Chapter

Soil Carbon Biogeochemistry in Arid and Semiarid Forests

Wei-Yu Shi, Xiao-Cong Zhu, Feng-Bao Zhang, Kai-Bo Wang, Lei Deng and Ming-Guo Ma

Abstract

Soil is the largest carbon pool in the terrestrial ecosystem. Even small changes in the soil carbon pool would have huge impacts on atmospheric CO_2 concentrations and thus mitigate or intensify global warming. Global forest contains $383 \pm 30 \times 10^{15}$ g carbon stock in soils to a 1-m depth, which is approximately 50% of the carbon stored in the atmosphere. Arid and semiarid areas with more than 30% of the world's land surface are characterized by low and sporadic moisture availability and sparse or discontinuous vegetation, both spatially and temporally. Vegetation, water, and nutrients are intimately coupled in the semiarid environments with strong feedbacks and interactions occurring across fine to coarse scales. In this chapter, we will review the cutting-edge work in forest soil carbon biogeochemistry undertaken in the last three decades. We also attempt to synthesize recent advances in soil carbon biogeochemistry in arid and semiarid regions and discuss future research needs and directions.

Keywords: carbon cycle, soil respiration, water, soil, ecological restoration

1. Introduction

Arid and semiarid regions cover >30% of the earth's land surface in the world [1]. The soil carbon (C) in arid and semiarid forests plays an important role in global carbon storage and alleviates the increase of atmospheric carbon dioxide (CO_2) concentration, and its contribution to the global carbon cycle is increasingly significant [2]. Afforestation has occurred globally within the framework of the Kyoto Protocol [3] and has the potential to mitigate the rising atmospheric CO_2 concentration caused by anthropogenic emissions [4]. Recent studies also suggested that arid and semiarid ecosystems have strong soil C sequestration potential [5].

Therefore, soil C change in arid and semiarid forest ecosystem is a key process for understanding the global C cycle, assessing the responses of terrestrial ecosystems to climate change and to aid policy makers in making land use/management decisions [6]. In the past, the study of soil carbon cycle was mainly focused on soil organic carbon (SOC), and the behavior of soil inorganic carbon (SIC) was rarely considered. Global "Missing Carbon Sink" reaches $2–3 \times 10^{15}$ g C, and carbonate and carbon fixation in the arid and semiarid regions account for about 1/3 of global "carbon sinking" [7]. The SIC storage in arid and semiarid regions was huge, and it needs more attention in the soil carbon cycle. In this chapter, we will review the cutting-edge work in forest soil carbon biogeochemistry undertaken in the last three decades. We also attempt to synthesize recent advances in soil carbon biogeochemistry in arid and semiarid regions and discuss future research needs and directions.

2. Materials and methods

Traditional measurements of soil physical and chemical properties require the following steps [8, 9]. First, the typical plots are selected in the study area, clipping the vegetation to ground level, and litter (dead plant material) is cleared before soil sampling in each plot. A global positioning system (GPS) is used to determine grid point latitude, longitude, and altitude. Second, Soil samples from different soil layers are collected using a soil drilling sampler. Soil bulk density (D_b) (g cm^{-3}) is assessed by collecting undisturbed soil in a stainless steel cutting ring (volume: 100 cm^3), drying it at 105°C, and weighing it, with three replicates in each plot. Third, the samples from the same layer were mixed to produce one sample in a plot. All soil samples are taken to the laboratory, air-dried, and passed through a 2-mm sieve, and roots and other debris are removed by hand for soil physicochemical analysis. Several methods exist for determining SOC, and wet combustion methods, including Walkley-Black, Mebius, and Colorimetric determination, as well as dry combustion methods, such as elemental and gravimetric analysis, are usually used. Each method has its own advantages and limitations, and all methods require more than three replicates [10]. The soil total carbon content is measured by dry combustion, and the SIC content is calculated by the difference between soil total carbon and SOC content.

Recent studies employing laser-induced breakdown spectroscopy (LIBS) and visible-near infrared diffuse reflectance spectroscopy (vis-NIRS) indicate their potential for rapid in situ soil carbon (SOC and SIC) determination, and these spectroscopic methods differ fundamentally, with LIBS being foremost an elemental analyzer and vis-NIRS a molecular technique. These technologies currently require ideal control conditions, and soil in situ measurement accuracy cannot be confirmed. It is standard practice to pretreat soils using various combinations of air-drying, powdering, sieving, and pelletizing under pressure prior LIBS and vis-NIRS for soil carbon determination in laboratory conditions [11].

3. Factors affecting soil carbon dynamics

3.1 Effect of temperature and precipitation on soil carbon

Climate appeared to strongly modify the effects of afforestation on ecosystem carbon stocks in the arid and semiarid regions [12], due to their effects on the quantity and quality of organic residue soil inputs and on the rates of soil organic matter mineralization and litter decomposition [13, 14]. As water was the major factor that limited plant growth in these regions [15], the SOC accumulation after afforestation was found to vary according to the precipitation level. In regions with precipitation, Zhang et al. estimated the changes in SOC stocks after afforestation of arid and semiarid regions using meta-analysis based on the dataset compiled from published studies [16]. SOC increased in regions with precipitation of 0–250 mm, 250–400 mm, and >400 mm by 54.1, 75.75, and 7.02%, respectively. Jackson et al. found a clear negative relationship between precipitation and changes in SOC stocks after afforestation [17]. The above two cases suggest that the rate of SOC accumulation would decrease with the increase of precipitation, and regions with precipitation of 250–400 mm are ideal for SOC accumulation when afforestation is in arid and semiarid areas. Liu et al. report that soil organic carbon density (SOCD) was significantly higher in areas where the precipitation was greater than 500 mm than where it was less than 500 mm in the Loess Plateau region in China [14]. However, soil erosion could reduce the positive effect of increased precipitation on SOCD in these areas [18]. Semiarid areas are more likely to be cultivated than arid areas, and the semiarid areas are more susceptible to soil erosion by water than the arid areas, so that recently tilled bare soils are exposed to the erosive power of rainfall [14].

The differences in temperatures play a significant role in SOC accumulation processes in ecosystems [19]. Some studies have confirmed that the combination of warmer temperatures and wetter conditions could lead to higher biomass productivity and greater SOC accumulation [14]. Zhang et al. reported that SOC increased by 64.15% in regions with temperatures of 7–15°C, but it increased less than 10% in regions with temperatures of <7.5°C [16]. Relatively higher SOC accumulation in areas with temperatures of <7.5°C could be attributed to the less carbon accumulated in plant biomass; the input of soil organic matter also will be less due to the lower temperatures, as well as the drier conditions; microbial activity is also less intense at lower temperatures; and organic matter is not decomposed rapidly. However, high temperature does not necessarily increase SOC accumulation. Although heat and high precipitation contribute to high net primary productivity (NPP) and high carbon accumulation in plant biomass in tropical regions, climatic conditions also stimulate decomposition and thus reduce SOC stocks [16, 20]. These results suggest that in arid and semiarid regions, 7–15°C is a better option for accumulating C in comparison to <7.5°C and >15°C.

3.2 Effects of soil properties on soil carbon

The effects on soil C and soil properties are important to understand not only because these are often master variables determining soil fertility but also because of the role of soils as a source or sink for C on a global scale [21]. Brahim et al.'s study to develop two models of SOC under clayey and sandy soils in semiarid Mediterranean zones based on physical and chemical soil properties and structural equation modeling (SEM) was adopted to quantify the relative importance of potential direct and indirect pathways in soil properties' effect on SOC [22]. SEM is included in the class of generalized linear models. As a flexible multivariate analysis method that includes factor and path analyses, SEM is useful for evaluating the relative importance of the pathways in hypothetical models and for comparing models with experimental data [23, 24]. For modeling SOC, soil databases composed of various information for organic matter (OM), organic carbon (OC), total nitrogen, pH, D_b, clay, silt (fine and coarse fraction), sand (fine and coarse fraction), and calcium carbonate (C_aCO_3) were used.

"Physical properties" and "chemical properties and D_b/chemical properties" are the latent variables for two types of soils (clayey and sandy soils), and the latent variable is measured by multiple observed variables (i.e., clay, C-silt, F-sand, pH, OM, N, D_b, and OC) (**Figure 1**). Red double arrow line indicates correlations between the measurement errors for observable indicators of the exogenous latent variables. Brahim et al. attributed this fact to the OM and mineral fraction that constitute an organo-mineral complex [22], which are generally associated with clay [25], D_b is associated at a coarse soil fraction as the sand [26]. Brahim et al. also found that in clayey soils, chemical properties and bulk density play the most important role in controlling OC content [22]. The pH, OM, N, and D_b represent the key variables responsible for OC storage. In addition, in sandy soils, the findings show that chemical factors (i.e., OM and pH) are better indicators of OC content than did physical properties. **Figure 1** shows that for clayey and sandy soil model, chemical properties

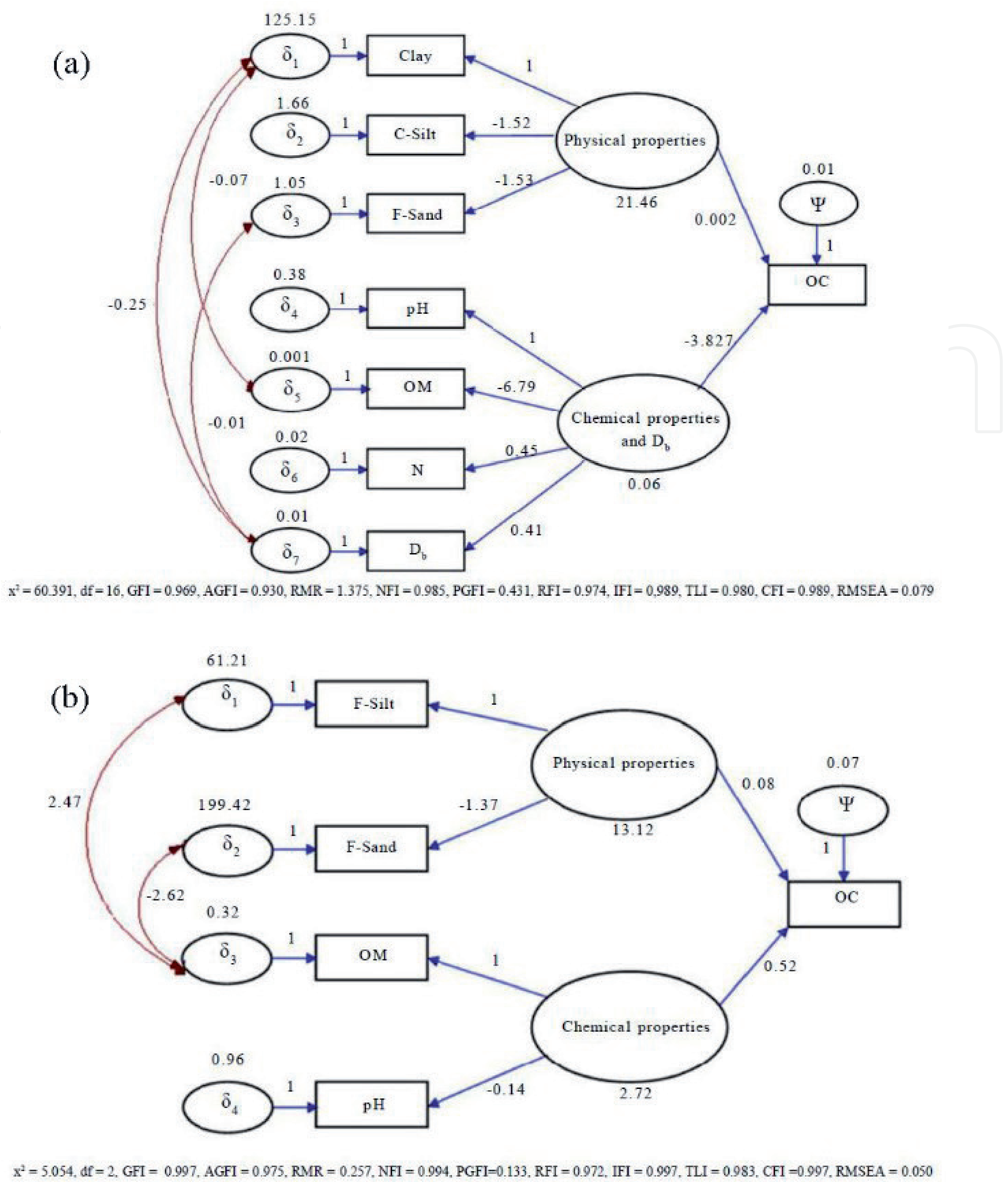

Figure 1.
The estimated parameters of the model predicting SOC in clayey soils (a) and sandy soils (b), respectively, cited from Brahim et al. [22].

and D_b/chemical properties had a stronger effect on OC, than did physical properties, and goodness-of-fit indices for the SEM are all acceptable. We should note the independent effects on OC content between physical properties and chemical properties. The above case studies were conducted mainly in semiarid Mediterranean regions. It is easy to speculate that the conventional relationship between OC and influencing factor in soil is influenced on a global scale, such as that found commonly in northwestern China, western America, and Midwestern Australia. Land degradation and desertification are pervasive in arid and semiarid climate, lands are especially threatened by erosion phenomena, and the restoration of these regions needs afforestation, which inhibits these land degradation phenomena and enhances soil carbon sequestration and soil fertility. Korkanç's study also concluded that afforestation increased the SOC budget, and this situation improved some soil properties, such as increasing water holding capacity (WHC) and total porosity (TP) and reducing D_b and dispersion ratio (DR) over a period of 15 years [27].

3.3 Effect of elevated CO_2 on soil carbon

The changes in the amount of carbon sequestered by soils are closely related to the increase or decrease in the amount of CO_2 accumulation in the atmosphere. Elevated atmospheric CO_2 frequently increases plant production and concomitant soil C inputs, which may cause additional soil C sequestration [28]. While the processes of C sequestration are ultimately regulated at the molecular level, atmospheric CO_2 concentration can greatly affect the way in which terrestrial ecosystems sequester C [29]. Niklaus et al. reported that the increases in leaf litter production at elevated CO_2 may exceed the response in standing biomass [30]. In addition, elevated CO_2 may also induce greater C fluxes from the growing plants to the soil through increasing rates of leaf litter and root material deposition [31]. Thus, elevated atmospheric CO_2 will likely affect soil carbon cycle through its indirect impact on photosynthesis. If C input into the soil is increased, and given that elevated atmospheric CO_2 increases plant production and allocation of photosynthate to below ground components, soil carbon sequestration would be expected to increase [32].

Diaz et al. found that increased C inputs under elevated CO_2 stimulated competition between the soil microbial biomass and plants for soil N, leading to a decline in soil N availability [33]. Hu et al. suggested that elevated CO_2 reduces the amount of N available to microbes through enhanced plant growth [34]. This could result in enhanced C accumulation in grassland soils at elevated CO_2. However, it remains unclear how initial increases in soil C input under elevated CO_2 affect microbial N transformation processes [28].

4. Dynamic characteristics of forest soil carbon

4.1 Evolution characteristics of soil carbon after afforestation

Land degradation and desertification are pervasive in arid and semiarid regions, often resulting in emission of CO_2 into the atmosphere as well as other environmental degradation [35]. Afforestation can increase sequestration of atmospheric carbon dioxide and hence attenuate global warming [36]. Farmland reclamation will exacerbate land degradation and desertification in arid and semiarid regions due to the special climate. Afforestation is the conversion of degraded farmland into vegetation in these regions and renovation without involving natural vegetation. This is similar to the method of Grain for Green Program (GGP) in central and western China [37]. In addition, we consider the choice of tree species to adapt to the arid climate is necessary. The contribution of afforestation to the C cycle has been estimated by many studies on a regional and global scale [6, 38]. Land use and land-cover changes have attracted increasing scientific interest in the past decades in relation to their contribution to potential impacts on soil carbon sequestration and soil nitrogen [39]. Liu et al. estimated the changes in SOC (a) and total nitrogen (TN) stocks (b) after afforestation of arid and semiarid regions using meta-analysis based on the dataset compiled from published studies (**Figure 2**) [40].

Afforestation on different land uses showed different impacts on SOC stock and TN stock. On average across all studies, afforestation significantly increased SOC stock and TN stock by 131 and 88%, respectively. SOC stock and TN stock decreased with different land uses in the following order: BF > CF > GF (CF: afforestation on cropland; GF: afforestation on grassland; and BF: afforestation on barren land); and they also reported significant increases in SOC stock as afforestation was observed for all tree species. SOC and TN accumulations in plantations with different tree species decreased in the following order: broadleaf deciduous > conifer > broadleaf

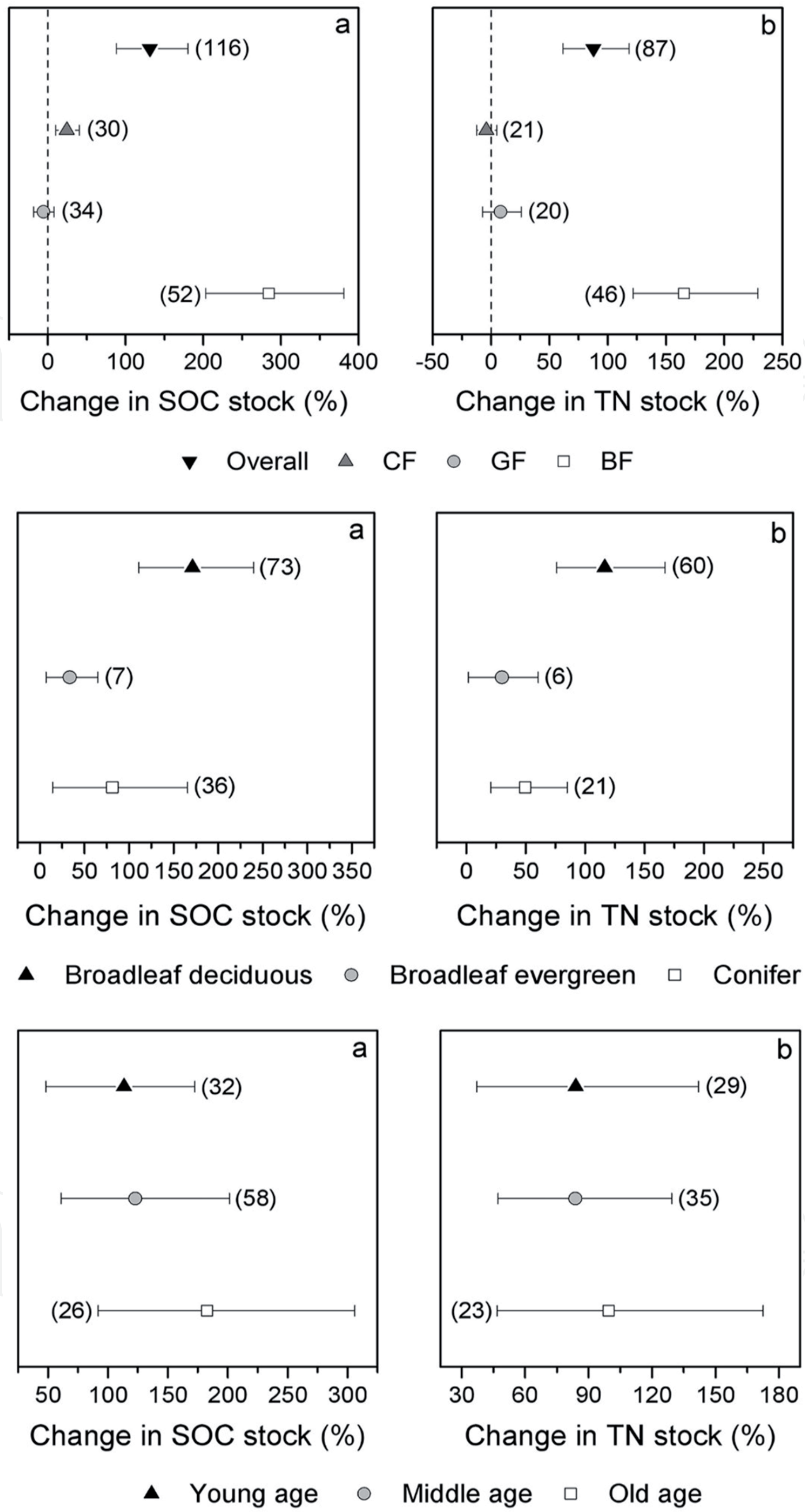

Figure 2.
Changes in soil organic carbon (SOC) (a) and total nitrogen (TN) stocks (b) after afforestation as influenced by prior land-use type, planted tree species, and plantation age, respectively, cited from Liu et al. [40]. CF, afforestation on cropland; GF, afforestation on grassland; and BF, afforestation on barren land. Planted tree species were classified into three categories: broadleaf deciduous, broadleaf evergreen, and conifer. The ages of afforestation were divided into three groups: young age (≤10 year), middle age (>10, ≤30 year), and old age (>30 year).

evergreen. SOC stock significantly increased following afforestation from 114 to 183% with the increase in plantation age. Nonetheless, afforestation-induced changes in SOC stock did not differ significantly among plantation ages. Afforestation significantly increased TN stock by 84–100% for plantations with different ages, with the largest increase being found in plantation with old age. However, the differences in changes in TN stock among plantation ages were not significant [40].

These results suggest that in arid and semiarid regions, BF is a better option for accumulating C and N in comparison to CF, while GF is not recommended as a way to sequester C and N into soils. Korkanç's study showed that the 0–10 cm soil layer of lands afforested with Cedar, a coniferous tree, sequestrated more organic carbon than Black Pine in the central Anatolia region [27]. The inconsistency between the above two research conclusions also proves the necessity to evaluate afforestation efforts using different species of trees on semiarid degraded land as measured by soil SOC and selected soil properties. This also may be useful for determining which species of trees to plant in future afforestation efforts aimed at combating the impacts of global warming [27]. Although all estimates of soil C loss due to land degradation are speculative, the numbers are large (20–30 × 10^{15} g) [35]. Cole et al. through desertification control and adoption of recommended land use and soil management practices, this would amount to 12–20 × 10^{15} g over a 50-year period [41]. After afforestation, SOC and TN accumulations generally showed increasing trends with the increase of plantation age, and restoration age is an important factor to consider when estimating SOC stock and TN stock after afforestation in arid and semiarid regions. Korkanç also reports that SOC values of the afforested lands are generally higher than those in the bare land soils, and the highest SOC value was obtained from the 0 to 10 cm layer in the soils of the Cedar site (1.49%), and the lowest value was from the 10 to 20 cm soil layer in the bare land (0.44%) [27]. According to Lima et al., afforestation of degraded grasslands led to a rise in SOC accumulation in the semiarid regions for a period of 30 years [42].

4.2 Soil carbon cycle process

The soil carbon (C) pool includes organic carbon pools and inorganic carbon pools with carbon stocks of 1555 × 10^{15} and 1750 × 10^{15} g, respectively [43]. Inorganic carbon mainly refers to carbonate carbon existing in arid and semiarid soil. Carbonate can retain atmospheric CO_2 during the formation process, and its formation and turnover have an important impact on the carbon cycle in arid and semiarid regions [2, 44]. Soil carbon cycle mechanisms in arid and semiarid regions include atmospheric pressure transport, carbonate dissolution, and soil water-in-gas percolation [45]. Li et al. showed that the evaporation in semiarid areas is greater than precipitation, forming an oasis landscape dominated by saline-alkali soils. Saline-alkali soil absorbs CO_2 in the air at a slow rate, and the absorbed CO_2 enters the underground saline layer; thus it is a huge potential inorganic carbon sink in the world (**Figure 3**) [46]. The SIC pool affects the SOC pool by affecting the status of soil aggregates, microbial activity, soil pH, and decomposition rate of organic matter. SOC is a very complex continuous mixture of residues of plants, animals, and microorganisms at all stages of decomposition. Many organic compounds in soil are closely related to inorganic soil particles [47].

Soil respiration consists of respiration by plant roots and respiration from catabolism by heterotrophy, mainly by soil microbes. Soil respiration is one of the major processes controlling the carbon budget of terrestrial ecosystems [48], the main export route of SOC and an important source of atmospheric CO_2. Its dynamic changes will directly affect the global carbon balance [49]. Soil temperature is an

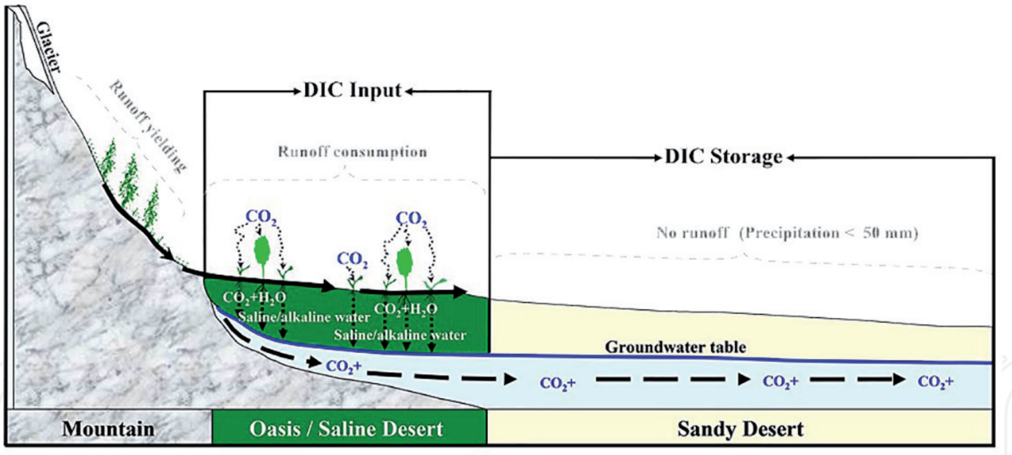

Figure 3.
Schematic diagram of DIC (dissolved inorganic carbon) leaching and transport in a closed arid basin: Tarim Basin, as an example cited from Li et al. [46].

important environmental factor, controlling a complex series of biochemical processes in soil respiration soil respiration rate sensitive to changes in soil temperature, soil temperature change will cause significant changes in soil respiration of terrestrial ecosystems carbon budget patterns have a significant impact [50]. Fierer et al. study have shown that with the increase of soil temperature, soil respiration rate of growth slowed, reducing sensitivity to temperature change, at lower temperatures, soil respiration mainly controlled by temperature changes [51]; when the temperature is high, soil respiration mainly affected by soil moisture and other factors. Soil moisture is a key limiting factor on soil respiration, soil moisture content in most ecosystems and soil respiration was significantly positively related to increased soil moisture will promote soil respiration [52]. Sponseller's study has shown that an increase in soil moisture accelerates the rate of soil respiration by affecting the vegetation's root metabolism and soil microbial activity [53]. After the soil temperature and moisture increase exceed a certain threshold range, microbial activity and soil permeability become lower, which will significantly inhibit soil respiration [54].

5. Main conclusions and future research lines

In the past few decades, many studies have explored the evolution of forest soil carbon after afforestation, but there is still no unified conclusion. We still need three issues in future studies of forest soil carbon biogeochemistry in arid and semiarid regions. First, soil N dynamics and C-N interactions should be focused on for considering soil C accumulation. Second, we should note the effect of changes in soil properties on soil carbon after afforestation in soil carbon cycle, and we need to consider the ecological benefit. Third, we should identify key environmental factors in soil CO_2 sequestration and its influence in climate change.

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