Effects of Biochar Application on Soil Water-Heat-Salt and Cotton Growth in Brackish Water Drip-Irrigated Cotton Fields: Postprint

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Abstract

To address the problems of freshwater shortage and declining soil quality in northern Xinjiang, a field experiment was conducted to investigate the effects of different irrigation salinity levels and biochar application rates on the soil water-heat-salt environment and cotton growth in cotton fields. Four biochar application levels (B0: 0 $t \cdot hm^{-2}$, B1: 20 $t \cdot hm^{-2}$, B2: 40 $t \cdot hm^{-2}$, B3: 60 $t \cdot hm^{-2}$) and three irrigation salinity levels (S1: 1 $g \cdot L^{-1}$, S2: 3 $g \cdot L^{-1}$, S3: 5 $g \cdot L^{-1}$) were established using a two-factor completely randomized combination experiment to study the effects of different treatments on soil water-salt-temperature distribution, cotton growth indicators, dry matter accumulation, yield, and water use efficiency. The results showed that both biochar application and increased irrigation salinity elevated soil moisture content and salt content. Increased biochar application rate raised the average soil temperature, with an increase ranging from 5.9% to 15.1%. Irrigation salinity had a significant effect on average soil temperature, but differences among treatments were not significant. Biochar application improved cotton plant height, leaf area index, and above-ground dry matter. The maximum seed cotton yield and water use efficiency both occurred in the B2S2 treatment, at 6526.4 $kg \cdot hm^{-2}$ and 2.01 $kg \cdot hm^{-2}$, respectively. The minimum values both appeared in the B0S3 treatment, decreasing by 18.50% and 26.87% compared with the B2S2 treatment, respectively. Multiple regression equations were constructed based on high cotton yield and high water use efficiency. Combined with normalization processing and spatial analysis, the optimal biochar application rate and irrigation salinity range were determined to be 26–46 $t \cdot hm^{-2}$ and 2.45–3.04 $g \cdot L^{-1}$, respectively.

Full Text

Effects of Biochar Application on Soil Hydrothermal Conditions, Salinity, and Cotton Growth in Brackish Water Drip-Irrigated Cotton Fields

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Abstract: To address the challenges of fresh water shortage and soil quality decline in northern Xinjiang, a field experiment was conducted to investigate the effects of different irrigation water salinity levels and biochar application rates on the soil hydrothermal-salinity environment and cotton growth in cotton fields. Four biochar application levels (0 t · hm^{-2}, 20 t · hm^{-2}, 40 t · hm^{-2}, and 60 t · hm^{-2}) and three irrigation water salinity levels (1 g · L^{-1}, 3 g · L^{-1}, and 5 g · L^{-1}) were established using a two-factor completely randomized design to examine their effects on soil water-salt-temperature distribution, cotton growth indicators, dry matter accumulation, yield, and water use efficiency. The results demonstrated that both increased biochar application and irrigation water salinity elevated soil water content and salinity. Higher biochar application rates increased average soil temperature by 5.9%-15.1%, while irrigation water salinity significantly affected average soil temperature, though differences among treatments were not significant. Biochar application enhanced cotton plant height, leaf area index, and aboveground dry matter. Maximum seed cotton yield (6526.4 kg · hm^{-2}) and water use efficiency (2.01 kg · hm^{-3}) both occurred in the 40 t · hm^{-2} biochar + 3 g · L^{-1} salinity treatment, while minimum values appeared in the 0 t · hm^{-2} biochar + 5 g · L^{-1} salinity treatment, representing reductions of 18.50% and 26.87%, respectively. Multiple regression equations were constructed, and based on high yield and water use efficiency combined with normalization and spatial analysis, the optimal biochar application rate and irrigation water salinity range were determined to be 26–46 t · hm^{-2} and 2.45–3.04 g · L^{-1}, respectively.

Keywords: biochar application rate; brackish water salinity; cotton growth; yield; multivariate regression analysis

Introduction

Xinjiang' s total water consumption reaches 565.38$\times10^{8}$ m^3, with irrigation water accounting for 527.68$\times10^{8}$ m^3, consuming vast freshwater resources and comprising 93.3% of the total water usage. To alleviate pressure on freshwater resources, brackish water irrigation has become an inevitable trend. Research indicates that brackish water irrigation can save 50%–67% of freshwater resources [1,2]. However, long-term brackish water use causes secondary salinization, leading to unstable soil structure, surface crusting, reduced permeability, and adverse effects on sustainable land use [3]. Simultaneously, excessive soil salinity reduces soil solution osmotic potential, inhibits root water uptake and crop growth, causes ion toxicity and nutrient imbalance, and affects normal crop metabolism. Studies have found that salt stress inhibits crop growth, accelerates senescence, reduces carbon assimilation accumulation, and decreases yield [4]. Therefore, improving soil quality and promoting stable, high crop yields while applying brackish water irrigation are crucial for Xinjiang' s agricultural development.

Biochar application can effectively reduce soil bulk density, improve acidic soils, and enhance soil aeration and water permeability [5]; it promotes nutrient uptake by plants under saline stress, improves leaf gas exchange systems, enhances photosynthetic capacity [6], and thereby stimulates crop growth. Huang et al. [7] found that applying biochar under brackish water irrigation significantly increased soil organic matter content, promoted corn root growth, and improved yield. Usman et al. [8] demonstrated that biochar under saline irrigation alleviated adverse effects of salt stress on soil productivity and increased tomato yield. Appropriate biochar application promotes crop growth and increases yield, but excessive application can be detrimental. Chen et al. [9] found that applying 20 $t \cdot hm^{-2}$ fruitwood biochar increased rice yield by 15.16%, while Jiang et al. [10] observed that sugar orange yield first increased then decreased with increasing biochar application rates.

Recent research on brackish water and biochar has primarily focused on the effects of brackish water irrigation or single biochar application rates on crop growth and soil physicochemical properties, lacking studies on the synergistic effects of brackish water irrigation and biochar application on soil hydrothermal-salinity regulation and crop growth under field conditions. Considering the prominent issues of abundant brackish water resources and declining farmland soil fertility in northern Xinjiang, this study addresses the key scientific question of "responses of drip-irrigated cotton field soil hydrothermal-salinity environment and cotton growth to the coupling effects of brackish water irrigation and biochar application." The experiment combined irrigation water salinity and biochar application rates to analyze their synergistic effects on soil water-salt distribution, soil temperature, cotton growth indicators, yield, and water use efficiency, aiming to identify optimal combinations for cotton fields in northern Xinjiang and provide technical guidance for brackish water irrigation and theoretical support for improving soil quality and promoting sustainable agricultural development.

1.1 Study Area Overview

The experiment was conducted at the Modern Water-Saving Irrigation Key Laboratory of Xinjiang Production and Construction Corps and Shihezi University Water-Saving Irrigation Experimental Station (86°03 47 E, 44°18 28 N, altitude

450 m). The region has a typical temperate continental climate. Daily temperature and precipitation during the 2022 cotton growing period are shown in [Figure 1: see original paper]. Annual sunshine duration, average precipitation, and evaporation are 2865 h, 207 mm, and 1660 mm, respectively. The test soil is loam, with physicochemical properties of the 0–100 cm soil layer presented in .

1.2 Experimental Design

The cotton variety "Xinluzao 61" was used. Based on production practices and previous research [11,12], three irrigation water salinity levels were established: 1 $g \cdot L^{-1}$ (S1), 3 $g \cdot L^{-1}$ (S2), and 5 $g \cdot L^{-1}$ (S3), achieved by mixing local irrigation water with industrial salt (main component: NaCl $\geq$ 99.1%). Four biochar application levels were set: 0 $t \cdot hm^{-2}$ (B0), 20 $t \cdot hm^{-2}$ (B1), 40 $t \cdot hm^{-2}$ (B2), and 60 $t \cdot hm^{-2}$ (B3), with B0 as the control. This created 12 treatments with three replications each, totaling 36 plots. Each plot measured 5 m $\times$ 3 m, with protective rows and 0.5 m-wide isolation strips between adjacent plots to prevent cross-effects from biochar.

Biochar was applied on October 15, 2021, by manual spreading followed by mechanical uniform tillage into the 0–40 cm soil layer. The biochar was cotton straw biochar with a bulk density of 0.4 $g \cdot cm^{-3}$, total carbon content of 71.6%, thermal conductivity of 0.172 $W \cdot m^{-1} \cdot K^{-1}$, specific surface area of 82.7 $m^2 \cdot g^{-1}$, pH of 9.37, and ash content of 16.50%.

Following local farmer planting patterns, a machine-harvested cotton mulching mode was adopted [Figure 2: see original paper]. Film width was 2.05 m, drip tape spacing was 76 cm, and emitter spacing was 30 cm. Independent water storage tanks controlled irrigation salinity for each treatment. Cotton was sown on April 25, 2022, and harvested on October 14, with a total growth period of 172 days. The irrigation schedule was determined based on previous research on drip-irrigated cotton under mulch in northern Xinjiang [13], as detailed in . Other agronomic measures followed local farmer practices.

1.3 Measurement Indicators

1.3.1 Soil Water Content Soil samples were collected before sowing and at the seedling, budding, flowering-boll, boll-opening, and post-harvest stages using a soil auger between the middle cotton row and drip tape [Figure 2: see original paper]. The 0–100 cm soil layer was sampled at 10 cm intervals. Soil water content was measured using the oven-drying method.

1.3.2 Soil Salinity Sampling times, methods, and locations matched those for soil water content. After oven-drying, soil electrical conductivity was measured using a conductivity meter (digital display, Shanghai Leici), and salt content was calculated as follows [14]:

$$y = 0.0712x + 0.5768$$

where y is salt content ($g \cdot kg^{-1}$) and x is electrical conductivity ($S \cdot cm^{-1}$).

1.3.3 Soil Temperature After seedling establishment, soil temperature dynamic collection systems (Handan Chuangmeng Electronics Technology) were buried at 10 cm, 20 cm, 30 cm, and 40 cm depths at 10 cm from the middle cotton row on the film at the end of each growth stage [Figure 2: see original paper] to monitor 0–40 cm soil temperature.

1.3.4 Plant Height and Leaf Area Index Five uniformly growing plants were marked in each plot, and their height and leaf area index (LAI) were measured at the end of each growth stage. LAI was calculated as [15]:

$$\mathrm{LAI} = 0.84 \times \rho \times \sum_{i=1}^{j} (L_i \times B_i)$$

where LAI is leaf area index (conversion coefficient 0.84), ρ is cotton planting density ($\text{plants} \cdot m^{-2}$), i is the ith leaf per plant, j is total leaf number per plant, and L and B are leaf length and width (cm), respectively.

1.3.5 Aboveground Dry Matter Accumulation Three representative plants were selected from each plot. At the end of the flowering-boll stage, stems, leaves, buds (bolls), and other organs were separated and oven-dried at 105°C for 30 minutes, then at 75°C to constant weight to measure dry matter mass of each organ.

1.3.6 Cotton Yield, Yield Components, and Water Use Efficiency After complete boll opening, two 2 m^2 uniformly growing plots were selected in each plot for actual yield measurement and conversion to standard yield. Five representative plants were randomly chosen to measure bolls per plant and 30 bolls were collected for hundred-boll weight measurement. Crop water consumption (ET) was calculated as [16]:

$$\mathrm{ET} = W + \mathrm{Pr} + I + V - D - R$$

where ET is crop water consumption (mm), W is soil water storage change (mm), Pr is effective precipitation (mm), I is irrigation amount (mm), and V, D, R are groundwater recharge, deep percolation, and runoff (mm), respectively. The experimental area is flat with low rainfall and strong evaporation, so D and R are negligible; groundwater depth exceeded 5 m, so V is ignored. Water use efficiency (WUE) was calculated as [17]:

$$\mathrm{WUE} = \frac{Y}{\mathrm{ET}} \times 0.1$$

where WUE is water use efficiency ($kg \cdot m^{-3}$) and Y is seed cotton yield ($kg \cdot hm^{-2}$).

1.4 Data Processing and Analysis Methods

Data were organized and calculated using Excel 2016. SPSS 26.0 was used for variance analysis, significance testing, and regression analysis. Origin 2021 was used for statistical analysis and figure creation.

2 Results and Analysis

2.1 Effects of Biochar Application and Brackish Water Drip Irrigation on Soil Water-Salt Distribution

Soil water content distribution across 0–100 cm layers under different treatments is shown in [Figure 3: see original paper]. During all growth stages, soil water content decreased with increasing soil depth. From seedling to budding stages, under the same biochar application rate, mean water content in 0–40 cm layers showed B3 > B2 > B1 > B0, with B1, B2, and B3 increasing by 7.5%–22.5% and 12.9%–33.3% compared to B0. No significant differences were observed among salinity treatments during these stages.

At the flowering-boll stage, under the same biochar application rate, S2 and S3 treatments increased 0–40 cm soil water content by 2.1%–13.1% and 2.1%–15.7% compared to S1, respectively, while no significant differences were found in 40–100 cm layers. This indicates that irrigation salinity increased soil water content, possibly because increased Na^+ causes soil particle swelling and reduced permeability, facilitating water infiltration to middle layers [18]. Under the same salinity level, biochar treatments showed higher water content than B0 in 0–50 cm layers, with B2 achieving maximum values, demonstrating that biochar application improved soil water retention. At the boll-opening stage, B2 increased 0–30 cm water content by 2.7%–9.3% and 12.0%–17.3% compared to B0, with no significant differences in other layers.

Soil salinity distribution across 0–100 cm layers under different treatments is shown in [Figure 4: see original paper]. During the seedling stage, no significant differences existed among treatments. From budding to boll-opening stages, under the same biochar application rate, soil salinity increased with irrigation salinity. At budding stage, S2 and S3 treatments increased 0–40 cm salinity by 11.6%–12.9% and 14.1%–22.2% compared to S1, respectively, while biochar treatments increased salinity by 2.4%–14.2% compared to B0. From flowering-boll to boll-opening stages, both biochar application and salinity significantly affected soil salinity ($P < 0.05$). At flowering-boll stage, S2 and S3 increased 0–40 cm salinity by 24.1%–61.3% compared to S1. Under the same salinity, biochar treatments showed higher 0–40 cm salinity than B0 by 14.7%–32.7%, indicating that biochar increased soil salinity, likely due to its inherent salt content and strong adsorption capacity [19]. Different salinity treatments showed decreasing salinity with depth, with higher salt content in shallow layers (0–40 cm) because: (1) brackish water irrigation introduced salts, and (2) limited single irrigation amounts and strong evaporation caused upward salt movement via capillary action, accumulating salts in surface layers [20].

2.2 Effects of Biochar Application and Brackish Water Drip Irrigation on Average Soil Temperature in 0–40 cm Layer

Average soil temperature in the 0–40 cm layer during the growth period first increased then decreased [Figure 5: see original paper]. At seedling stage, biochar significantly increased soil temperature, with B1, B2, and B3 increasing by 2.1%–4.3% and 7.8%–11.5% compared to B0, while salinity effects were not significant. At budding stage, soil temperature peaked; under the same salinity, B2 and B3 significantly increased average temperature by 2.98°C and 1.37–2.66°C compared to B0, respectively. At flowering-boll stage, B1, B2, and B3 increased temperature by 1.61–3.52°C, 0.23–2.66°C, and 0.79°C compared to B0, respectively, while salinity effects remained non-significant. At boll-opening stage, B1, B2, and B3 increased temperature by 0.08–0.21°C and 0.06–0.31°C. Both biochar and salinity showed extremely significant interactive effects on soil temperature ($P < 0.01$). Biochar demonstrated good warming effects during cotton growth, while different salinity levels affected soil temperature without significant differences.

2.3 Effects of Biochar Application and Brackish Water Drip Irrigation on Cotton Plant Height and Leaf Area Index

Effects of different treatments on cotton plant height and leaf area index are shown in [Figure 6: see original paper]. No significant differences existed among treatments at seedling stage. At budding stage, S2 significantly increased plant height by 1.2%–12.4% compared to S1 ($P < 0.05$), while leaf area index showed no significant differences. Compared to B0, biochar treatments significantly increased plant height by 11.2%–43.2% ($P < 0.05$) and leaf area index by 0.9%–12.4%, though differences were not significant. From flowering-boll to boll-opening stages, both biochar and salinity significantly affected plant height ($P < 0.05$) and leaf area index. At flowering-boll stage, suitable salinity promoted plant height and leaf area index, but excessive salinity inhibited them; S2 increased plant height and leaf area index by 2.0%–4.0% and 1.8%–9.2% compared to S1, while S3 decreased them by 2.5%–5.7% and 0.6%–17.3%, respectively. Compared to B0, biochar increased plant height by 2.8%–20.3% and leaf area index by 1.2%–5.7%. Biochar application helped improve cotton plant height and leaf area index.

2.4 Effects of Biochar Application and Brackish Water Drip Irrigation on Aboveground Dry Matter Mass

Flowering-boll stage is critical for aboveground dry matter accumulation. Effects on stem, bud, leaf, and total aboveground dry matter are shown in [Figure 7: see original paper]. Under the same biochar rate, S2 increased stem, bud, leaf, and total dry matter by 2.9%–14.2%, 5.7%–43.5%, 5.2%–15.7%, and 5.9%–12.6% compared to S1, respectively, while S3 decreased them by 0.4%–16.2%, 7.8%–10.1%, 2.7%–13.5%, and 0.6%–17.3%. Under the same salinity, biochar treatments increased these parameters by 7.5%–25.2%, 6.7%–44.1%, 5.7%–43.5%, and 6.0%-45.9% compared to B0, respectively. Both biochar and salinity had extremely significant effects on stem, bud, leaf, and total dry matter ($P < 0.01$), with extremely significant interactive effects on bud dry matter ($P < 0.01$). Maximum values occurred in the B2S2 treatment. Biochar significantly promoted aboveground dry matter accumulation.

2.5 Effects of Biochar Application and Brackish Water Drip Irrigation on Cotton Yield, Yield Components, and Water Use Efficiency

Effects on cotton yield, yield components, and water use efficiency are shown in . Appropriate salinity and biochar application increased bolls per plant and boll weight, thereby improving yield and water use efficiency. Under the same biochar rate, increasing salinity first increased then decreased yield and water use efficiency. Compared to S1, S2 increased yield by 4.2%-12.8% and water use efficiency by 2.8%-14.4%, while S3 decreased yield by 4.5%-8.6% and water use efficiency by 0.1%-16.2%. Compared to B0, biochar significantly increased yield by 2.9%-8.3% ($P < 0.05$), bolls per plant by 1.7%-11.5%, and boll weight by 2.6%-10.6%, while reducing water consumption by 2.8%-14.4% and increasing water use efficiency by 4.2%-12.8% ($P < 0.01$). The B2S2 treatment achieved the highest water use efficiency (2.01 $kg \cdot m^{-3}$), while B0S3 showed the lowest (1.47 $kg \cdot m^{-3}$). Both factors had extremely significant interactive effects on water use efficiency ($P < 0.01$).

2.6 Analysis of Optimal Biochar Application Rate and Irrigation Salinity

Using biochar application rate and irrigation salinity as independent variables and cotton yield and water use efficiency as dependent variables, quadratic regression equations were constructed. Nonlinear regression analysis showed both factors had extremely significant effects on each dependent variable ($P < 0.01$) with high coefficients of determination. Since yield and water use efficiency could not simultaneously reach maximum values and had different dimensions, normalization was performed for evaluation. [Figure 8: see original paper] shows relative values of each indicator. The overlapping region of relative value $ 0.96forbothyieldandwateruseefficiencywasdeemedacceptable.Projectingthecontourlinesofrelativevalue0. biocharapplicationof26–46t · hm^{-2}$ and irrigation salinity of 2.45–3.04 $g \cdot L^{-1}$ [Figure 9: see original paper].

3 Discussion

3.1 Effects of Biochar Application and Brackish Water Drip Irrigation on Soil Water-Salt Distribution

Soil water-salt changes reflect the crop growth environment and evapotranspiration water consumption. Soil water carries salts that move continuously, following the principle of "coming with water, leaving with water." This study showed that soil water content increased with irrigation salinity, consistent with Wu et al. [21], because brackish water irrigation improved soil porosity and water-holding capacity, while increased soil salinity indirectly inhibited root water uptake, raising soil water content [22]. Zhao et al. [23] found biochar reduced infiltration and increased water content, matching our results. Biochar altered soil pore distribution, reducing water percolation and horizontal migration, thereby improving water storage [24]. Biochar application increased 0–40 cm salinity, similar to Wu et al. [19], because biochar contains soluble salts that increase with application rate [25]. Salinity decreased with depth, with higher salt accumulation in shallow layers due to: (1) salt input from brackish water, and (2) upward salt movement via capillary action under strong evaporation [20].

3.2 Effects of Biochar Application and Brackish Water Drip Irrigation on Soil Temperature

All life activities in soil involve heat absorption and release, with soil temperature directly affecting microbial activity. This study found that under the same biochar rate, irrigation salinity significantly affected soil temperature during the growth period, but differences were not significant, similar to Li et al. [26] and Zhang et al. [27], because increased salinity inhibited plant height, reduced ground cover, and allowed direct solar radiation to the soil surface, increasing temperature. Li et al. [28] found that average soil temperature in 10–40 cm layers increased with biochar application, consistent with our results. Biochar' s black color absorbs various wavelengths of light, especially ultraviolet and visible light [29], and its complex porous structure provides favorable habitats for microbial reproduction, releasing substantial heat [30] and raising soil temperature. Additionally, increased soil water content from biochar enlarged soil heat flux and reduced temperature decline rate [31], maintaining higher soil temperature for cotton growth.

3.3 Effects of Biochar Application and Brackish Water Drip Irrigation on Cotton Growth

Plant height, leaf area index, and dry matter accumulation are important indicators of cotton growth and population structure. This study found that the 3 $g \cdot L^{-1}$ salinity treatment produced higher plant height, leaf area index, and aboveground dry matter than freshwater treatment, consistent with Song et al. [32], who found that salinity $<4.0\ g \cdot L^{-1}$ promoted dry matter accumulation, as appropriate salt concentrations provide essential micronutrients for cotton roots [33]. However, high salinity (5 $g \cdot L^{-1}$) inhibited normal growth, reducing plant height, leaf area index, and dry matter, consistent with Guo et al. [34], because excessive salinity caused osmotic pressure imbalance [35] and reduced root water uptake. Biochar application significantly promoted cotton plant height, leaf area index, and aboveground dry matter, similar to Li et al. [36] on cotton, wheat, and bermudagrass. Biochar' s unique structure benefits microbial survival, enhances soil ecosystem function, and improves soil nutrient availability [37], positively affecting cotton growth.

3.4 Effects of Biochar Application and Brackish Water Drip Irrigation on Cotton Yield and Water Use Efficiency

Different salinity levels and biochar application affect cotton growth, ultimately reflecting in yield and water use efficiency. This study found that yield and water use efficiency first increased then decreased with salinity, consistent with Li et al. [38], who reported that appropriate salinity promoted nutrient transfer from vegetative to reproductive organs [39]. However, Guo et al. [40] found no significant difference between low salinity and freshwater treatments, possibly due to regional climate and soil type differences. Under the same salinity, cotton yield and water use efficiency first increased then decreased with biochar rate, peaking at B2, likely because appropriate biochar facilitated nutrient and water uptake, promoting growth and yield [41], while excessive biochar disrupted soil structure and nutrient balance [42], reducing yield. This study' s optimal ranges based on one-year data require further field validation.

4 Conclusion

1) Both biochar application and increased irrigation salinity raised soil water content and salinity, with maximum increases of 15.7% and 61.3%, respectively. Salinity of 5 $g \cdot L^{-1}$ increased salt content and affected root water uptake. Both factors had extremely significant effects on soil temperature ($P < 0.01$), with 40-60 $t \cdot hm^{-2}$ biochar producing maximum warming of 12.0%-15.1%. Different salinity levels affected soil temperature without significant differences.

2) Coupled biochar application and appropriate salinity promoted cotton growth, increasing plant height, leaf area index, and aboveground dry matter, thereby improving yield and water use efficiency. Increased salinity caused yield and water use efficiency to first increase then decrease. Biochar significantly increased yield and water use efficiency by 2.9%-8.3% and 2.8%-14.4%, respectively.

3) Multiple regression equations were constructed. Based on high yield and water use efficiency combined with normalization and spatial analysis, the optimal biochar application rate and irrigation salinity range were 26-46 $t \cdot hm^{-2}$ and 2.45-3.04 $g \cdot L^{-1}$, respectively.

Therefore, for northern Xinjiang, to promote cotton yield increase and soil quality improvement, the recommended combination is biochar application of 40 $t \cdot hm^{-2}$ with irrigation salinity of 3 $g \cdot L^{-1}$, providing theoretical basis and technical guidance for sustainable agricultural development in the region.

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Note: Figure translations are in progress. See original paper for figures.