

Article

The Contribution of Saline-Alkali Land to the Terrestrial Carbon Stock Balance: The Case of an Important Agriculture and Ecological Region in Northeast China

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Abstract: Saline-alkali land is an important component of terrestrial ecosystems and may serve as a carbon sink but its net contribution to the overall terrestrial carbon sink is unknown. Using methods recommended by the IPCC, this study evaluates the impacts of interconverting saline-alkali and non-saline-alkali land on terrestrial carbon stocks by measuring two major carbon pools (soil organic carbon and vegetation carbon) in the saline-alkali land of China's Songnen Plain. Distinct phases in the evolution of the region's terrestrial carbon stock were delineated, factors contributing to transitions between phases were identified, and the effects of changes in the saline-alkali land carbon stock on the overall terrestrial carbon sink were estimated. Between 2005 and 2020, the region's saline-alkali land carbon stock initially increased, then declined, and finally increased again. However, the overall terrestrial carbon stock decreased by 0.5 Tg (1 Tg = 10^{12} g), indicating that the increase in the saline-alkali land carbon stock was due primarily to expansion of the saline-alkali land area. The conversion of non-saline-alkali land to saline-alkali land was a carbon-emitting process; consequently, in areas undergoing saline-alkali land change, the lower carbon density bound was equal to the carbon density of unconverted saline-alkali land and the upper bound was equal to the carbon density of unconverted non-saline-alkali land. In general, changes in the carbon stock of saline-alkali land correlated negatively with changes in the overall terrestrial carbon stock. The conversion of saline-alkali land into grassland and cropland through biochar improvement and the planting of saline-tolerant crops (*Leymus chinensis*, *salt-tolerant rice*) has a positive effect on promoting the enhancement of terrestrial carbon stocks.

Keywords: saline-alkali land; terrestrial carbon sink; contribution; Songnen Plain



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1. Introduction

Global warming is one of the most pressing challenges to the sustainable development of human society and is largely driven by massive anthropogenic carbon dioxide emissions [1–3]. Another important contributing factor is a decline in carbon sequestration resulting from anthropogenic damage to ecosystems that is causing losses of cropland, severe deforestation, and soil erosion [4]. To address this problem, the Paris Agreement set a long-term goal of controlling global heating and achieving carbon neutrality, in part by increasing the size of current carbon dioxide sinks. A carbon sink refers to the process of absorbing carbon dioxide in the atmosphere and reducing the concentration of greenhouse gases in the atmosphere through measures such as afforestation and vegetation restoration [5]. At present, many countries have taken measures to control carbon emissions [6]. However, controlling carbon emissions cannot achieve the goal of carbon neutrality because human production activities inevitably emit carbon dioxide [7]. Therefore, the importance of enhancing the capacity of carbon sinks to achieve carbon neutrality is self-evident.

Terrestrial ecosystems provide diverse ecosystem services including soil and water conservation, carbon storage, and protection of biodiversity. In addition, they act as major

carbon sinks and thus contribute significant carbon storage [8]. The sizes of terrestrial carbon sinks are more variable than those of marine ecosystems because they can be altered by restoring or degrading surface vegetation [9]. During 2010–2019, about 31% of anthropogenic CO₂ emissions were absorbed by terrestrial ecosystems [10,11]. The main carbon pools in terrestrial ecosystems are the soil organic carbon pool and the vegetation carbon pool, both of which are important indicators of global climate change and important variables for estimating terrestrial carbon stocks [12]. Among them, soil organic carbon (SOC) is the largest terrestrial carbon pool, and its accumulation contributes to climate change mitigation [13,14], and the content of soil organic carbon pools can be effectively increased by inorganic fertilizer and crop residue inputs [15]. Vegetation carbon, on the other hand, mainly comes from four sources: woodland, grassland, cropland, and wetland, and its rich vegetation resources on the surface are important carbon pools [5]. Soil salinity is a major ecological problem in terrestrial ecosystems around the world; the global area of saline-alkali land is currently around 10×10^9 hm², corresponding to about 25% of the Earth's land area and 76% of its potential cropland. In addition, soil salinity is also considered as one of the important factors affecting global agriculture and food security [16]. Data show that about 412 million hectares of agricultural land are affected by saline-alkali land globally, especially in regions such as Egypt, Saudi Arabia, and northwestern China, which seriously constrains the sustainable development of agriculture in the aforementioned regions [17,18]. Moreover, saline-alkali land area is expanding under the influence of anthropogenic activities and climate change [19]. By 2050, about 50 per cent of the cropland will be affected by saline-alkali land without proper mitigation measures. Although saline-alkali land constrain agricultural development, they possess some potential for carbon sequestration as an important component of terrestrial ecosystems [20,21]: studies have shown that soil solutions in saline-alkali land absorb and dissolve atmospheric carbon dioxide, gradually pushing it into deep underground aquifers to form a carbon sink [21,22]. Moreover, the development and utilization of saline-alkali land can increase the carbon sequestration capacity, and saline-alkali land absorbs and retains a large amount of carbon during the process of utilization and improvement [23,24]. China has 9.9×10^7 hm² of saline-alkali land with a potentially very large carbon sink capacity. However, the impact of saline-alkali land and its spread on the overall carbon sink capacity of terrestrial ecosystems is currently unclear because saline-alkali land is merely one part of a broader terrestrial ecosystem, and changes in the extent or properties of saline-alkali land may have additional effects on other parts of the ecosystem. Consequently, there is a clear need to determine whether changes in the carbon stock of saline-alkali land have positive or negative effects on the overall carbon sink capacity of terrestrial ecosystems.

The Songnen Plain is located in northeastern China and is one of the world's three largest saline-alkali soil areas despite being known for its black soils. In recent decades, agriculture, animal husbandry, and forage farming in the region have been inhibited by rising salinity, making the region a typical ecologically fragile agro-pastoral zone [25]. Between 1980 and 2000, large amounts of the Songnen Plain's grassland and cropland were degraded into saline-alkali land as a result of cropland expansion as well as the development of animal husbandry and the accompanying grazing pressure, and the region's soil salinity has increased [26]. At the same time, saline lakes, ponds, and marshes have been depleted by evaporation due to the region's shallow water table, causing large amounts of salt to be deposited on the land surface. It is therefore important to determine how the carbon sink capacity of saline-alkali land in a critical condition like that of the Songnen Plain contributes to the overall carbon sink capacity of terrestrial ecosystems.

Research on terrestrial carbon stocks began in the 1970s. At that time, it was generally accepted that land was a net carbon sink because plants can absorb atmospheric carbon dioxide. However, some scholars argued that factors such as vegetation destruction could reduce carbon dioxide uptake or even cause the release of carbon dioxide [27]. Since 1990, research on terrestrial carbon sinks using field measurements, model simulations, and other methods has confirmed that terrestrial ecosystems are globally important

carbon sinks [28]. Most of these studies have focused on provincial, national, or global spatial scales [29–34]. In addition, the research objects of these studies have generally been regions dominated by a single land use type or sub-ecosystem such as forests or grasslands [35–39]. Broadly, previous studies on the carbon sink capacity of saline-alkali land can be divided into two major groups. The first group comprises studies on land use conversion, i.e., converting saline-alkali land into other land types with different uses to influence ecosystem processes such as carbon uptake and hydrological processes and thereby change its carbon sink capacity [40–42]. Studies in the second group have focused on improving the saline-alkali land carbon sink by changing the land's physicochemical properties; improvement measures examined in these studies have included planting salt-tolerant crops, salt-washing, improving drainage, and applying chemical improvement agents [43,44]. In addition, scholars have investigated the effects of salinization on carbon stocks in terms of soil organic carbon [45–47], soil inorganic carbon [48], and the relationship between soil aggregates and carbon stocks [24]. It was found that saline-alkali land expansion leads to a decrease in soil organic carbon and an exponential decrease in soil inorganic carbon. However, these studies only considered the carbon pool of saline-alkali land and did not measure the carbon pool of vegetation on the saline surface. Furthermore, they only quantified changes in carbon stocks and did not further investigate the impact of changes in saline-alkali land carbon stocks on the total terrestrial carbon stock. In summary, previous studies on terrestrial carbon stocks have generally had a single research object that was studied over a large spatial scale and have used a wide array of research methods. Consequently, there is a lack of consistency within the available data that makes it difficult to compare published findings. Because of its potentially important role in terrestrial carbon sequestration, saline-alkali land has mainly been studied from the perspective of improving its carbon sink capacity. However, the positive and negative impacts of the saline-alkali land carbon sink in terrestrial ecosystems are poorly understood.

Therefore, the Songnen Plain in northeast China was selected as the study area for this study. The methodology recommended by the IPCC was used to comprehensively consider the soil organic carbon and vegetation carbon pools of saline-alkali land, and to analyze the impact of changes in their carbon stocks on total terrestrial carbon stocks. We hypothesized that (1) saline-alkali land carbon stocks are characterized by an annual decline over time, and (2) changes in saline-alkali land carbon stocks have a significant negative impact on terrestrial carbon stocks. Our objectives are (1) to investigate the characteristics of changes in saline-alkali land carbon stocks in the Songnen Plain from 2005 to 2020, and (2) to determine the contribution of changes in saline-alkali land carbon stocks to the balance of terrestrial carbon stocks.

2. Material and Methods

2.1. Study Area

The Songnen Plain is located in the central region of northeast China, extending across Heilongjiang Province and Jilin Province north of the Songliao Watershed. Its terrain is generally low and open with an undulating topography and areas of granites and depressions that have resulted in the development of marshy wetlands. The region examined in this work is located between N43°59'21"–N48°55'34" and E121°38'09"–E128°32'44", with a total area of 1.8×10^5 km² (Figure 1). The Songnen Plain was formed by alluvial deposits from the Songhua River, the Nenjiang River, and their tributaries. These rivers flow through the southwestern part of the plain and eventually form a closed-flow area in the form of a tailless river.

The central part of the Songnen Plain has a large number of wetlands and lakes, including Momog, Zalong, and Xianghai [49]. Major wetland plants in the Songnen Plain include *Puccinellia distans*, *Phragmites australis*, and *Leymus chinensis* [50]. The geological structure of the Songnen Plain is the depression area of the Songliao Fracture Zone, and the soil is very fertile, with black soil and black calcium soil accounting for more than 60% of the soil. The Songnen Plain is the main grain-producing area, and the main crops are

soybeans, wheat, corn, sugar beet, flax, and potatoes. Due to the high concentration of grassland, animal husbandry is also very developed in the Songnen Plain. The climate of the Songnen Plain is a temperate monsoon climate with four distinct seasons, and it is a semi-humid and semi-arid zone [51]. The average annual temperature increases gradually from north to south, with a latitudinal distribution. In winter, the climate is cold and dry. The coldest month is January, with average temperatures ranging from -16°C to -26°C . Total rainfall in January is usually 10–24 mm. In spring, the temperature rises quickly, the southwest wind is frequent, and precipitation is relatively low. In summer, the Songnen Plain is affected by southeast winds, with strong precipitation and even heavy rainfall, with total precipitation of about 270–417 mm, accounting for 70–80% of the annual precipitation [52]. In autumn, the intensity of solar radiation decreases with the duration of sunshine, the temperature drops sharply, and the precipitation is slightly higher than in spring [53].

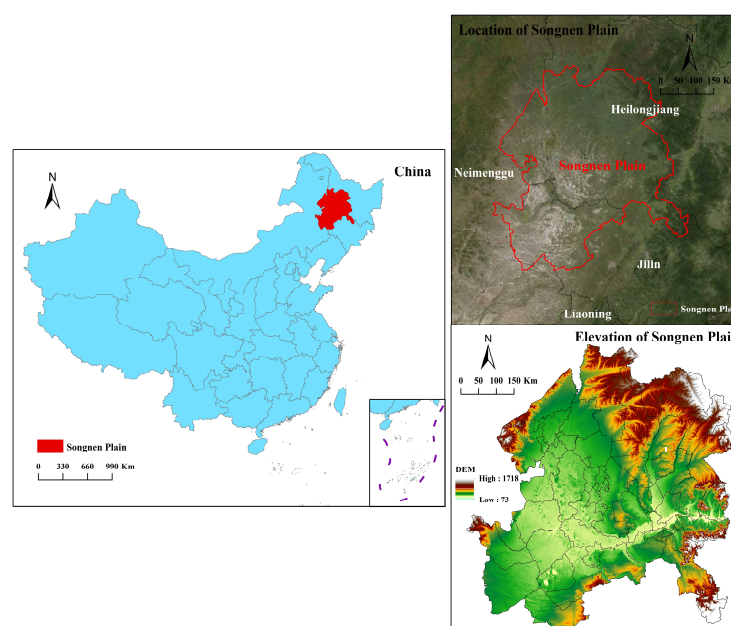


Figure 1. The study area and its location within China.

2.2. Data

Land use cover data for 2005, 2010, 2015, 2018, and 2020 were obtained from the Resource and Environment Science and Data Centre of the Chinese Academy of Sciences (<http://www.resdc.cn/>) (accessed on 25 March 2023)) [54]. In this case, land use data from 2018 were used to calculate soil organic carbon density. Soil data were obtained from the Soil Centre within the National Earth System Science Data Centre, which is a part of China's National Science and Technology Resources Shared Service Platform (<http://soil.geodata.cn>) (accessed on 18 February 2023)) [55]. Soil organic carbon data were obtained from the Global Soil Organic Carbon Map (2018) of the FAO Soil Database (<https://www.fao.org/home/en/>) (accessed on 18 February 2023)) [56]. Net Primary Productivity (NPP) data (2005, 2010, 2015, and 2020) were obtained from the MODIS satellite-based MOD17A3HGF product released by the National Aeronautics and Space Administration (NASA) of the United States (<https://lpdaac.usgs.gov/products/mod17a3hgf061/>) (accessed on 20 March 2023)) [57].

2.3. Methodology

2.3.1. Classification of Land Use Types

This study classifies the land use types based on the land use type classification criteria given by Resource and Environment Science and Data Centre of the Chinese Academy of Sciences (<http://www.resdc.cn/>). Eight land use types were represented within the

land use cover data: cropland, woodland, grassland, wetland, water, construction land, underutilized land, and saline-alkali land. Cropland includes paddy fields and drylands; woodland includes forested land, shrubland, open woodland, and other woodland; grassland includes high-cover grassland, medium-cover grassland, and low-cover grassland; water include rivers, lakes, reservoirs, ponds, and mudflats; construction land includes urban land, rural settlements, and other construction land; and underutilized land includes sandy land, bare land, and bare rocky gravel land. Because the subsequent analysis relied on soil organic carbon and NPP data, the water land use type was excluded from the analysis.

2.3.2. Soil Organic Carbon Assessment

Based on the global soil organic carbon map (2018) and soil type data, the organic carbon densities of 33 soil types in the study area were calculated and overlaid onto the land use cover data (2018) at the corresponding time points to obtain the average organic carbon density of each soil type for different land use cover types, which was in turn used to estimate the soil organic carbon stock. Because this procedure relied on the soil organic carbon map, it was not possible to estimate the soil organic carbon stock in watersheds. In accordance with the main method suggested by the IPCC [58], the soil organic carbon stock was calculated using the following expression. A more detailed description of the calculation formula can be found in Tian et al. and Potma Gonçalves et al. [59,60].

$$SOC_{ij} = SOCD_{ij} \times Area_{ij} \quad (1)$$

here, SOC_{ij} is the soil organic carbon stock (kg) for land use cover category j and soil type i ; $SOCD_{ij}$ is the soil organic carbon density (kg/m^2) for land use cover category j and soil type i ; and $Area_{ij}$ is the area of land use cover category j with soil type i (m^2).

2.3.3. Vegetation Carbon Assessment

Remote sensing data are a key tool for studying vegetation carbon sequestration. This study examined the Songnen Plain, which extends over a very large area, so remote sensing data were used to quantify its distribution of biogenic carbon (vegetation). Specifically, this was carried out using the NPP data provided by the NASA MODIS satellites. Previous studies have shown that remote sensing data provide greater objectivity than traditional NPP measurements and have the important advantage of enabling near real-time monitoring [61]. According to the stoichiometric equation of photosynthesis, 1.62 g of carbon dioxide is fixed for every 1 g of dry matter formed. The NPP is the organic dry matter production of green plants per unit time and unit area after subtracting autotrophic respiration, and carbon comprises roughly 45% of plant organic dry matter. Therefore, using the IPCC's recommended methodology, the vegetation carbon sink can be estimated using the following expressions. A more detailed description of the calculation formula can be found in Song et al. [62].

$$BioD_i = NPP/0.45 \times 1.62; Cbio_i = BioD_i \times Area_i \quad (2)$$

here, $BioD_i$ is the carbon density of vegetative biomass for land use cover class i (kg/m^2), NPP is the net primary productivity (kg/m^2), $Cbio_i$ is the biomass carbon stock of vegetative biomass for land use cover class i (kg), and $Area_i$ is the areal extent of land use cover class i (m^2).

2.3.4. Calculating Contributions

The degree of contribution is a quantitative measure of the impact of a change in one component of a system on the system's overall change. Here, this concept is used to quantify the impact of changes in saline-alkali land carbon stock on terrestrial carbon stock. The degree of contribution is calculated using the following expression [63]:

$$DX_i = (X_{i1} - X_{i0})/Y_0 \quad (3)$$

here, DX_i is the contribution to the change in saline-alkali land carbon stock in stage i ; X_{i1} and X_{i0} are the saline-alkali land carbon stocks at the end and beginning of stage i ; and Y_0 is the terrestrial carbon stock at the beginning of stage i .

3. Results

3.1. Saline-Alkali Land Carbon Stock

Overall, the carbon stock in the Songnen Plain's saline-alkali land decreased by 0.5 Tg (Tg is the Teragram, 1 Tg = 10^9 g) over the studied period (Figure 2). However, the decrease was not continuous: the carbon stock increased by 0.6 Tg between 2005 and 2010, reaching a maximum of 54.75 Tg in 2010, when saline-alkali land held 5.54% of the study area's total carbon stock. However, the study area's carbon density also fell to its lowest value (4.75 kg/m^2) in 2010, indicating that the increased carbon stock in saline-alkali land during this period was due to an increase in the area of saline-alkali land rather than an increase in the carbon density of existing saline-alkali land. Between 2010 and 2015, the study area's carbon stock fell by 1.23 Tg, but the carbon stock in vegetation increased significantly, resulting in an overall increase in carbon density. The carbon stock in saline-alkali land fell to a minimum in 2015, and its proportion of the study area's total carbon stock decreased to 5.39%, falling below that in 2005–2010. In 2015–2020, there was a continuous increase in carbon density and a small increase in the carbon stock in saline-alkali land (0.14 Tg) but a decrease in the soil organic carbon content (0.67 Tg). The overall increase was thus due to an increase in the vegetation carbon stock (0.81 Tg). In addition, although the saline-alkali land carbon stock in 2020 was higher than that in 2015, its proportion of the total carbon stock in the study area was lower than in 2015, indicating that the total carbon stock in the study area increased during this period.

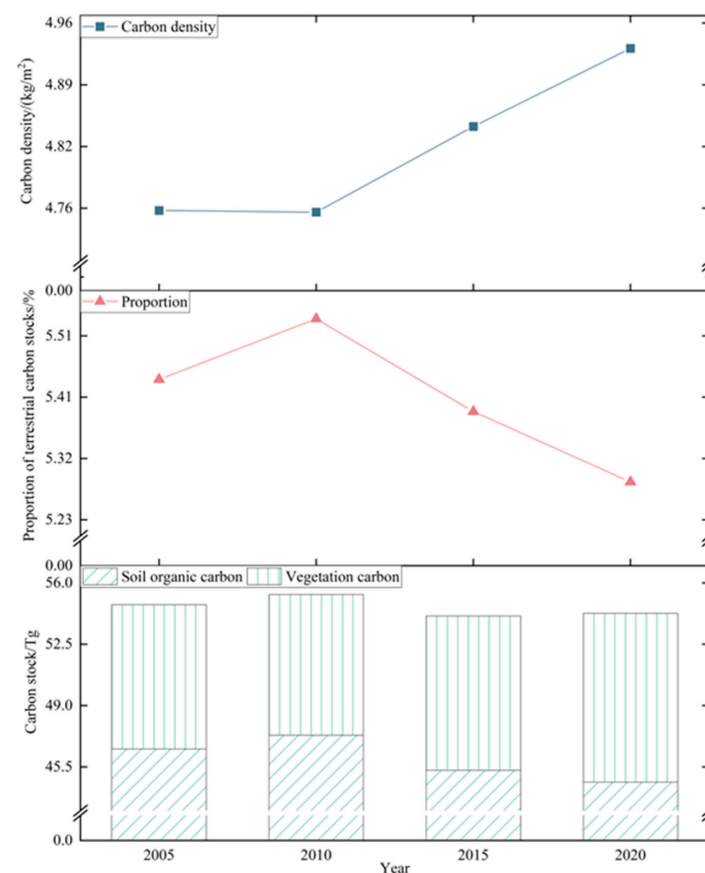


Figure 2. Carbon stocks, carbon density, and proportion of carbon stocks in saline-alkali land from 2005 to 2020.

3.2. Spatial and Temporal Changes in the Saline-Alkali Land Distribution

As shown in Figure 3, saline-alkali land in the Songnen Plains from 2005 to 2020 is concentrated in the southern region. The area of saline-alkali land that changed accounted for a smaller proportion of the total area, with an area of 1350.98 km² transferred out and an area of 871.69 km² transferred in. Overall, the area of saline-alkali land that was transferred out during the study period was larger than the area of saline-alkali land that was transferred in, indicating that saline-alkali land exploitation and use activities were more frequent during this period.

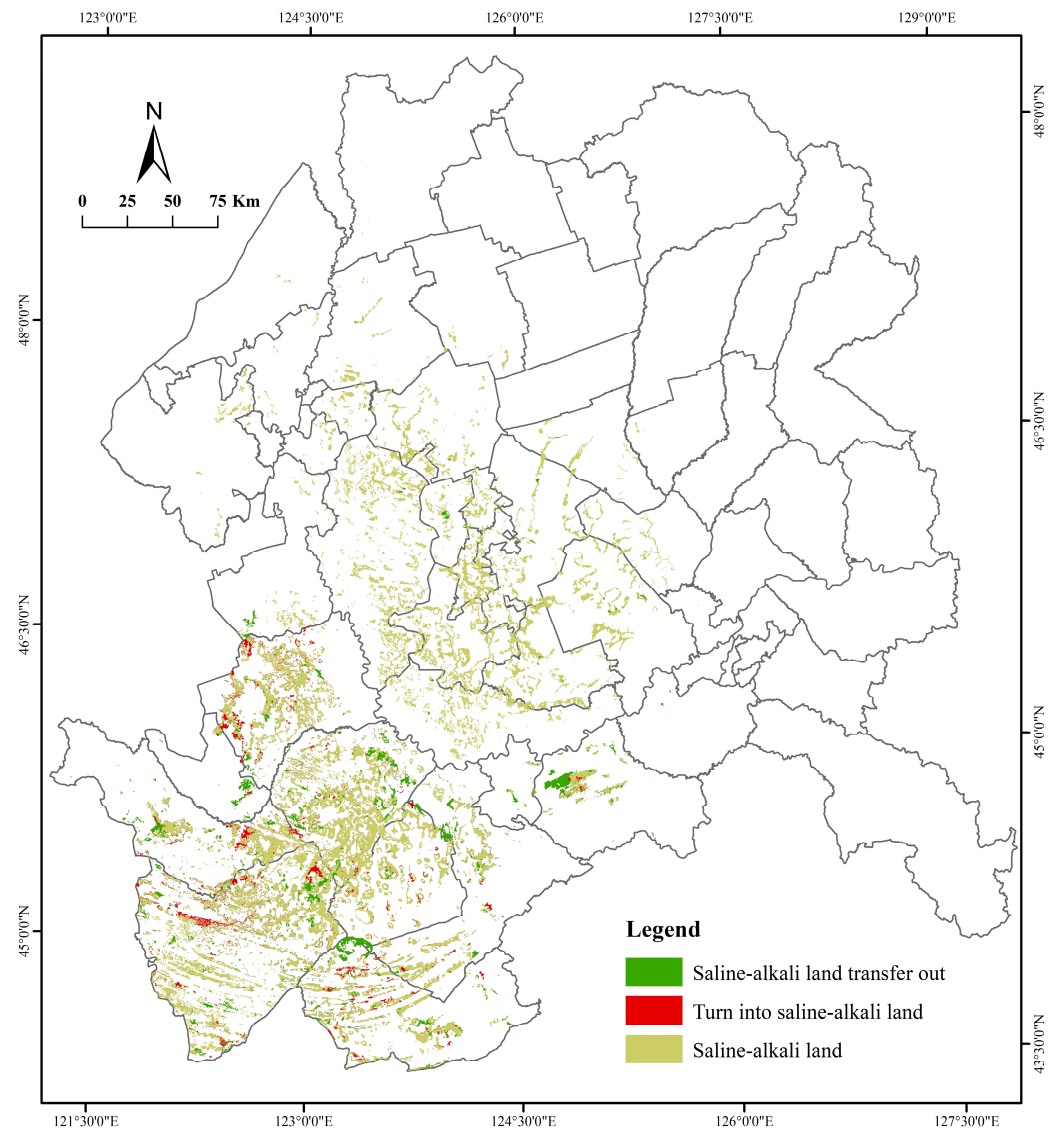


Figure 3. Spatial variation and extent of saline-alkali land, 2005–2020.

From the perspective of the saline-alkali land transfer ratio, the intensity of saline-alkali land transfer activities decreased year by year during the study period (Figure 4). Grassland was the land type with the largest area converted into saline-alkali land (1056.47 km²), followed by cropland (733.59 km²). The period 2005–2010 was the most intensive phase of saline-alkali land conversion, with the area of saline-alkali land converted out of the area and the area of saline-alkali land converted into the area increasing (848.95 km² and 927.41 km², respectively). From 2010 to 2015, the area of saline-alkali land transferring out of the area (432.69 km²) was significantly larger than the area of saline-alkali land transferring in (18.08 km²), which is completely opposite to the characteristics of the previous stage. The

total area of saline-alkali land transferring in from 2015 to 2020 was only 186.32 km², and there was no transfer of construction land and wetlands to saline-alkali land in this stage.

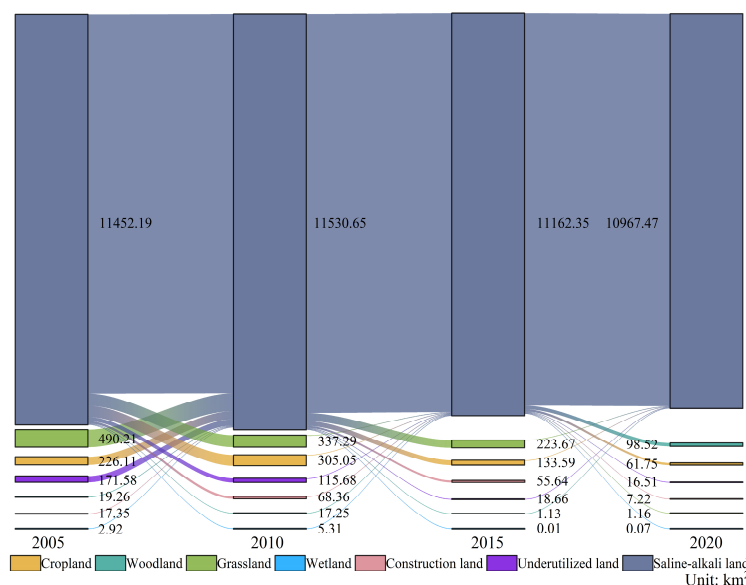


Figure 4. Transfer relationship between saline-alkali and non-saline-alkali land.

3.3. Impact of Saline-Alkali Land on the Total Carbon Stock

The data indicate that the overall carbon stock fell when non-saline-alkali land was converted into saline-alkali land, meaning that this conversion process can be regarded as a carbon source, i.e., something that releases carbon dioxide. Conversely, the carbon stock increased when saline-alkali land was converted into non-saline-alkali land, making this process a carbon sink that promotes carbon dioxide uptake (Figure 5a,c,e). The most intense period of both carbon sequestration and carbon emission was 2005–2010, when the regional carbon stock of saline-alkali land converted into non-saline-alkali land increased by 11.87 Gg (1 Gg = 10⁹ g). The majority of this increase (7.83 Gg) was due to the conversion of saline-alkali land into cropland. Conversely, when non-saline-alkali land was converted into saline-alkali land, the carbon stock decreased dramatically, falling by as much as 91.46 Gg. The largest contributor to this decrease was the conversion of grassland into saline-alkali land, which accounted for 40.85 Gg of the total. The rate of the reduction in the carbon stock declined gradually from 2010 to 2020, eventually stabilizing at around 1 Gg. This was mainly due to a reduction in the area of non-saline-alkali land converted to saline-alkali land, especially from 2015 to 2020 when the conversion of wetlands and construction land into saline-alkali land was largely halted and the overall carbon stock rose to 120.55 Gg. Cropland was the largest contributor to this increase, accounting for 49.26 Gg, but woodland and grassland also contributed significantly (25.52 Gg and 31.56 Gg, respectively).

The changes in carbon stocks discussed above reflect both changes in carbon sequestration within individual land types and changes in the area covered by individual land types. To isolate the effect of the former, we examined the effects of saline-alkali land conversion on carbon density. As shown in Figure 5b,d,f, the carbon densities of saline-alkali land were consistently lower than those of non-saline-alkali land converted from or to saline-alkali land throughout the studied period, and the reduction in carbon density upon converting non-saline-alkali land into saline-alkali land significantly exceeded the increase in carbon density induced by the opposite transformation. Saline-alkali land conversion had a particularly strong effect on carbon density in wetlands: the carbon density of land converted from wetland to saline-alkali land fell by 0.11 kg/m² in 2005–2010 and by up to 0.53 kg/m² in 2010–2015. The overall carbon densities of all land types increased gradually from 2005

to 2020, but two land types stood out: the carbon density of cropland was consistently high, while wetland exhibited the largest increase in carbon density.

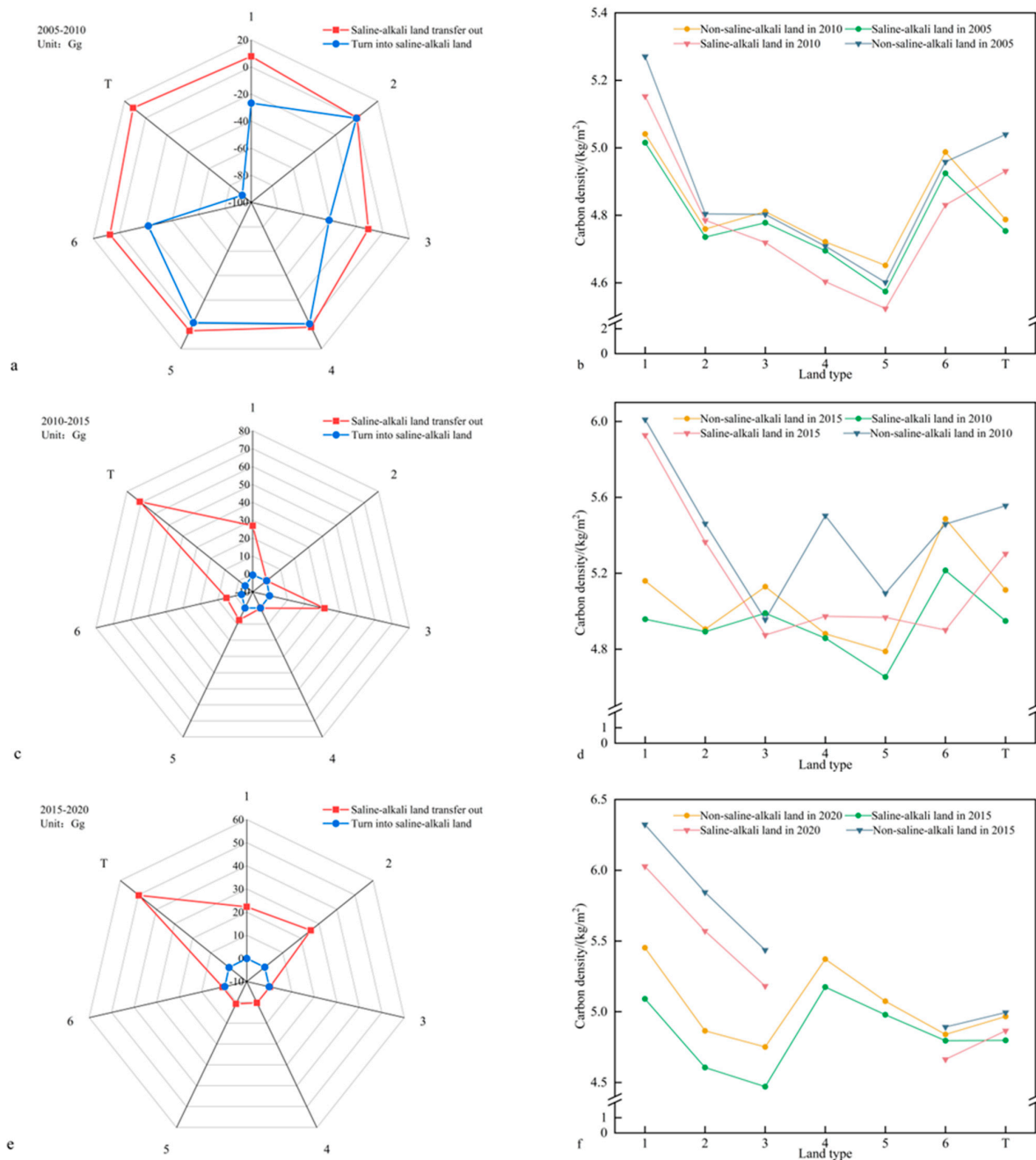


Figure 5. Changes in carbon stocks and carbon density due to conversion of saline-alkali and non-saline-alkali land. In the figure, (a,c,e) represent the changes in carbon stocks after the conversion of saline-alkali and non-saline-alkali land; (b,d,f) represent the comparison of carbon density before and after the conversion of saline-alkali and non-saline-alkali land. 1, 2, 3, 4, 5, 6, and T denote cropland, woodland, grassland, wetland, construction land, underutilized land, and all land, respectively.

Upon comparing these results to the carbon stock transfer relationship data shown in Figure 6, it became apparent that the observed increases in the carbon stock were mainly due to the conversion of saline-alkali land into cropland, woodland, and grassland. These three conversion processes increased the overall carbon stock by 57.09 Gg, 25.76 Gg, and 20.50 Gg, respectively. The incremental increases in carbon stock for saline-alkali

land converted into construction land were similar to those for underutilized land, while conversion into wetland produced the smallest increase. In contrast, the largest reductions in carbon stock resulted from the conversion of grassland, cropland, and underutilized land into saline-alkali land; these processes reduced the overall carbon stock by 41.18 Gg, 27.24 Gg, and 25.73 Gg, respectively. Conversion of construction land, woodland, and wetland had a comparatively small effect. Overall, saline-alkali land conversion processes increased the carbon stock within the study area between 2005 and 2020. This increase was largely due to the reclamation of saline-alkali land via conversion into cropland. Reductions in the carbon stock were mainly due to the degradation of cropland and grassland into saline-alkali land.

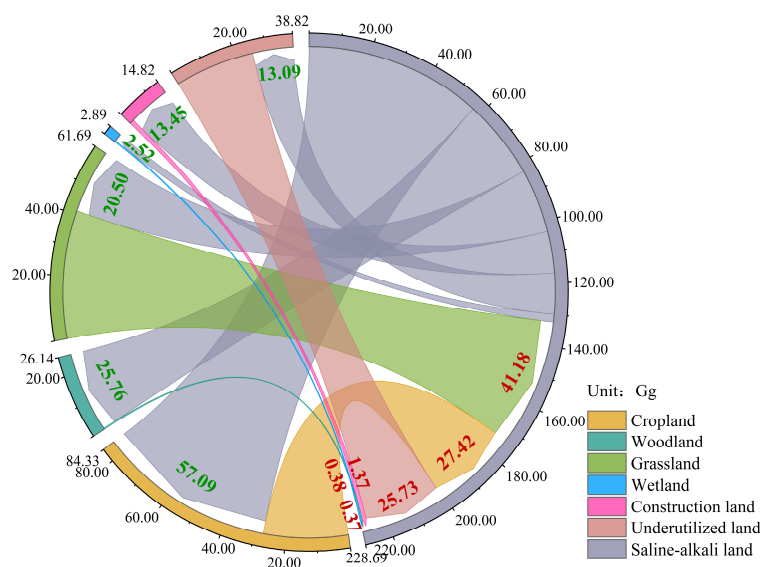


Figure 6. Increases or decreases in carbon stocks due to conversion of saline-alkali to non-saline-alkali land, 2005–2020. In the figure, green labels indicate an increase in carbon stocks and red labels indicate a decrease in carbon stocks.

4. Discussion

4.1. Reliability of Results

The reliability of our analysis depends heavily on the accuracy of the estimates on which it is based. The BK model has been widely used to calculate changes in carbon stocks caused by land use and cover changes [64,65] and can account for the effects of basic ecological processes on carbon stocks. However, it usually treats the carbon density for each land use type as a fixed value. Additionally, it is mathematically complex, with many parameters that have a relatively high degree of uncertainty [66,67]. In contrast, this study used NPP data to estimate the carbon density of vegetation in different time periods. This approach makes the carbon density a dynamic variable and should thus improve the accuracy of the carbon stock estimates. In addition, changes in carbon stocks were calculated using the method recommended by IPCC, which is relatively simple in mathematical terms, requires less input data than the BK model, and gave results similar to those reported by Chang et al. in a study on carbon stocks in the same region [68]. The estimates used in this work are thus reasonable and reliable.

Compared with the results of previous studies, this study found that soil salinization resulted in an overall decreasing trend in soil organic carbon stocks, which is consistent with the findings of Liang et al. and Setia et al. [45,46]. They found a decrease in soil organic carbon in different soil layers with deeper salinization. However, unlike them, this study found that although saline-alkali land leads to a decrease in soil organic carbon stocks, it also leads to some increase in vegetation carbon stocks. This finding was also verified in the findings of Ma et al. This is mainly due to the restoration of surface vegetation [69]. In addition, the conversion process between saline-alkali land and other land use types

is often associated with carbon emissions and carbon sequestration. When other land use types are converted to saline-alkali land, the carbon stock tends to decrease, which is regarded as the process of carbon emission. The degradation of grassland to saline-alkali land resulted in a large decrease in soil organic carbon and soil inorganic carbon as found by Xu et al. [48], a phenomenon that is precisely the process of carbon emission. Previous studies have confirmed that saline-alkali land has some carbon sink capacity [21]. However, the results of our study showed that the carbon sink capacity of saline-alkali land seems to be unstable.

4.2. Carbon Stock Analyses in Saline-Alkali Land

The carbon stock measurements indicate that the changes in the carbon stock of the saline-alkali land on the Songnen Plain from 2005 to 2020 can be divided into distinct phases: growth phases extending from 2005 to 2010 and 2015 to 2020, and a decline phase extending from 2010 to 2015. The region's carbon stock decreased over the studied period as a whole, from 54.75 Tg in 2005 to 54.25 Tg in 2020, in accordance with the findings of Yang et al. [70]. However, it is worth noting that the biological carbon stock of saline-alkali land vegetation declined during the first growth phase, resulting in a decrease in carbon density. The increase in the saline-alkali land carbon stock during this period was thus due to expansion of the area of saline-alkali land and an increased rate of salinization that was accompanied by degradation of surface vegetation and a severe decline in the vegetation carbon stock [71,72]. The implementation of ecological protection and restoration measures in the Songnen Plain caused the area of saline-alkali land to contract from 2010 to 2020, leading to a significant increase in the ecological safety index [52,73]. During this period, the vegetation carbon stock of saline-alkali land increased substantially together with the vegetation carbon density, the soil organic carbon density increased, as well as the quality of carbon sequestration in saline-alkali land. The reduction in the total area of saline-alkali land during this period caused its total carbon stock to decline compared to the preceding phase. However, its carbon density increased, indicating that saline-alkali land has some capacity for carbon sequestration that can be increased through carefully planned land use, making it an important part of the terrestrial carbon sink.

The main reason for the low carbon stock in the saline-alkali land of the Songnen Plain at present is the poor physicochemical properties of its soil, whose structure has been degraded by salinization, reducing its capacity to sequester organic carbon [74]. Hydrogeological and hydrochemical conditions play a major driving role in soil salinization in the Songnen Plain, with the main influencing factors being groundwater salinity, depth to groundwater, surface runoff, and intensity of subsurface runoff. The groundwater depth in the Songnen Plain is low (about 1.5–3 m) and its salinity is high (usually 2–5 g/L, up to 10 g/L), which favors surface aggregation of soil salts, making it difficult for vegetation to grow, which in turn affects the sustained input of organic carbon to the soil [75]. The carbon stock of saline-alkali land therefore tends to be low for extended periods of time [76].

4.3. Impact of Saline-Alkali Land on Land Use Structure

The formation of saline-alkali land is the main cause of land degradation in the Songnen Plain, but saline-alkali land is also an important resource. Before 2010, the land use structure of the Songnen Plain underwent profound changes, with large areas of wetland and grassland being converted into saline-alkali land in a process of degradation and fragmentation [77,78]. Between 2005 and 2010, the areas of grassland and cropland degraded to saline-alkali land were as high as 490.21 km² and 226.11 km², greatly exceeding the area of saline-alkali land that was reclaimed. Moreover, the problems of soil salinization and wetland degradation have continued to worsen since then [79]. However, the Songnen Plain is also an important area of agricultural production in China and will be essential for ensuring the country's food security [80]. This strategic importance has motivated the introduction of policies to control and slow down the continuous expansion of saline-alkali land in the region, resulting in extensive land use transformations [81]. The area of saline-

alkali land began to contract in 2010, and the area degraded to saline-alkali land became much smaller than the area of saline-alkali land that was restored; in 2015, only 4.14 km² and 7.09 km² of grassland and cropland were degraded to saline-alkali land, while the areas of new cropland and grassland reached 133.59 km² and 223.67 km². This shows that remediation and improvement efforts could enable development of the Songnen Plain in a way that will ensure that social needs are met for the foreseeable future.

4.4. Impact of Saline-Alkali Land on Terrestrial Carbon Stock Balance

The measurements obtained in this work indicate that the conversion of saline-alkali land and non-saline-alkali land in the Songnen Plain significantly affected its overall carbon stock. The conversion of non-saline-alkali land into saline-alkali land caused a decline in the carbon stock, making this conversion a carbon-emitting process that directly causes the release of sequestered organic carbon from the soil and a significant reduction in surface vegetation carbon [82]. The degradation of non-saline-alkali land into saline-alkali land over the past 50 years has largely been driven by land use changes related to the agricultural sector, notably the rapid development of animal husbandry and the resulting increase in grazing pressure [72,83]. Dong et al. reported that the carbon uptake and soil evapotranspiration rates of saline-alkali land were 43% and 32.1% lower, respectively, than those of pre-degraded grassland, which is consistent with the results presented here [84]. The carbon density in areas converted into saline-alkali land within the Songnen Plain (Figure 7) between 2005 and 2020 was always lower than in non-saline-alkali land. The largest loss of carbon density following conversion to saline-alkali land was observed for underutilized land, whose carbon density fell by 0.21 kg/m² following conversion. This may be related to an increase in the land's water table following conversion, which would trigger the release of large amounts of sequestered soil organic carbon [85]. In relation to Figure 5, it is notable that the carbon density changes caused by conversion between saline-alkali land and non-saline-alkali land in the same region during the same period of time all showed a uniform pattern: the lower limit of the carbon density was equal to the carbon density of saline-alkali land before conversion, while the upper limit was equal to the carbon density of non-saline-alkali land before conversion.

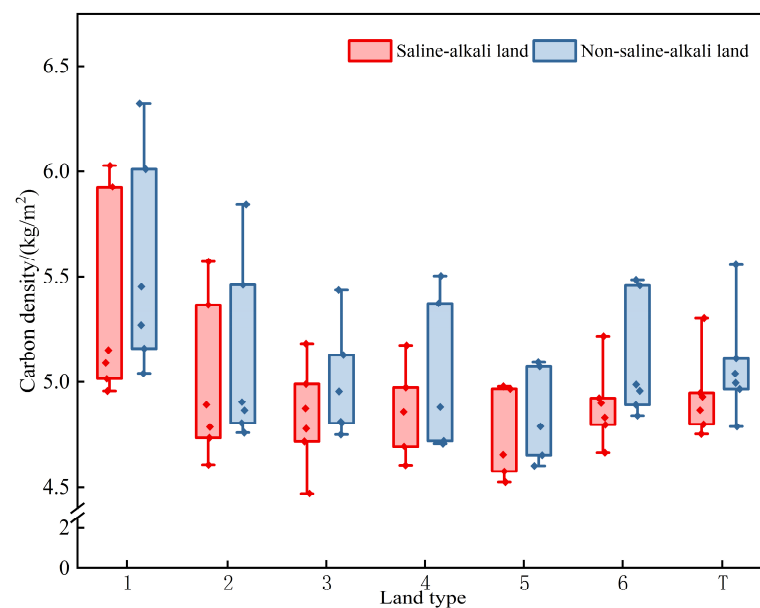


Figure 7. Comparison of carbon density before and after conversion of non-saline-alkali to saline-alkali land. The labels 1, 2, 3, 4, 5, 6, and T denote cropland, woodland, grassland, wetland, construction land, underutilized land, and total land, respectively.

Saline-alkali land contributes to the capture of CO₂ from the atmosphere by soil and can therefore be seen as a carbon sink [21]. In addition, CO₂ from soil respiration dissolves in saline-alkali soil solutions and is transported into underground aquifers, forming a hidden carbon sink [86,87]. However, the results presented here suggest that these carbon sinks in saline-alkali land are unstable. The carbon stock in the saline-alkali land of the Songnen Plain fluctuated markedly between 2005 and 2020, and its carbon sink capacity peaked as a result of expansion of the saline-alkali land area rather than any increase in its carbon density or sequestration capacity. Additionally, the impact of changes in the saline-alkali land carbon stock on the overall terrestrial carbon stock remains unclear. Our data (Table 1) show that the overall carbon stock in the Songnen Plain fell by 0.63% from 2005 to 2010 but the carbon stock in saline-alkali land increased by 1.08% (equivalent to an increase of 0.06% in the region's overall carbon stock) during this period. The change in the saline-alkali carbon stock thus did not significantly affect the overall terrestrial carbon stock. Conversely, between 2010 and 2015, the terrestrial carbon stock in the Songnen Plain increased by 0.39% but that of the region's saline-alkali land declined by 2.22% (equivalent to 0.12% of the overall carbon stock). The changes in the carbon stock of saline-alkali land were thus opposed to those of the region as a whole. The contribution of saline-alkali land to the 2.33% increase in carbon stock in the Songnen Plain from 2015 to 2020 is only 0.01%, indicating a small positive effect. These results clearly show that saline-alkali land can act as a carbon sink but is not an isolated system and in general an increase in the carbon sink capacity of saline-alkali land reduces the region's overall terrestrial carbon stock.

Table 1. Contribution of saline-alkali land to the terrestrial carbon stock between 2005 and 2020.

		Beginning		Ending		Carbon Stock Rate of Change	Contribution
		Stock/Tg	Density/(kg/m ²)	Stock/Tg	Density/(kg/m ²)		
2005–2010	Total carbon stock	1006.03	5.74	999.66	5.70	−0.63%	0.06%
	Saline carbon stock	54.75	4.75	55.35	4.75	1.08%	
2010–2015	Total carbon stock	999.66	5.70	1003.56	5.73	0.39%	−0.12%
	Saline carbon stock	55.35	4.75	54.12	4.84	−2.22%	
2015–2020	Total carbon stock	1003.56	5.73	1026.90	5.86	2.33%	0.01%
	Saline carbon stock	54.12	4.84	54.26	4.93	0.26%	
2005–2020	Total carbon stock	1006.03	5.74	1026.90	5.86	2.07%	−0.05%
	Saline carbon stock	54.75	4.75	54.26	4.93	−0.90%	

4.5. Implications for Land Management and Carbon Sequestration

From the above analyses, it can be seen that the transformation of saline-alkali land to other land use types is usually accompanied by the process of carbon emission and carbon sequestration. Therefore, the rational adjustment and control of the land use structure and conversion process is an important factor to ensure the stable increase in terrestrial carbon stocks [88,89]. Our results showed that the process of transformation of saline-alkali land to other land use types can be considered as carbon sequestration, so how to effectively increase this process of carbon sequestration becomes the key to increase terrestrial carbon stock. Combined with the actual situation of the Songnen Plain, the Songnen Plain performs important functions of food production and ecological protection in China [79]. As an important land reserve resource [72], saline-alkali land should be developed based on a comprehensive consideration of the degree of soil salinization and the feasibility of improvement measures. Moderate development of saline-alkali land into cropland and grassland can meet the needs of food production and ecological protection in the Songnen Plain, and also promote the improvement of terrestrial carbon stock.

In addition, while increasing carbon sequestration capacity, consideration should also be given to reducing carbon emissions. Reducing carbon emissions mainly involves two aspects: first, limiting the conversion of other land use types into saline-alkali land, and second, strengthening the management of saline-alkali land to prevent the deepening of salinization. In the Songnen Plain, the main land use types converted to saline-alkali land

are grassland and wetland [72]. Ecological protection and restoration is an important tool to effectively curb conversion. Ecological protection measures implemented in the Songnen Plain from 2010 to 2020 have significantly contributed to the enhancement of terrestrial carbon stocks [52]. Existing grassland and wetland have been effectively protected, and the expansion of saline-alkali land has been prevented [90]. Second, soil salinization in saline-alkali land can be effectively mitigated and improved through soil improvement, water conservation, and planting salt-tolerant crops. This has a significant impact on reducing carbon emissions from salinization.

4.6. Uncertainties

This study analyzed changes in the carbon stock resulting from the interconversion of saline-alkali and non-saline-alkali land as well as the effect of saline-alkali land on the overall terrestrial carbon stock. Its findings have practical significance, but the analysis has some limitations that should be noted. The first is that although NPP data were used to analyze the dynamics of the vegetation carbon density in the study area (thereby avoiding the limiting assumption of static carbon density made in the BK model), the organic carbon density of different soil types was assumed to remain constant over time, which may reduce the accuracy of the results. Second, the terrestrial carbon stock is a dynamic quantity that is constantly changing, but this study only estimated the terrestrial carbon stock at specific points in time within specific land use types. While this approach may capture general trends in the carbon stock of the study area, it cannot accurately determine the timing of specific carbon stock transitions.

Therefore, future research should further improve the dynamics of the data, and carbon density data, especially soil organic carbon data, should be obtained over several time periods using methods such as field sampling or model predictions. This will help to further improve the accuracy of carbon stock estimates. In addition, changes in terrestrial carbon stocks are not only related to land use changes, but climate change is also one of the important factors affecting terrestrial carbon stocks. Therefore, future research should incorporate climate factors into the process of measuring terrestrial carbon stocks and fully consider the forcing effect of climate change on carbon stocks.

5. Conclusions and Policy Proposals

By assessing the saline carbon stock in Songnen Plain from 2005 to 2020, we verified the hypotheses of this study. Firstly, the saline-alkali land carbon stock showed fluctuating changes, but the overall decrease was dominated. Second, the change of saline-alkali land carbon stock has a positive effect on terrestrial carbon stock, but the effect is weak and still dominated by a negative effect. The specific conclusions are as follows. Over the study period as a whole, the saline-alkali land carbon stock decreased by 0.5 Tg. During periods when the carbon stock of saline-alkali land increased, this increase was primarily due to an increase in the total area of saline-alkali land. By the end of the study period, the average carbon density of saline-alkali land was considerably higher than it had been to begin with, largely as a result of ecological restoration efforts and other activities. Our results also show that the conversion of non-saline-alkali land into saline-alkali land is a carbon-emitting process and the conversion of grassland and cropland into saline-alkali land is a major cause of carbon stock reduction. In regions where saline-alkali land conversion occurred, the lower limit of the carbon density over the studied period was equal to the carbon density of land that began as saline-alkali land whereas the upper carbon density limit was equal to the carbon density of land that began as non-saline-alkali land. Although saline-alkali land is an important part of the overall terrestrial carbon sink, its potential for carbon sequestration remains to be developed, and changes in the carbon stock of saline-alkali land correlated negatively with changes in the overall terrestrial carbon stock in the Songnen Plain over the study period as a whole. While this trend was reversed in sites where late-stage conservation measures are being implemented, the resulting positive effect was too weak to overturn the prevailing negative correlation.

Saline-alkali land is a widely distributed and important land resource within the Songnen Plain. The results presented here show that ecological restoration measures implemented in the study area have significantly increased the carbon stock of saline-alkali land. Moreover, grassland and cropland are the land use types that are most frequently converted to saline-alkali land. Therefore, in combination with the lower carbon density of saline-alkali land, improving saline-alkali land into grassland and cropland has a positive effect on increasing the terrestrial carbon stock in the Songnen Plain. Specifically (following the principle of proximity), on the one hand, the saline-alkali land around the grassland can be improved with biochar to improve the poor physical and chemical properties of saline-alkali soils, and then plant saline-tolerant crops (e.g., *Leymus chinensis*) to improve the overall environmental conditions of the saline-alkali land, and to further realize the benign cycle of saline-alkali land ecosystems. On the other hand, for saline-alkali land in good condition around cropland, it is possible to build a high-quality arable layer and promote the cultivation of saline-alkali-tolerant grain and oil crops such as dry-alkali wheat, seawater rice, sunflower, soybeans, and sorghum, through the implementation of soil fertilization and improvement projects. The implementation of the saline-alkali land improvement policy mentioned above will not only effectively increase terrestrial carbon stocks, but also meet the needs of food production and ecological protection in the Songnen Plain.

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