

Carbon Storage in Soil-Vegetation Systems under Different Land Use Patterns in Coastal Saline Areas: A Postprint

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Abstract

Investigating the coupling relationship between land use change and soil-vegetation system carbon sequestration potential in saline areas holds significant theoretical and practical importance for implementing optimal land use practices aimed at vegetation construction and carbon sink enhancement in these regions. This study used coastal abandoned saline bare land as a control, continuously observed and quantitatively described the dynamic changes in soil organic carbon and vegetation biomass in 3-year and 10-year tamarisk forests, 2-year and 8-year artificial wolfberry forests, and cotton fields under winter brackish water ice irrigation combined with plastic film mulching, to explore the carbon sequestration capacity of soil-vegetation systems under different land use patterns, thereby providing a theoretical basis for further enhancing regional carbon storage. The results indicate: 1) After implementing land use practices such as tamarisk and wolfberry planting and ice irrigation combined with film mulching on abandoned saline land, the carbon sequestration capacity of the soil-vegetation system was significantly enhanced, and soil bulk density was notably reduced; the 10-year tamarisk forest and 8-year wolfberry forest exhibited the highest soil-vegetation system carbon storage, reaching $118.24 \text{ t} \cdot \text{hm}^{-2}$ and $96.27 \text{ t} \cdot \text{hm}^{-2}$ respectively, which represent increases of $58.51 \text{ t} \cdot \text{hm}^{-2}$ and $36.54 \text{ t} \cdot \text{hm}^{-2}$ compared to cotton fields with winter brackish water ice irrigation and plastic film mulching, and increases of $83.39 \text{ t} \cdot \text{hm}^{-2}$ and $61.42 \text{ t} \cdot \text{hm}^{-2}$ compared to abandoned saline bare land. 2) Analysis of carbon sequestration trends across different land use patterns revealed that the 3-year tamarisk forest and 2-year wolfberry forest exhibited relatively high soil-plant system carbon sequestration rates, at $10.08 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ and $2.71 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ respectively. Cotton fields under winter brackish water ice irrigation combined with plastic film mulching showed a lower carbon sequestration rate of only $0.53 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$. In the 10-year tamarisk and 8-year wolfberry plots, plant carbon sequestration rates slowed markedly, with the soil-vegetation system

functioning as a weak carbon source. Spring surface film mulching treatment resulted in low cotton survival rates and straw removal after plant maturity, leading to a net annual carbon storage reduction of $0.86 \text{ t} \cdot \text{hm}^{-2}$. Abandoned saline bare land, without exogenous carbon supplementation, acted as a carbon source, with soil-vegetation system carbon storage decreasing at a rate of $1.42 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$. In summary, artificial planting of tamarisk and wolfberry in coastal saline areas represents an effective approach for enhancing regional carbon storage.

Full Text

Carbon Storage of Soil-Vegetation System Under Different Land Use Patterns in Coastal Saline Region

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Abstract: Research on the coupling relationship between land use change and carbon sequestration potential in saline regions is of significant theoretical and practical importance for implementing optimal land use strategies aimed at vegetation construction and carbon sink enhancement. This study used abandoned coastal saline bare land as a control to conduct continuous observations and quantitative descriptions of soil organic carbon content and vegetation biomass changes under several land use patterns, including 3-year and 10-year *Tamarix chinensis* plantations, 2-year and 8-year *Lycium barbarum* plantations, cotton fields under frozen saline water irrigation with plastic mulching, and cotton fields with spring plastic mulching only. The results showed that: (1) The 10-year *T. chinensis* plantation and 8-year *L. barbarum* plantation exhibited the highest carbon storage, at $118.24 \text{ t} \cdot \text{hm}^{-2}$ and $96.27 \text{ t} \cdot \text{hm}^{-2}$ respectively, representing increases of $83.39 \text{ t} \cdot \text{hm}^{-2}$ and $61.42 \text{ t} \cdot \text{hm}^{-2}$ over abandoned bare saline-alkali land. (2) The 3-year *T. chinensis* plantation and 2-year *L. barbarum* plantation demonstrated the highest carbon sequestration rates, at $10.08 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ and $2.71 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ respectively. (3) The carbon sequestration rate was lowest ($0.53 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) for the 10-year *T. chinensis* and 8-year *L. barbarum* plantations. (4) Carbon storage in cotton fields with plastic film mulching alone decreased by $0.86 \text{ t} \cdot \text{hm}^{-2}$ per year due to cotton straw removal. (5) The abandoned bare saline-alkali land functioned as a carbon source because of no exogenous carbon input, with carbon storage decreasing at $1.42 \text{ t} \cdot \text{hm}^{-2}$ per year. By comparing the advantages and disadvantages of each land use type, *T. chinensis* and *L. barbarum* cultivation was identified as the most efficient approach for increasing regional carbon storage in saline coastal regions.

Keywords: Saline coastal region; Soil organic carbon; Vegetation biomass; Land use change; Frozen saline water irrigation

Introduction

The continuous rise in greenhouse gas concentrations, particularly CO₂, and the resulting global climate change have attracted increasing worldwide attention [1-2]. Fossil fuel combustion and land use change represent important causes of CO₂ accumulation [3]. In recent years, although international society has made considerable efforts to control fossil fuel combustion, rapid global socioeconomic development has meant that emission reduction requirements have not yet been met [4]. Therefore, consideration should be given to how land use changes can increase terrestrial ecosystem carbon sinks [5].

Saline-alkali land constitutes a special type of land resource with vast area and great utilization potential [6]. In the Bohai Rim region, large areas of heavy saline-alkali land have remained abandoned for long periods due to freshwater scarcity. How to improve the utilization efficiency of heavy saline-alkali land and achieve carbon sequestration through land use change represents an urgent problem [7]. Among various approaches, biological improvement measures represented by planting halophytes such as *Tamarix chinensis* and *Lycium barbarum* have become important methods for saline-alkali land remediation both domestically and internationally [8], and constitute key components of China's "South Red, North Willow" ecological engineering project. Current research on *T. chinensis* and *L. barbarum* has focused primarily on community species diversity [9] and soil physicochemical properties [10-11], with few studies on their carbon storage [12]. Some research has shown [13-14] that the formation of *T. chinensis* and *L. barbarum* communities can effectively increase ecosystem carbon storage.

The technology of winter saline water freezing irrigation combined with plastic mulching has achieved the remarkable feat of growing crops on heavy saline-alkali land [15]. However, existing research has mainly concentrated on soil water and salt movement patterns [16-18], with relatively weak investigation of carbon storage aspects [19-20].

This study conducted continuous observations and quantitative descriptions of changes in soil organic carbon content and vegetation biomass under different land use patterns, including artificially planted *T. chinensis* and *L. barbarum* plantations of different ages, as well as freezing irrigation and surface mulching. The objective was to explore differences in carbon storage and future change patterns following implementation of different land use patterns in coastal saline regions, thereby providing a theoretical basis for coastal saline-alkali land construction aimed at vegetation establishment and carbon sequestration enhancement.

1.1 Study Site Overview The experimental site was located at the Coastal Saline Land Efficient Utilization Demonstration Area of the Chinese Academy of

Sciences in Haixing County, Hebei Province (117°33 49 E, 38°10 02 N). This region is a coastal plain with low-lying and flat terrain. The soil is predominantly coastal saline soil, with numerous abandoned lands. Abandoned lands have no shrub growth, with patches of herbaceous plants and bare ground interspersed. The main plant species include *Aeluropus sinensis*, *Imperata cylindrical*, and *Suaeda salsa*. Soil salt composition is dominated by chlorides, with Cl^- accounting for 70%~80% of total anions, and Na^+ being the main cation. The groundwater table is 0.9–1.5 m, with high mineralization and salt content of 7–27 $\text{g} \cdot \text{L}^{-1}$. The climate is warm temperate semi-humid continental monsoon, with mean annual temperature of 12.1 °C and mean annual precipitation of 582.3 mm, unevenly distributed across seasons and concentrated in July–August. Soil salt content shows distinct seasonal characteristics: high evaporation and low precipitation in spring create an evaporation-salt accumulation stage; increased summer precipitation leaches soil salts downward, creating a desalination stage; low groundwater tables in autumn cause renewed salt accumulation; and salt movement basically ceases in winter [21].

1.2 Experimental Design and Field Management The experiment consisted of seven treatments, each with three replicates: 3-year and 10-year *T. chinensis* plantations, 2-year and 8-year *L. barbarum* plantations, cotton fields under winter frozen saline water irrigation combined with plastic mulching, cotton fields under spring plastic mulching without freezing irrigation, and abandoned saline-alkali bare land as a control.

The *T. chinensis* experimental plots were strip-shaped, each 400 m long (north-south) and 15 m wide (east-west). Plots planted in 2006 and 2013 represented the 10-year and 3-year treatments, respectively. The planted *T. chinensis* was a variety bred from superior individual plants selected from local coastal *T. chinensis* populations [22]. Initial planting involved inserting micro-cuttings through perforated mulch film, with 1 cm of the cutting tip exposed above ground. No management measures such as pruning or weeding were applied after planting. The 3-year *T. chinensis* plantation had average plant height of 208 cm, spacing of 45 cm, row spacing of ~1.3 m, and canopy density of ~85%. Dominant community species were *Suaeda salsa*, *Plantago asiatica*, and *Aeluropus sinensis*, with coverage of ~80%. The 10-year plantation had average height of 317 cm, spacing of 60 cm, row spacing of 1 m, and canopy density of ~95%. Dominant species were *Plantago asiatica* and *Aeluropus sinensis*, with 90% coverage.

The *L. barbarum* experimental plots were strip-shaped, each 120 m long (north-south) and 16 m wide (east-west). Plots planted in 2008 and 2014 represented the 8-year and 2-year treatments, respectively. The planted *L. barbarum* was a local elite variety [23]. The 2-year plantation had average height of 75 cm, spacing of 60 cm, row spacing of ~1.5 m, and canopy density of ~75%. Dominant species were *Suaeda salsa* and *Aeluropus sinensis*, with 80% coverage. The 8-year plantation had average height of 105 cm, planted on ridges with ~2 m

spacing between north-south ridges, 60 cm plant spacing, and ridge height of ~30 cm. Canopy density was ~85%, with dominant species *Plantago asiatica* and *Aeluropus sinensis* at 90% coverage.

The two cotton land use patterns—frozen saline water irrigation with plastic mulching (FSWI+Mulch) and spring mulching without freezing irrigation (Mulch)—had been implemented for eight years [24]. Plots were 6 m long and 5 m wide, with 1 m wide and 0.5 m high ridges between plots to prevent lateral seepage and overflow. For the FSWI+Mulch treatment, irrigation occurred in mid-January each year at a rate of 180 mm, using water with salinity of $9.59 \text{ g} \cdot \text{L}^{-1}$. To ensure uniform freezing, water was applied in small amounts over three days when air temperature was $-10.3 \text{ }^\circ\text{C}$. After irrigation, an ice layer formed on the plot surface. In early March, after ice meltwater infiltration was complete, plastic film (non-degradable, 0.07 mm) was manually applied to both treatments. Cotton (*Gossypium hirsutum*) cultivar ‘Yanmian 28’ was sown on April 23 with row spacing of 65 cm and plant spacing of 30 cm. Cotton survival rates were 72.78% and 19.44% under FSWI+Mulch and Mulch treatments, respectively.

The abandoned land was heavy saline-alkali land that had not been affected by human factors for many years, with typical halophytic herbaceous plants growing on it. Because different plants existed in substantially different soil environments, creating considerable uncertainty for carbon storage research, this study measured only soil carbon storage changes in abandoned saline-alkali bare land.

1.3.1 Soil Organic Carbon Content and Bulk Density Determination

Soil carbon comprises primarily soil organic carbon and soil inorganic carbon. The soil organic carbon pool consists mainly of plant residues, root exudates, soil microorganisms, soil fauna, and their secretions. The soil inorganic carbon pool primarily includes carbonate-containing salts deposited in soil, mostly existing as nodules or mycelia in soil profiles. In coastal saline regions, soil salt composition is dominated by chlorides (Cl^- accounts for 70%~80% of total anions), so soil inorganic carbon represents a relatively small proportion of the soil carbon pool compared to soil organic carbon and can be neglected [25].

For *T. chinensis* and *L. barbarum* strip plots and abandoned saline-alkali bare land, 3-5 sampling points were established monthly from April to November 2015-2016 using an S-shaped layout. For FSWI+Mulch and Mulch treatments, three sampling points were established monthly from June to November 2015-2016. Soil samples were collected by layers (0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-100 cm) using an auger. Soil organic carbon content in each layer was determined using the potassium dichromate volumetric method [26].

In July 2015 and July 2016, during the typical growth season period, three soil profiles were excavated for each treatment. Soil samples were collected by layers (0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-100 cm) using a cutting ring (100

cm³), then oven-dried and weighed to obtain bulk density for each layer.

1.3.2 Plant Biomass Determination At the beginning (April 5, 2015) and end (November 20, 2016) of the experiment, seven standard plants were selected from *T. chinensis* and *L. barbarum* strip plots, and three standard plants were selected from FSWI+Mulch and Mulch treatments. Samples were taken by organ (root, stem, lateral branch, leaf) and fresh and dry weights were measured. Carbon contents for the three plant species (*T. chinensis*, *L. barbarum*, and cotton) were cited from studies by Xu Yongrong et al. [27-28].

1.3.3 Calculation Methods and Data Processing Soil organic carbon storage per unit area was calculated using soil organic carbon content and bulk density. The calculation formula was:

$$M_i = \frac{c_i \times B_i \times d_i}{100}$$

where M_i is the organic carbon density of the i th soil layer ($\text{kg} \cdot \text{m}^{-2}$), c_i is the soil organic carbon content of the i th layer ($\text{g} \cdot \text{kg}^{-1}$), B_i is the bulk density of the i th layer ($\text{g} \cdot \text{cm}^{-3}$), and d_i is the thickness of the i th layer (cm).

The calculation method for carbon storage per unit area of the soil-vegetation system was:

$$D = C + M$$

where D is the carbon storage per unit area of the soil-plant system (g), C is the vegetation carbon storage per unit area (g), and M is the soil organic carbon storage per unit area (g).

All experimental data were processed using Microsoft Excel for graphing and SPSS 18.0 for one-way ANOVA and significance analysis. Differences among treatments were tested using LSD multiple comparison methods.

2.1.1 Differences in Soil Organic Carbon Storage and Vertical Distribution Characteristics

As shown in [Figure 1: see original paper], soil organic carbon content differed significantly among land use patterns ($P < 0.05$). Soil organic carbon content increased gradually with the growth of *T. chinensis* and *L. barbarum*. The 10-year *T. chinensis* land and 8-year *L. barbarum* land had the highest average soil organic carbon content in the 1 m soil profile, at $5.81 \text{ g} \cdot \text{kg}^{-1}$ and $5.76 \text{ g} \cdot \text{kg}^{-1}$ respectively, significantly higher than FSWI+Mulch, Mulch treatments, and the control. Soil organic carbon content under FSWI+Mulch treatment was significantly higher than under Mulch treatment and the control.

The vertical distribution pattern of soil organic carbon content in the 1 m soil profile was basically consistent across land use patterns, decreasing with soil depth (Fig. 1b). The 10-year *T. chinensis* land and 8-year *L. barbarum* land had the highest surface soil organic carbon content, at $7.50 \text{ g} \cdot \text{kg}^{-1}$ and $7.49 \text{ g} \cdot \text{kg}^{-1}$ respectively. The growth of *T. chinensis* and *L. barbarum* roots effectively supplemented soil organic carbon content in all layers, which increased gradually with planting duration. Under FSWI+Mulch and Mulch treatments, cotton field surface soil and 20–40 cm layers had the highest organic matter content. The higher cotton survival rate under FSWI+Mulch treatment resulted in significantly higher organic carbon content in all layers compared to Mulch treatment.

[Figure 1: see original paper]

2.1.2 Characteristics of Soil Organic Carbon Storage Changes

As shown in [Figure 2: see original paper], soil bulk density differed significantly among land use patterns ($P < 0.05$). Compared with the control, soil bulk density decreased significantly under halophyte planting (*T. chinensis* and *L. barbarum*) and under both cotton treatments (FSWI+Mulch and Mulch). Bulk density decreased gradually with increasing planting duration of *T. chinensis* and *L. barbarum*. The 10-year *T. chinensis* plantation and 8-year *L. barbarum* plantation had soil bulk densities of $1.41 \text{ g} \cdot \text{cm}^{-3}$ and $1.46 \text{ g} \cdot \text{cm}^{-3}$ respectively, significantly lower than other land use patterns.

The vertical pattern of soil bulk density was basically consistent across land use patterns, increasing with soil depth (Fig. 2b). Bulk density in each layer decreased gradually with *T. chinensis* planting duration. The 10-year *T. chinensis* plantation had significantly higher root biomass in lower soil layers than younger plantations, and root growth effectively loosened the soil, resulting in lower bulk density in deeper layers. Similarly, bulk density in different layers of the 8-year *L. barbarum* plantation was significantly lower than that of the 2-year plantation. Surface soil bulk densities under FSWI+Mulch and Mulch treatments were $1.32 \text{ g} \cdot \text{cm}^{-3}$ and $1.29 \text{ g} \cdot \text{cm}^{-3}$ respectively. Abandoned saline-alkali bare land had higher bulk density, which increased gradually with soil depth.

[Figure 2: see original paper]

As shown in [Figure 3: see original paper], the 10-year *T. chinensis* plantation and 8-year *L. barbarum* plantation had the highest organic carbon storage in the 1 m soil profile, at $75.73 \text{ t} \cdot \text{hm}^{-2}$ and $77.57 \text{ t} \cdot \text{hm}^{-2}$ respectively, significantly higher than the cotton field under Mulch treatment. This indicates that *T. chinensis* and *L. barbarum* planting had higher carbon sequestration efficiency than freezing irrigation and mulching measures. Soil carbon storage under FSWI+Mulch treatment was $54.40 \text{ t} \cdot \text{hm}^{-2}$, representing increases of $21.32 \text{ t} \cdot \text{hm}^{-2}$ and $40.87 \text{ t} \cdot \text{hm}^{-2}$ compared to Mulch treatment and the control, respectively.

[Figure 3: see original paper]

As shown in [Figure 4: see original paper], from the beginning (April) to the end (November) of the 2015–2016 growing season, average organic carbon content in the 1 m soil profile of both *T. chinensis* plantations showed a decreasing trend, while increasing significantly during the non-growing season. The 10-year *T. chinensis* plantation had greater average soil organic carbon content than the 3-year plantation. The 8-year *L. barbarum* plantation had significantly higher soil organic carbon content than the 2-year plantation. *L. barbarum* experiences two leaf-fall periods annually in August and November, and the figure shows clear increasing trends in soil organic carbon content during these stages. Soil organic carbon content under FSWI+Mulch and Mulch treatments was low and significantly lower than in *T. chinensis* and *L. barbarum* lands.

Soil organic carbon content changes in abandoned saline-alkali bare land were completely different from planted plots. Without external carbon input from litter or other sources, the 1 m soil profile average organic carbon content showed an overall decreasing trend, functioning as a carbon source.

[Figure 4: see original paper]

2.2.1 Differences in Vegetation Carbon Storage

As shown in [Figure 3: see original paper] and [Figure 6: see original paper], soil carbon storage per unit area was greater than vegetation carbon storage. As shown in [Figure 6: see original paper], aboveground carbon sequestration was greater than belowground. Plant carbon sequestration increased significantly with *T. chinensis* planting duration, with the 10-year plantation reaching $42.51 \text{ t} \cdot \text{hm}^{-2}$, significantly greater than other land use patterns. The 8-year *L. barbarum* plantation had much lower plant carbon sequestration than *T. chinensis* plantations, related to planting density and resulting differences in plant biomass per unit area. Cotton biomass under FSWI+Mulch and Mulch treatments was significantly lower than that of 3-year and 10-year *T. chinensis* plants and 8-year *L. barbarum* plants.

[Figure 6: see original paper]

2.2.2 Characteristics of Vegetation Carbon Storage Changes

From April 2015 to November 2016, the 3-year *T. chinensis* and 2-year *L. barbarum* plantations grew rapidly, with significant increases in root, stem, leaf biomass, and total biomass. In contrast, biomass increase in the 10-year *T. chinensis* and 8-year *L. barbarum* plantations was very slow, consisting mainly of annual leaf growth and fall (Table 2).

Under FSWI+Mulch treatment, cotton taproot biomass was significantly greater than under Mulch treatment, while branch and leaf biomass were significantly lower (Table 3).

As shown in [Figure 7: see original paper], from April 2015 to November 2016, the 3-year *T. chinensis* plantation had the highest carbon sequestration, followed by the 2-year *L. barbarum* plantation and cotton under FSWI+Mulch treatment. The 10-year *T. chinensis* and 8-year *L. barbarum* plants had basically stopped carbon sequestration.

[Figure 7: see original paper]

2.3.1 Differences in Soil-Vegetation System Carbon Storage

As shown in [Figure 8: see original paper], halophyte planting represented by *T. chinensis* and *L. barbarum* could fix more carbon than other land use patterns. The 10-year *T. chinensis* plantation and 8-year *L. barbarum* plantation had the highest soil-vegetation system carbon storage, at $118.24 \text{ t} \cdot \text{hm}^{-2}$ and $96.27 \text{ t} \cdot \text{hm}^{-2}$ respectively, representing increases of $83.39 \text{ t} \cdot \text{hm}^{-2}$ and $61.42 \text{ t} \cdot \text{hm}^{-2}$ over abandoned saline-alkali bare land, and increases of $58.51 \text{ t} \cdot \text{hm}^{-2}$ and $36.54 \text{ t} \cdot \text{hm}^{-2}$ over FSWI+Mulch treatment.

[Figure 8: see original paper]

2.3.2 Characteristics of Soil-Vegetation System Carbon Storage Changes

As shown in [Figure 9: see original paper], from April 2015 to November 2016, the soil-vegetation system carbon increases in the 3-year *T. chinensis* plantation and 2-year *L. barbarum* plantation were $20.16 \text{ t} \cdot \text{hm}^{-2}$ and $5.42 \text{ t} \cdot \text{hm}^{-2}$ respectively, far exceeding other land use patterns and functioning as CO_2 sinks. The 10-year *T. chinensis* and 8-year *L. barbarum* plantations showed slight decreases in soil-vegetation system carbon of $0.14 \text{ t} \cdot \text{hm}^{-2}$ and $0.35 \text{ t} \cdot \text{hm}^{-2}$ respectively, functioning as weak carbon sources. Compared with Mulch treatment and the control, cotton fields under FSWI+Mulch treatment showed slow carbon sequestration, but because mature plants were removed annually, further verification of changes is needed.

[Figure 9: see original paper]

3.1 Soil Carbon Storage Changes Under Different Land Use Patterns in Coastal Saline Regions

The study found that compared with abandoned saline-alkali bare land, planting *T. chinensis* and *L. barbarum* significantly increased soil carbon storage. In cotton fields where mature plants were removed after harvest, soil organic carbon accumulation was greatly affected, resulting in low soil organic carbon content significantly lower than in *T. chinensis* and *L. barbarum* lands. In abandoned saline-alkali bare land without vegetation growth or external carbon input, soil organic carbon content depended mainly on soil parent material [29].

With plant growth, annual litter quantity in *T. chinensis* and *L. barbarum* plantations gradually increased, effectively supplementing soil organic carbon

content and showing a yearly increasing trend. Although the 10-year *T. chinensis* and 8-year *L. barbarum* plantations had high leaf biomass, root growth had ceased while soil microorganisms continued decomposing organic carbon, placing the two processes in dynamic equilibrium with no significant change trend in soil organic carbon. Due to lack of plant growth, carbon fixation and consumption in saline bare land related mainly to soil temperature and water-salt conditions, with change trends requiring further research [30].

Compared with abandoned saline-alkali bare land, planting *T. chinensis* and *L. barbarum* and growing cotton under freezing irrigation with mulching significantly reduced soil bulk density, indicating that plant growth can effectively improve soil water permeability and aeration, greatly enhancing nutrient and water transport efficiency [31]. Humus and new litter generally accumulate in surface soil, resulting in higher surface organic carbon content. Sometimes root growth secretes certain organic substances, and the special rhizosphere environment can significantly increase local soil organic carbon content [32]. The abandoned area represents heavy saline land with extremely high salt content and groundwater tables of only 1-2 m, where soil clayification leads to significantly increased bulk density [33].

Although *T. chinensis*, *L. barbarum* planting, and freezing irrigation with mulching significantly increased soil carbon storage compared with abandoned saline-alkali bare land, their organic carbon content was generally low [34], with the 10-year *T. chinensis* plantation having soil organic carbon content less than $10 \text{ g} \cdot \text{kg}^{-1}$, related to the saline environment. Although plants could grow normally, high soil salinity hindered further organic carbon accumulation. Soil organic carbon content is affected by multiple factors, may fluctuate in the short term, but does not change dramatically, with research time and spatial scales, locations, and replication numbers all affecting final results [35].

3.2 Vegetation Carbon Storage Changes

The 10-year *T. chinensis* and 8-year *L. barbarum* plants had significantly higher carbon sequestration than other treatments, but total biomass increase had become very slow, consisting mainly of annual leaf growth and fall. Due to sparse planting density, the 8-year *L. barbarum* plantation had much lower plant carbon sequestration than *T. chinensis* plantations. Therefore, determining optimal planting patterns for different land use patterns to maximize carbon sequestration without mutual growth inhibition represents an urgent problem [36].

Under FSWI+Mulch treatment, the leaching effect of melted freshwater from frozen saline water resulted in significantly lower salt content in the cultivated soil layer, enabling more rapid and deeper root growth. However, higher survival rates caused leaf shading that affected photosynthesis. Under Mulch treatment, lower cotton survival rates meant individual plants received more light and nutrients, resulting in higher branch and leaf biomass per plant, with significantly

higher average cotton yield per plant than under FSWI+Mulch treatment.

3.3 Soil-Vegetation Carbon Storage Changes

After implementing different land use patterns, soil carbon storage dominated carbon fixation in the soil-vegetation system, with vegetation carbon storage being less than soil carbon storage. However, interannual changes in soil-vegetation system carbon storage showed that vegetation carbon storage changes were the decisive factor determining whether the system functioned as a carbon source or sink.

From a carbon sequestration perspective, halophyte planting represented by *T. chinensis* and *L. barbarum* could fix more carbon and play a positive role in regional carbon cycling. However, carbon sequestration trends require further research to ensure continuous carbon fixation under various land use patterns. If they become carbon emission processes in the future, land use patterns or vegetation will need to be changed. The study found that after reaching certain ages, *T. chinensis* and *L. barbarum* showed slowed carbon sequestration rates or even functioned as carbon sources, requiring land use changes. Frozen saline water irrigation combined with mulching has achieved remarkable success in growing crops on heavy saline-alkali land, but from a carbon sequestration perspective, annual plant biomass should be returned to the field through measures such as grinding and burying or surface residue mulching to maintain carbon storage. Cotton field carbon sequestration was far lower than halophyte planting techniques represented by *T. chinensis* and *L. barbarum*. Moreover, freezing irrigation implementation depends on topography and climate conditions and requires considerable labor and resources, whereas halophytes can survive on heavy saline-alkali land naturally, requiring no intervention after initial planting, saving time and costs while demonstrating significant carbon sequestration effects.

Compared with abandoned saline-alkali bare land, artificially planted *T. chinensis* and *L. barbarum* plantations and cotton fields under freezing irrigation with mulching could fix more carbon in the soil-vegetation system. The 10-year *T. chinensis* plantation and 8-year *L. barbarum* plantation had the highest system carbon storage, at $118.24 \text{ t} \cdot \text{hm}^{-2}$ and $96.27 \text{ t} \cdot \text{hm}^{-2}$ respectively, representing increases of $83.39 \text{ t} \cdot \text{hm}^{-2}$ and $61.42 \text{ t} \cdot \text{hm}^{-2}$ over abandoned saline-alkali bare land, and increases of $58.51 \text{ t} \cdot \text{hm}^{-2}$ and $36.54 \text{ t} \cdot \text{hm}^{-2}$ over FSWI+Mulch treatment.

Research on carbon sequestration trends under different land use patterns revealed that the 3-year *T. chinensis* plantation and 2-year *L. barbarum* plantation grew rapidly, with rapid soil organic carbon decomposition during growth, showing a gradual decrease in soil organic carbon during the growing season. However, when combined with aboveground plant carbon fixation, the soil-plant system showed significant carbon sequestration rates of $10.08 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ and $2.71 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, respectively. The FSWI+Mulch treatment had low carbon se-

questration rates of only $0.53 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$. The 10-year *T. chinensis* and 8-year *L. barbarum* plantations showed significantly slowed plant carbon sequestration rates, with the soil-vegetation system functioning as a weak carbon source, requiring measures such as planting pattern and management changes to enhance carbon sequestration. The Mulch treatment had low cotton survival rates and essentially no plant retention after maturity, with net carbon storage decreasing by $0.86 \text{ t} \cdot \text{hm}^{-2}$ annually. Abandoned saline-alkali bare land functioned as a carbon source without external carbon input, with soil carbon storage decreasing at $1.42 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$. In summary, artificial planting of *T. chinensis* and *L. barbarum* in coastal saline regions represents an effective approach for increasing regional carbon storage.

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