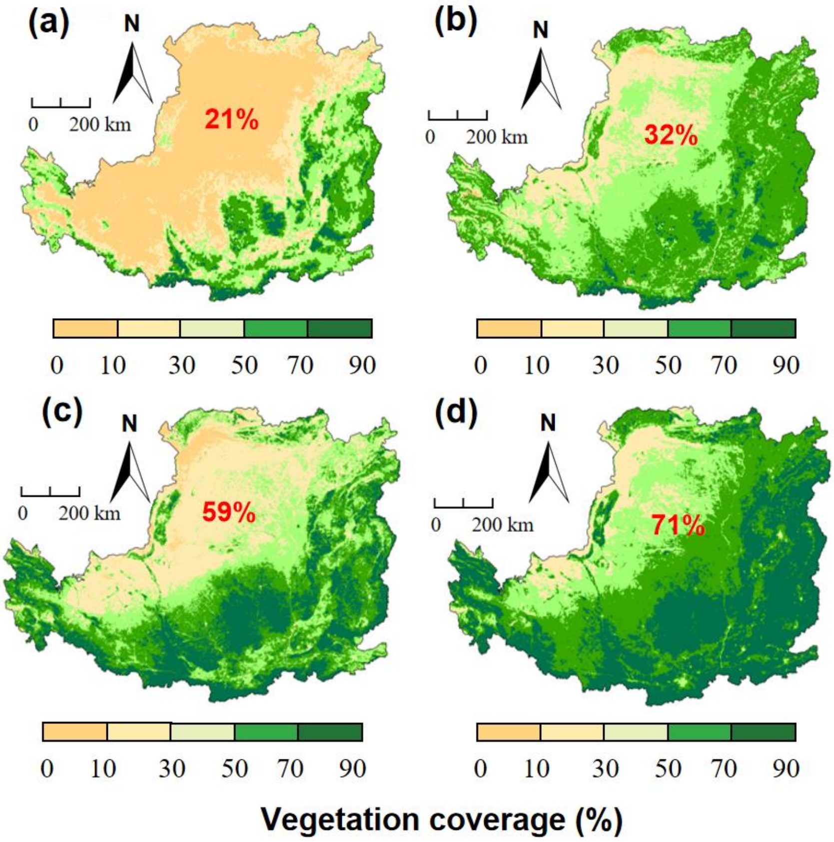

Figure 4. The vegetation coverage of the Loss Plateau from 1982 to 2020. (**a**) 1982; (**b**) 1999; (**c**); 2010; (**d**) 2020.

The area of the Loess Plateau involved in the national project of returning farmland to forestry is relatively large [32]. Although SOC studies indicated that vegetation restoration limits changes in SOC, most studies confirmed that SOC content increased with vegetation restoration [21]. With the development of vegetation restoration on the Loess Plateau, positive succession of vegetation communities occurs [33,34]. As litter accumulates and decomposes, SOC accumulation continuously increases [35]. In turn, it promotes plant growth and community development, and, thus, vegetation restoration and SOC sequestration are mutually reinforcing, and this effect continues to increase with vegetation restoration [21,36–39]. The current evidence suggests that the vegetation restoration on the Loess Plateau played a significant positive role in soil and water conservation and improvement of the ecological environment [18,35,38,40,41]. It had significant and far-reaching effects on the ecosystem C cycle and soil C sink function [1,6,18,39], and SOC studies showed that returning farmland to forests will accumulate more SOC in the future [14,32]. The interactions between vegetation cover changes, SOC sequestration, and erosion ratios and their interaction effects were studied on multiple scales [6]. The results showed that (1) in the short-term (about 30 years), returning farmland to *Robinia pseudoacacia* forest can significantly increase surface and deep SOC storage; (2) on the slope surface scale, the combination of returning farmland and returning to grassland is more effective than that of a single reclaimed farm or grassland, and the irrigation and compound-returning farmland can reduce the slope erosion C storage; and (3) after returning farmland to forests (in 30 years), SOC storage significantly increased in the arid regions. In humid areas, the SOC contents in the 10–20 cm layer showed a pattern of initial decline. Further research shows that, when the conversion of cropland to grassland is implemented, the implementation of returning farmland to forests in the southern region is conducive to increasing SOC sequestration in the project of vegetation restoration [18].

During the period from 2000 to 2008, the C sequestration on the Loess Plateau increased by 96.1 Tg (equivalent to 6.4% of the country's C emissions in 2006). The ecosystem changed from C source to C sink. The net C sequestration capacity of the ecosystem rose from 0.011 Pg to 0.108 Pg during 2000–2008. The results confirmed that returning farmland to forests and grasslands is the main reason for the increase in SOC sequestration in the ecosystem in the region [1]. Vegetation C sequestration continues to increase at an annual rate of 9.4 g·C m^{-2}, and the highest value of the increase in vegetation C sequestration occurred in an area where the average annual precipitation is about 500 mm. A further increase in the number of years of forest and grassland reclamation shows great potential [6]. Over time, the return of farmland to forest project areas in the next few decades will accumulate more SOC storage, which has great potential for mitigating the effects of climate change in the future [42]. Recently, Deng et al. [38] estimated the SOC stock on the Loess Plateau ecosystem to be approximately 2.29 Pg, accounting for only 2.3% of China's total C stock. This estimate includes 0.98 Pg in forest ecosystems, 1.09 Pg in grasslands, and 0.21 Pg in croplands. The SOC stock is estimated to be 1.52 Pg, while the C stocks of above- and below-ground living organisms are 0.44 Pg and 0.32 Pg, respectively. The latest inventory data suggest that the C stock on the Loess Plateau ecosystem is approximately 2.84 Pg, accounting for only 2.5% of China's total C stock. This estimate includes 0.36 Pg in forest ecosystems, 1.18 Pg in grasslands, 1.05 Pg in croplands, and 1.05 Pg in shrublands [43]. Other studies suggest that the SOC stock in the shallow layer (0–20 cm) of the Loess Plateau is 1.64 Pg, which increases to 2.86 Pg in the 0–40 cm soil layer. In the deep soil layer (0–100 cm), the SOC stock is estimated to be 4.78 Pg, and it reaches 5.85 Pg in the 0–200 cm soil layer. The SOC stocks in the 0–100 cm and 0–200 cm layers account for 8.21% and 5.32% of the total SOC stock in China, respectively [35].

3. SOC Sequestration Mechanism Following Vegetation Restoration

3.1. Soil Chemical C Sequestration

Vegetation restoration can change the characteristics of SOC sources and decomposition, and further decomposition usually depolymerizes large fragments, reducing the size and functionalizing the organic residue [44]. Soil fauna and microorganisms will affect C input, accelerate the decomposition of sugars, lipids, and lignin, and change the structure of SOC [21,45]. During vegetation restoration, organic matter entering the soil, apart from physical fragmentation and leaching, under the action of the selection of microorganisms and enzymes, carbohydrates, and proteinaceous substances (including water-extracted and hydrolyzed sugars, such as monosaccharides, polysaccharides and peptides, amino acids, etc.) first decomposes [46,47]. Then, the particles of organic matter decrease, and the ratio of C to nitrogen decreases, resulting in the decomposition of complex chemical (such as lignin and alkyl structure C with aromatic structure) structures that are more difficult to degrade [40]. In the process of SOC formation, organic matter can reduce its bioavailability by combining with iron–aluminum minerals (iron–aluminum oxide, iron–aluminum ions, etc.), thereby increasing its stability, and it eventually integrates into the soil to form stable organic matter [48,49]. Soil iron–aluminum minerals, clay content and surface properties (specific surface area and surface charge), and clay mineral composition, especially high valence iron–aluminum oxides and clay minerals, strongly influence SOC sequestration, through ligand replacement, high valence ion bond bridges [50], Van der Waals forces, and complexation, which can lead to a significant decline in the bioavailability of SOC, that is, the increase in SOC sequestration capacity [51]. More and more studies have also begun to pay attention to the great role of iron–aluminum oxides in SOC sequestration, especially in oxidized or acidic soils. The interaction between amorphous iron–aluminum oxides and organic C is probably the main C sequestration mechanism [52,53]. For example, it was found that the amorphous iron–aluminum oxide extracted from oxalic acid determines the stability of SOC through ligand replacement by investigating the acidic soil substratum [54,55]. Indoor culture experiments also showed that aluminum–organic matter formed a biologically stable complex [56]. However, the relative importance of iron and aluminum in the Loess Plateau may be less than expected. Most parts of the Loess Plateau belong to the parent material of loess, which has a strong surface adsorption capacity, and it is more likely to adsorb hydrophobic organic C with poor degradability, and the clay particles occupy most of them [2,5]. Therefore, it is not difficult to understand that the content of clay is usually positively correlated with the content of SOC, and the stabilizing effect of loess to SOC has been widely validated both indoors and in the field [23,57–59]. In fact, the specific surface area of the soil and cation exchange capacity determine the ability of SOC sequestration [60,61]. More studies reported that amorphous calcium oxides are the decisive factor in promoting SOC sequestration on the Loess Plateau [23,57,58]. Therefore, soils rich in amorphous calcium oxides on the Loess Plateau may be the dominant mechanism for the soil chemical C sequestration.

3.2. Soil Physical C Sequestration

The soil aggregates are formed by binding the organic–inorganic composites or free-particle organic C through aggregate structures [21]. When the aggregates are formed, the internal pores of the aggregates are reduced, and the mineral particles are cemented tightly with the organic C, thus forming SOC [45]. For example, the reduction of porosity of large aggregates directly impedes the entry of air and water, thereby reducing the decomposition of organic C in large aggregates [62]. The pores in the micro-aggregates are extremely small, and, if the micro-aggregates are smaller than the limits that the bacteria can pass, the organic C can only be degraded by extracellular enzyme inward diffusion, which is a very energy-consuming process for the micro-organisms, thus reducing SOC decomposition [63,64]. The small aggregates are cemented to form large aggregates, because the surface area in contact with air is reduced, and the probability of decomposition of SOC on the surfaces of large aggregates is also reduced [65]. The degree of SOC decomposition in aggregates is not uniform due to the different strengths of different grades of aggregates and different cementitious materials [66,67]. Studies have pointed out that water-stable aggregates with a diameter greater than 0.250 mm contain more particulate organic C (POC), lighter-group organic C (LFOC), and higher microbial biomass C (MBC). This indicates that the large aggregates have low organic C stability [68–70]. Based on the study of loess soil, it is also shown that the oxidizable organic C in loess soils mainly concentrates in the 0.2–2 mm large aggregates particle group, while the stable aromatic organic C concentrates in the particle groups smaller than 0.002 mm [71]. Previous studies showed that roots and mycelium can directly promote the formation of large aggregates, and micro-aggregates can form in large aggregates [68]. Henson et al. [72] further emphasized that the large aggregate-wrapped particulate organic matter (POC) creates the conditions for the formation of micro-aggregates, while the particulate organic matter encapsulated by the micro-aggregates is more physically protected and has important effects on the stability of organic C. Similarly, Lin et al. [73] demonstrated that the turnover of large aggregates was faster than micro-aggregates. Although large aggregates cannot directly protect SOC in the long term, they can sequester more SOC, and passing through the interaction of organic matter with the soil environment promotes the formation of micro-aggregates [74], thus providing conditions for the long-term protection of SOC by micro-aggregates [75–77]. Therefore, large aggregates can sequester more organic C and accelerate the formation of micro-aggregates through the interaction between the soil environment and organic matter [78–81]. Large aggregates are the guarantee for the long-term storage of organic C by micro-aggregates.

3.3. Soil Microbial C Sequestration

Soil microorganisms, a major regulator of the dynamics of SOC and nutrient availability, are involved in a variety of biochemical reactions [3]. More than 90% of soil microorganisms are bacteria and fungi, so the effect of microorganisms on SOC is mainly affected by fungi and bacteria (Figure 5) [41,82,83]. But, in the process of decomposing SOC, fungi is more conducive to the accumulation and stability improvement of organic matter than bacteria [84]. During this process, soil biological decomposers have evolved various strategies to take advantage of the refractory organic C. They can degrade all kinds of organic C, in theory [83]. Therefore, the stability of organic C is not only affected by the degradation of SOC, but also depends on the degradation capacity of the microorganisms [85]. When the degradation of SOC is blocked, soil microorganisms produce more enzymes, but, if the enzyme production exceeds a critical value and the decomposition products can not meet the energy consumption, microbial activity is controlled by negative feedback and the decomposition process of SOC is blocked. In the process of SOC sequestration by microorganisms, bacteria tend to use litters that are rich in carbohydrates and sugars, while fungi tend to take advantage of the litters that are rich in phenolic material. Meanwhile, the hydrolysis of extracellular enzymes is required before SOC mineralization [84]. By secreting extracellular enzymes, the microorganisms enable the microbial cells to fix on the surface of the soil. The bacterial extracellular polymer is used as a contact medium by the biofilm, which forms a special micro-environment to realize the decomposition of SOC through the complexation of glucuronic acid and other residues on the mineral surface [85]. The extracellular polymer contains varieties of hydroxyl groups that possess adsorption ability, and they have obvious adsorption effects on SOC organic acids and inorganic ions. The hydroxyl groups destroy certain chemical bonds in the mineral crystal lattice directly to promote the decomposition of organic matter through the adsorption effect of large molecules such as extracellular polysaccharides [86,87].

Soil microorganisms not only release C into the atmosphere through decomposition metabolism but also through the synthetic metabolism that converts C into a certain form to be stored in the soil [88–90]. The soil microbial assimilation process leads to the iterative continuous accumulation of microbial residues in order to promote the formation of a series of organic materials, such as microbial residues, and such compounds stabilize in soil eventually, which we called the "microbial C pump" [41]. There are two microorganism-mediated pathways, which we called "ex vivo modification" and "in vivo turnover". On the one hand, microorganisms regulate the chemical composition of soil organic compounds through "ex vivo modification" and "in vivo turnover". On the other hand, microorganisms regulate the soil stable organic C storage through the "priming effect "and "entombing effect" to realize the contribution to SOC sequestration [41]. Based on this theoretical system, the concept model of the C cycle of the "microbial C pump" is proposed [41]. At present, more and more research results have revealed that microbial residues play an important role in SOC sequestration. Using nuclear magnetic resonance technology, Feng and Simpson [91] analyzed the chemical functional groups of chernozem soil and vegetation, and they found that microbial residue carbon contributed to more than 50% of the SOC pool. By using a Markov model, Liang et al. [92] estimated that the number of soil microbial residues is 40 times that of living organisms. Wang et al. [40] compiled global data and found that microbial residues contribute an average of 51%, 47%, and 35% to the SOC in the surface soil layer of 0–20 cm in croplands, grasslands, and forests, respectively. At the same time, it was found that the microbial formation pathway of organic carbon, namely the buried effect of microbial residues, was dominant in farmland and grassland, while the plant formation pathway of organic carbon, namely the physical migration of plant residues, was dominant in forests. Furthermore, soil microorganisms also directly participate in the decomposition, heterotrophic respiration, and fixation of SOC, driving its cycling [93,94]. A large number of studies have confirmed that soil microbial residues play an important role in the accumulation of SOC in the process of forestation [95–97]. Yang et al. [35] confirmed that microbial residues were the main source of soil organic carbon on the Loess Plateau, and the contribution of microbial carbon (4.9–13 g kg^{-1}) to organic carbon was much greater than that of plant C (1.3–2.3 g kg^{-1}), and the contribution of microbial residues to SOC changed from fungal residues to bacterial residues. As for the afforestation on the Loess Plateau, with an increase in restoration time, the concentrations of both the microbial- and plant-derived residues increased [1,98].

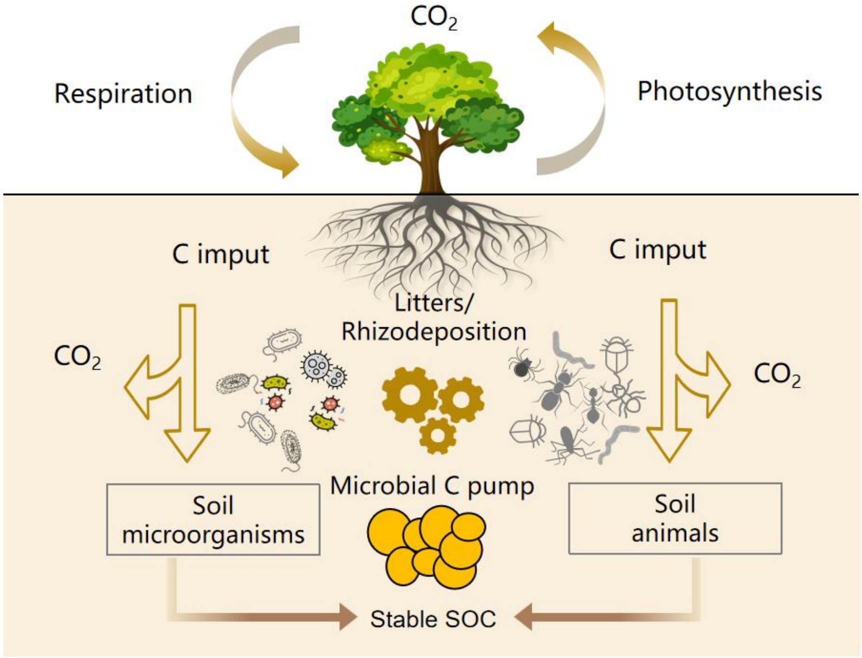

Figure 5. Soil microbial C sequestration mechanisms on the Loess Plateau.

4. Controlling Factors of SOC on the Loess Plateau

Determining the turnover time of SOC on the Loess Plateau is crucial for estimating C flux and budget [1,99]. However, the migration and transformation processes in different environmental mediators and the turnover rates of SOC are influenced by various factors (Figure 6) [100,101]. In fact, the turnover rate of plant C is primarily influenced by plant primary productivity and decomposition rates, while litter turnover is affected by environmental factors (such as temperature and humidity) and litter quality [102]. For soil

C, its turnover rate is influenced by biological factors (vegetation type and microorganisms), abiotic factors (temperature, humidity, soil physicochemical properties, topography, landform characteristics, hydrological regime, acid deposition, nitrogen deposition, CO_2 concentration, and soil freeze-thaw cycles), and human activities (land use and management practices) [100,101]. The decomposition and transformation of SOC is driven by soil extracellular enzymes, which play a pivotal role in C cycling [103]. Plants transport organic matter to the soil through litter and root exudates, which contribute to the formation of SOC through the mineralization by extracellular enzymes and assimilation by microorganisms [103]. In addition, atmospheric-precipitation-induced surface runoff can cause soil erosion, resulting in soil-eroded C [38]. During the migration process, eroded C may undergo selective degradation, sedimentation, and other biogeochemical and physical processes, ultimately leading to the formation of stable SOC through the burial effect.

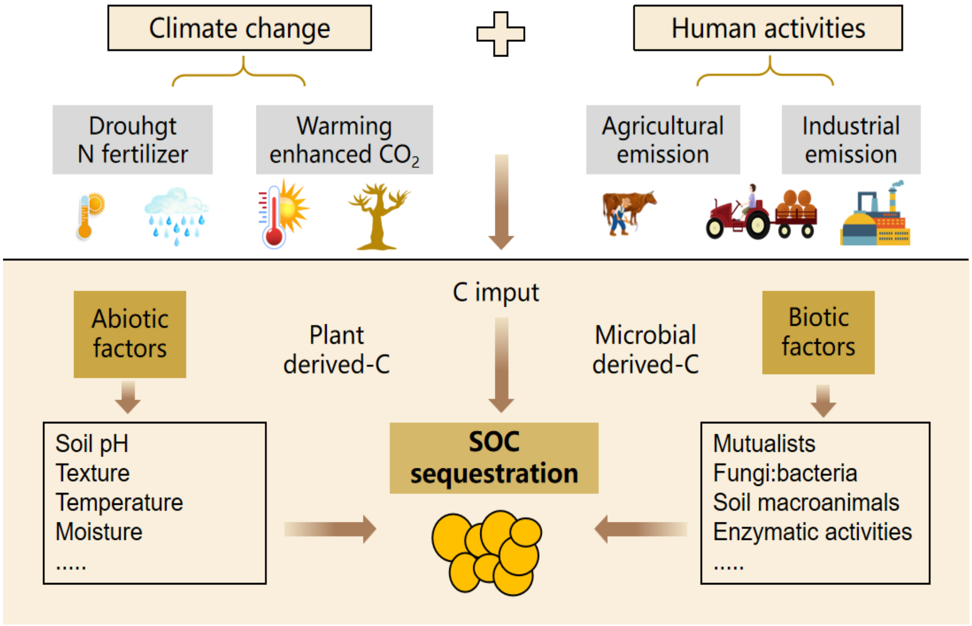

Figure 6. Controlling factors of SOC sequestration on the Loess Plateau.

Previous studies showed that precipitation was the dominant factor affecting C sequestration in surface soil, but soil pH, microorganisms, and roots were the main factors in subsurface soil in grassland because there were large roots and microorganisms in surface soil [18]. In addition, nitrogen is the core of limiting the long-term C sequestration of grassland soils in China [38]. The limiting factor is that increasing nitrogen supply later in the restoration period can increase the potential for C sequestration in grasslands [38]. The results also showed that SOC stocks after abandonment showed a logarithmic (logarithmic model) trend, with a significant reduction in SOC sequestration rates alongside vegetation restoration [104–106]. In the early stage of vegetation restoration, the reason for the higher SOC sequestration rate may be due to the fact that C in the mineral soils does not reach saturation early in the early recovery. In addition, the input of above-ground and underground biomass C and the increase in perennial herbs after vegetation restoration reduced soil erosion and increased SOC [105]. After abandonment, the SOC sequestration rate in deep soil (40–100 cm) was higher than that of the upper soil (0–40 cm) [107]. In general, more soil organic matter (root system, root exudates, etc.) is input into the deep layer as vegetation is restored after abandonment [108,109]. Therefore, after abandoning the tillage, the deep layers of soil have the potential to increase SOC.

5. Managing for SOC Sequestration on the Loess Plateau

On the Loess Plateau, soils are the potential means of C sink, which is regulated by vegetation restoration and management regimes [23]. In fact, SOC is a vital pathway for attaining several sustainability purposes. Increasing SOC storage for the purpose of climate mitigation may require the preservation of current SOC stocks and the increase in SOC stocks [110]. Therefore, the information regarding the SOC and associated C sequestration potential in the soil ecosystem is essential in determining the source and sink of C altered by various biotic influences. Here, there are several ways in which the sink of soil C can be improved by management on the Loess Plateau.

First, labile (active) SOC is susceptible to soil management and significantly affects soil nutrient cycles to maintain the quality and output of the soil [111]. Recalcitrant organic C (passive pool) resides in the soil system for a longer period, resulting in long-term carbon sequestration [63]. Hence, a good balance between labile and recalcitrant organic C stocks offers favorable circumstances for soil sustainability. Appropriate SOC management is important to sustain soil productivity and protect it from degradation on the Loess Plateau. A previous study stated that active fractions (i.e., microbial biomass C and N, particulate C and N, potentially mineralizable C and N [112], which respond quickly to changes in management practices) can better reflect the variations in both soil quality and productivity through altering the nutrient dynamics owing to immobilization mineralization processes. Thus, we should keep the soil active fractions in SOC management.

Second, managing SOC sequestration on the Loess Plateau can prevent current SOC stock losses through preventing land use alterations that release soil C, such as through minimizing soil erosion [18]. During the late stage of vegetation restoration, SOC stocks have decreased via time because the inputs are comparatively low (e.g., because of biomass harvest or small root systems) and outputs are comparatively high [25]. An efficient approach to counteracting the above phenomenon is to increase inputs for promoting effective SOC generation [35]. Examples include living roots, high-quality plant litter, root exudates, and compost. Moreover, all of these inputs can facilitate microbial activity and foster the formation of microbial metabolites and necromass, resulting in aggregate and mineral-associate organic C (MAOC) formation [113]. A caveat for the above strategy is that effective SOC generation needs large amounts of nutrients. Increasing SOC stocks during vegetation restoration may need nutrients like N or P in order to be successful, and it is identified to be the possible hinderance of the aforementioned management objective [35,113]. Nevertheless, management practices that increase soil nutrient levels or tighten nutrient cycles and minimize nutrient losses, including planting legumes, using enhanced efficiency fertilizers, or implementing improved grazing management, can potentially offer these necessary nutrients without requiring elevated inputs of synthetic fertilizers [114]. Other strategies to combat nutrient limitations to C storage include reducing the nutrient demand of C storage, for instance, through elevating the direct sorption of C-rich and plant-derived C to MAOC. Consistent with the C-surplus hypothesis [115], plants are able to exude C-rich soluble compounds if photosynthetic C uptake is greater than plant biosynthesis, like in the case of water or nutrient restraint conditions. Increasing C-rich substance influx into the soil can promote the contributions to MAOC, probably by means of organo–organic bonding, thus elevating the C:N ratio in MAOC while decreasing N consumption in persistent MAOC storage.

Third, based on the increases in inputs that enhance SOC generation, it is important to regenerate SOC through enhancing SOC persistence, probably through elevating the soil-stabilized SOC content [89]. Practices that are likely to increase persistence are the reduction of tillage for maintaining soil structure, the prioritization of inputs to induce increased MAOC compared with particulate organic C (POC) generation, and the increase in inputs to deep soils when avoiding priming [116]. In addition, this can also be obtained through concentrating regeneration efforts on soils which show high capacity for additional MAOC storage and which are likely to have higher SOC persistence [113]. The Loess Plateau experiences persistently obvious SOC losses with time, is far from the physicochemical saturation thresholds of SOC, and shows a great capacity to store MAOC; thus, it is appropriate to regenerate persistent SOC [117]. Managing SOC sequestration on the Loess Plateau can induce soil C accrual via multiple intercorrelated mechanisms. For example, cropland conversion into grasslands/shrublands/forestlands on the Loess Plateau can eliminate the disturbance from tillage while increasing root carbon inputs into soil [35]. This can promote plant yield while increasing microbial turnover and necromass entombment.

Moreover, the SOC storage in this region can be increased directly by changing classical tillage into conservation agriculture, organic and inorganic mulch usage to diminish the loss of nutrients through leaching and volatilization, cover crops, balanced use of macro-and micro-nutrients, compost application, plant growth-promoting rhizobacteria, biofertilizers, and the variation and diversification of land use types [118,119]. Further, sowing legumes may elevate soil C and N inputs through increasing fine root turnover, root biomass, and root exudates [120]. Applications of inorganic and organic fertilizers may stimulate primary productivity and high quality plant C inputs to soil, causing more efficient microbial C use [121]. This will maintain C balance in the atmosphere and mitigate the ongoing burning issue of the changing climate and help to create a more sustainable environment. However, at the global and regional scales, there are great uncertainties in projected soil C sequestration, which may result from the complicated interactions across human activities, climate change, and spatio-temporal changes of soil responses and ecosystems. Thus, scientific studies and management innovations may be needed to maximize SOC storage on the Loess Plateau.

Finally, soil management, combating climate change, and improving the vegetation production need to be transformed through best practices having an eco-friendly approach on the Loess Plateau. However, better management practices of different land use systems would be helpful in enhancing the potential of C sequestration into the soils that not only build soil fertility and microbial populations, but also to solve the problem of climate change and creating environmental sustainability in this region.

6. Prospectives and Conclusions

First, during vegetation restoration of the Loess Plateau, the main sources of SOC are plant residues, litters, rhizosphere deposits, and microbial assimilation C. Future study should be focused on the identification and ecological interpretation of molecular markers, the regulation function, and the mechanism of biology on the conversion process of SOC. Thus, new SOC molecular structures and large scale environmental/ecological processes should be identified.

Second, the soil and water loss have caused large areas of land degradation on the Loess Plateau. At present, there may be SOC errors for the assessment of ecosystem C sequestration. Excessive ecological C sequestration projects will lead to further degradation and soil C loss if local climatic conditions and soil environmental conditions are not fully considered. Therefore, it is necessary to carefully consider and weigh the priority of various resources on the adoption of C sequestration measures on the Loess Plateau. For example, returning farmland to forestland is conducive to increasing C stock. However, converting land use patterns or increasing cultivation intensity can produce more valuable crops, which may cause C loss.

Finally, as for the vegetation construction, arbor forest and shrubland are both C sinks, but conversion to each other would cause SOC to be reduced. Thus, in terms of forest, it is more suitable to maintain the current situation as soil C would be lost after converting tree species due to the disturbance of soil. Thus, the ecosystem C sink function of the Loess Plateau should be realized by increasing input quantity and reducing C output. We should combine vegetation carrying capacity with C sequestration ability effectively strengthen our understanding of SOC sequestration processes and their physical, chemical, and biological mechanisms, and weigh the relationship between vegetation restoration and SOC sequestration.

Overall, this review will help enhance SOC sequestration functions and ecological benefits from vegetation restoration on the Loess Plateau.

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