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Use of biochar to manage soil salts and water: Effects and mechanisms

Xinqing Lee[a*], Fang Yang[a], Ying Xing[a], Yimin Huang[a], Liang Xu[b], Zhongtang Liu[c], Ran Holtzman[d], Iddo Kan[e], Yunlong Li[a], Like Zhang[a], Hui Zhou[a]

[a.] State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, Guizhou, China

[b.] The Kashgar Prefecture Meteorological Bureau, Kashgar 844099, Xinjiang Autonomous Region, China

[c.] The Kashgar Prefecture Agricultural Technology Extension Center, Kashgar 844099, Xinjiang Autonomous Region, China

[d.] Fluid and Complex Systems Research Centre, Coventry University, Coventry, CV1 2NL, United Kingdom

[e.] The Robert H. Smith Faculty of Agriculture, Food and Environment, The Hebrew University of Jerusalem, Rehovot 7610001, Israel

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*Corresponding author.

E-mail address: lee@mail.gyig.ac.cn (X. Lee)

Abstract

Soil salinization is a widespread land degradation, especially in water-stressed regions, jeopardizing agriculture sustainability. Current desalinization methodology involves excessive water consumption. Biochar has the potential to mitigate soil salinization while increasing water holding capacity. As a saline and sodic material, however, how it works and whether it can be used to sustain the agriculture at reduced water resource remain to be studied. Here, by monitoring transport of water, salts and nutrients in the profile of irrigation-silt soil during watering and evaporation in both laboratory and field in Kashgar oasis, Xinjiang, China, we find biochar exacerbates salinization upon application. This is changed, however, after several cycles of irrigation-evaporation due to strengthened salt leaching in irrigation and salt removal out of the depth through intensified top accumulation by evaporation, both resulting from increased capillary effect and thereby the enhanced movement of salts despite the competing electrical adsorption to the cations. The resulted salt distribution facilitates desalinization by removing the top 2 cm soil. Biochar also promotes evaporation after irrigation due to inceased water content and capillary suction. This is reversed once the soil cracks, a common phemomenon in irrigated land. Biochar counteracts the cracking through alleviation of soil compaction, saving tillage while lowering water evaporation, e.g., by 43% at 10% biochar. Our findings indicate that application of biochar changes salt distribution, enabling desalinization with little water consumption. Together with the effect of anti-fracturing and enhanced salt leaching, it lowers water demand substantially, providing a novel solution for agricultural sustainability in salt-affected regions.

1. Introduction

Salinisation is one of the major soil degradations (Daliakopoulos et al., 2016; Shao et al., 2019), especially in arid and semiarid regions (Rengasamy, 2006). Globally, it affects about 23% of farmland (Amini et al., 2016). In water-stressed regions such as Xinjiang in western China, and California, USA, the infliction is as high as 40% (Wang et al., 2008) and 50% (Letey, 2000), respectively. Dry climate, high evaporation and irrigation-based agriculture make soil salinization inevitable (Kamphorst and Bolt, 1976). Irrigation introduces soluble salts such as Na^+, Cl^-, SO_4^{2-} and HCO_3^- into the land, these ions are driven up by the strong evaporation through capillary movement of water, accumulating subsequently in the top soil. Due to inadequate leaching that ensues from the dry climate, the accumulation results in undue content of salts in the rhizosphere, especially the top 2 cm soil, making the soil salinized (Rengasamy, 2006). The salinization degrades soil chemical and physical properties (Wongpokhom et al., 2008), as well as carbon availability (Wong et al., 2010) and microbial activities (Wong et al., 2008), as results, reducing soil productivity or even making it barren once the salinity exceeds a certain level (Rengasamy, 2010). Current practice to remove the salts is leaching through excessive watering of the land, such that the accumulated salts are suppressed down or out of the rhizosphere in case of adequate drainage (Amini et al., 2016). The leaching technique is easy to practice and therefore adopted widely. It consumes substantial water resource, however. Due to the global warming, population explosion, urbanization and industrialization in the past decades, agricultural water resource has been dwindled dramatically (Jiang et al., 2005), jeopardizing sustainability of the current methodology. This calls for a new technology to combat soil salinization at reduced water supply.

Biochar, a form of charcoal produced from pyrolysis of biomass waste under limited or no oxygen availability for soil amendment purpose (Lehmann et al., 2006), has the potential to alleviate salinization (Farhangi-Abriz and Torabian, 2017; Lashari et al., 2015; Sadegh-Zadeh et al., 2018; Yue et al., 2016; Zhang et al., 2019) due reportedly to adsorption of salts (Akhtar et al., 2015a; Amini et al., 2016; Lashari et al., 2013; Thomas et al., 2013; Zhang et al., 2019), replacement of Na^+ from the exchangeable site of soil particles (Amini et al., 2016; Sadegh-Zadeh et al., 2018), reduction of the sodium adsorption ratio (Farhangi-Abriz and Ghassemi-Golezani, 2021; Xiao and Meng, 2020), mitigation of the oxidative stress of NaCl (Akhtar et al., 2015b), and reduction of salts in plant seedlings (Zhang et al., 2019). It also improves soil water holding capacity substantially (Allen, 2007; Cheng et al., 2006; Glaser et al., 2002; Jones et al., 2010; Karhu et al., 2011; Laird et al., 2010). These make it possible to desalt the soil at changed water supply. However, biochar is high in both salinity and sodicity (Gundale and DeLuca, 2006; Kloss et al., 2012; Saifullah et al., 2018), especially the one produced from the biomass of arid regions, which can be ~2 and ~25 times that of humid regions in salinity and sodium content, respectively (Yang et al., 2015), and the increased water holding capacity promotes water content of the soil, enhancing water loss in evaporation. How such a saline, sodic and evaporation-promoting material can be used to manage the problem of salt at reduced water resource remains to be examined. This study aims to answer these questions by elucidating the mechanisms by which biochar affects soil salts and water, which are closely associated in the process of salinization and desalinization. Since irrigation and evaporation are the primary exogenous constraints on soil salts and water, and the vertical transport is key to understanding their movement (Daliakopoulos et al., 2016), this study focuses on the change of water, major salts and nutrients in the vertical profile of soil in both irrigation and evaporation based on field observations and laboratory experiments.

2. Materials and methods

2.1. Soil, biochar and water

The soil is the irrigation-silt soil by genetic classification or sandy loam by soil texture. As the prevailing soil in the Kashgar oasis in Xinjiang Autonomous Region, China, it was originally deposited by flooding and irrigation, and subsequently modified by cultivation (Wang et al., 2008). By the degree of salinization, the soil in the field experiments includes the leached, ready-for-sowing “mellow soil” as nicknamed by the locals (Table 1), and the ones with medium and high salinization (abbreviated hereafter as MS and HS, respectively). The soil used in the laboratory is the mellow soil.

Biochar was pyrolyzed from the local cotton stalk at maximum temperature 550℃. It is characterized by high pH and electrical conductivity (EC), as well as high content of salts that are roughly 1-2 orders of magnitude higher than the mellow soil except SO_4^{2-}, which is lower than the soil (Table 1).

Local groundwater was used for irrigation in the field experiments (for its properties see Table 2). An analog solution was used in the leaching and evaporation experiments in laboratory. It was made in the laboratory by dissolving salts of $CaSO_4$, K_2SO_4, $MgSO_4$, NaCl, $Mg(NO_3)_2$ and $MgCl_2$ in ultra-pure water (18.2 MΩ) at the quantity of 4080.0 mg, 128.8 mg, 1565.7 mg, 1049.7 mg, 47.6 mg, 52.4 mg and 10 L, respectively. The properties of the solution are also shown in Table 2.

2.2. Climate background and field experiments

2.2.1. Climate background

The Kashgar oasis, where field experiments were conducted, is characterized by typical dry climate in the westernmost China. According to the Kashgar Prefecture Meteorological Bureau from 2013 to 2016, the temperature changes between an average -6℃ in January and an average 26℃ in July with an annual average 11.6℃. Annual precipitation averages 65mm, sunshine 2650 hours and evaporation 2100mm. Cold weathers, gales and sandstorms are frequent in spring, affecting the time for sowing of cotton, the staple of the region.

2.2.2. Field experiments

Three plots were applied with biochar at weight ratio of 5% in the top 20 cm of the soil (bulk density ~1.6 g/cm^3), and thoroughly mixed by rotary tillage. The first plot consists of the mellow soil, in which biochar was applied a week after leaching in late March, 2013. The observations started from July, 2013. The other two plots are the soil with medium or high degree of salinization. Biochar was applied in late March, 2014, and the observation was performed in July, 2014.

The plot of mellow soil was sown with cotton 2 days after the application of biochar. The seeds were sown manually in 2 cm depth, about 10 cm apart in the row, 20 cm apart between two rows (small row pitch) and 50 cm apart every two small-pitch rows (large row pitch). Every 4 rows of seed thus sown were covered by one sheet of plastic film of 145 cm wide.

To try desalting the soil mechanically as an alternative of the intended leaching, the plot of biochar-amended mellow soil was removed the top 2 cm instead of land flooding in the beginning of April, 2014 and after 6 months of winter fallow. It was performed after a round of soil sampling and 2 days before sowing for the year. This time the cotton seeds were sown directly in biochar-amended soil without tillage but at the same way as last year.

The planted field was irrigated the local ways. It was done by flooding the field 4 times at: (i) a week before sowing in the beginning of April; (ii) the end of June when the crop began to flower; (iii) mid-July; and (iv) the second week of August. Each time the volume of water consumed was in between 750-1200 m^3/ha. After the harvest, the field was flooded in November to leach the salts. This time the water consumption was as high as ~5000 m^3/ha.

Soil sampling was performed using a custom-made corer 300 mm long and 60 mm of diameter. The sampled soil columns were sectioned on site every 1 cm in the top 3-4 cm and every 2-3 cm below.

2.3. Laboratory experiments

Laboratory experiments were conducted in two ways: (i) leaching followed by air drying, and (ii) evaporation interrupted by brief watering. The second experiment was performed two times, one for geochemical analysis the other for water evaporation measurement, because soil sampling for geochemical analysis influences water evaporation. The procedures for these experiments were described below.

2.3.1. Leaching experiments

Air-dried soil was sieved through a 2 mm mesh, aliquots of 1.37 kg were mixed with the biochar at 4 weight ratios, 0%, 1%, 5% and 10%, where 0% is the control. Each was packed into a Polyvinylchloride (PVC) bottle, which is 30 cm high and 60 cm^2 in basal area. The bottle was used upside down with base removed and mouth filled with quartz sand and covered by a nylon net (Fig. 1a). The soil columns thus prepared were each applied with 0.293 g of urea in the top 5 cm, which is equivalent to ~225 kg N/ha, roughly the average amount of N fertilization in China (Zhu and Chen, 2002), and then moistened with 60 mL of water every day to mineralize the urea for a week. The watering increased to 120 mL each time but the frequency reduced to once a week to leach the soil in the following weeks. After the total volume reached 1740 mL (equivalent to 290 mm precipitation), the columns were left air-dried for 30 days before sampled for analysis.

2.3.2. Evaporation experiments

Evaporation experiment was performed with soil columns compacted in PVC tubes. The tube was 15.3 cm in diameter and sealed in the bottom but opened sideway to a Markov bottle through a latex pipe (Fig. 1b). An infrared lamp (Philips PAR38 IR 175R) was installed over the column at a distance of 77.6 cm, creating a radiation about 24.2 MJ/m^2 on the surface, mimicking the average solar radiation in Kashgar oasis during April-July (Liao, 1999). Three kinds of soil columns were prepared, each containing 5 kg of dry soil but mixed with biochar at the weight ratio of 0%, 5% and 10%. The phreatic water level of the columns was maintained at 2 cm high by the Markov bottle. The soil was first saturated with the artificial water solution, and then subject to evaporation for 7 weeks. At the end of the 7^{th} week, it was moistened from the top with 1L of the water solution, followed by 5 more weeks of evaporation.

The soil columns were sampled once a week during the evaporation. The sampling was made in the top 10 cm of the column by a stainless steel corer (1.5 cm diameter). The void left was filled with the same soil. The sampled cores were sectioned every 1 cm in the top 4 cm, and every 2 cm in the lower 6 cm.

2.3.3. Water loss by evaporation

The experiments were conducted by the same setup as evaporation described above. The soil columns were subject to continuous evaporation for 14 weeks after the first saturation with the artificial water solution, and then saturated again at the end of the 14th and 21st week. The soil columns and the Markov bottle were weighed every week to record the water loss.

2.4. Geochemical analysis

All samples were first oven-dried at 105℃ for 24 hours, ground to pass 1 mm sieve for geochemical analysis.

pH was measured in 1:2.5 (g:mL) solution of soil to water using a pH meter (PHS-3CT, Shanghai Wei Ye instrument) and EC in 1:5 (g:mL) solution with a HANNA HI9033 conductivity meter. In both analysis, the oven-dried soil samples were mixed thoroughly with water by magnetic stirring at 1600 rpm for 15 min, the mixed solution was determined directly by the instruments.

Cation Exchange Capacity (CEC) was determined by the international recommended method (Page et al., 1982). 10 mL of saturated ethanol solution of sodium acetate and sodium chloride was added to 0.5 g of the oven-dried sample. The mixture was shaken for 30 min and then centrifuged for 20 min at 4200 rpm. The supernatant was decanted. These operations were repeated 3 times to ensure that the cation exchange site of the sample is loaded with Na^+, then the sample was added with 10 mL of saturated magnesium nitrate solution, shaken for 1 h to exchange the loaded Na^+ with Mg^{2+}. The mixture was centrifuged and the supernatant decanted into a 50 mL centrifuge tube. The procedures were repeated 3 times to ensure all Na^+ is exchanged into the supernatant. The collected supernatant was measured for Na^+ concentration by atomic absorption spectrophotometry (PE PinAAcle 900F). CEC was calculated by the Na^+ concentration as follows.

$$CEC = V \times (C - C_0)/23 \times m \times 10$$

Where: CEC is in CMol(+)/kg; V – Volume of the collected solution, mL; C - Sodium concentration in the collected solution, mg/L; C_0 - Sodium concentration in blank solution, mg/L; 23 - Conversion coefficient from g/L to Mol/L, g/Mol; M - Mass of the oven-dried soil sample, g; 10 - Conversion factor from MMol/kg to CMol/kg.

Total carbon and nitrogen content were measured by an element analyzer (Vario MACRO CNS; Elementar, Germany). About 1 g of the oven-dried sample was wrapped in aluminum foil and delivered to the automatic sampling plate. C and N content was measured automatically by the instrument.

The salts and nutrients were measured using a 1:10 (g:mL) solution. About 1 g of the oven-dried sample was added with 10 mL of ultra-pure water in a flask, shaken for 1 h before filtering for the analytic solution. An aliquot of the solution was introduced to an inductively coupled plasma-optical emission spectroscopy (Varian Vista Pro, Varian Inc., Palo Alto, CA, USA) for K^+ and Na^+ measurement, another to an ion chromatography (DIONEX ICS-90) for Cl^-, SO_4^{2-} and NO_3^- mesurement.

2.5. Data processing

All data are presented as mean values of at least three replicates. For statistical analysis, SPSS Statistics 17.0 was used. Values of $P \leq 0.05$ were considered statistically significant (ANOVA), and pairwise comparisons were performed with the Tukey´s post-test. Prior to analysis, Bartlett's test and the Shapiro–Wilk test were applied to verify the assumptions of homogeneity of variance and data normality, respectively. Graph plotting was done with Origin Pro 8.0.

3. Results

3.1. Field experiments

3.1.1. Salts and nutrients

Concentrations of Na^+, Cl^-, NO_3^- and K^+ were ~1-3 mg/g in the surface soil (0-2 cm depth) of the control of mellow soil depending on the ion and sampling site (W or E), reducing to ~0.1 mg/g in the lower soil profile (Fig. 2a-b). In contrast to these ions, SO_4^{2-} was an order of magnitude higher and quite different in its vertical distribution. It was as high as ~10-15 mg/g in the surface soil and decreased generally with depth, ending up to ~2-3 mg/g at 15 cm.

Application of biochar substantially reduced SO_4^{2-} while increasing the others in the subsoil before the mechanical desalting, i.e., removal of the top 2 cm soil (Fig. 2c-f) (Table 3). The increased salts indicate that biochar application exacerbates salinization due to its high content of salts (see Table 1), a result that was also observed in other studies (Dong et al., 2021; Saifullah et al., 2018). At the surface, all salts were increased, particularly after the winter fallow (Fig. 2e-f) (Table 3). This is another way for biochar to aggravate salinization, i.e., promoting salt accumulation at the surface. After the mechanical desalting, all the salts were reduced while nutrients increased substantially in the entire soil profile (Fig. 2g-h) (Table 3), indicating that the aggravations to salinization have been reversed but more nutrients are retained in the soil by the application of biochar in conjunction with the mechanical desalting. On the other hand, the concentration ratio of SO_4^{2-} between the surface and subsoil was enlarged by 3-13 times relative to the control, suggesting that biochar application strengthens salt migration from the subsoil to the surface despite the mechanical desalting.

The distribution of salts and nutrients in the control plot of MS and HS was similar to that of the mellow soil except for the higher amounts at the surface (Fig. 3a, c), which consist with the respective state of salinization. Application of biochar reduced SO_4^{2-} in the subsoil while increasing it substantially in the surface (Fig. 3b, d; Table 3), making the surface-subsoil ratio 2 and 22 folds the control in case of MS and HS, respectively. Again, more SO_4^{2-} is driven to the surface from the subsoil by application of biochar. The nutrients and other salts (except Na^+) were increased in the entire soil profile, especially at the surface. These effects are quite similar to the mellow soil prior to the mechanical desalting.

3.1.2. Electrical conductivity

To understand the effect of biochar on the salinity, we monitored the variation of EC despite the predominance of SO_4^{2-} over it (Fig. 2, 3). In the control of the mellow soil, the average EC was 2.51 mS/cm in the subsoil and increased generally upwards, exceeding 4 mS/cm at the first centimeter (Fig. 2a-b), which is a threshold above which growth of many crops is restricted (Abrol et al., 1988). Biochar application substantially reduced the salinity in the subsoil, and also at the surface after the mechanical desalting (Table 3), indicating that, despite its high salinity, biochar can be used to solve the problem of salt in combination with other engineering measures. In the following two years, the salinity was maintained below 1 mS/cm in the entire soil profile (Fig. 4), suggesting that seeds sowed in the soil would fare well even without the prior leaching. In contrast, it remained at 1-4 mS/cm in the control, with an average salinity of 3-4 mS/cm at the surface and 2-3 mS/cm in the subsoil. The high salinity explains well why the cultivated land has to be leached before sowing every year. Despite the reduction of salinity in the entire soil profile by biochar, the ratio of EC between the surface and subsoil was still 37% higher than the control, proving again the strengthened salinization in the top soil and desalinization below.

EC averaged ~3 and ~4 mS/cm in the subsoil of MS and HS, respectively, increasing above 6 and 7mS/cm at the surface (Fig. 3a, c). Biochar application increased the salinity in the entire soil profile, especially at the surface (Fig. 3b, d) (Table 3). The increase of salinity in the subsoil seems in contrast to the mellow soil. Examining EC below 5 cm depth instead of 2 cm, however, shows that the salinity was also reduced, e.g., by 4% and 2% in case of MS and HS, respectively. Therefore, the stronger enhancement of salinity at the top and the strengthened reduction in the lower soil profile remains the same. The change in the depth of the reduction, i.e., from 2 cm to 5 cm, is a result of high salinity of biochar as to be explained in the discussion below.

3.1.3. Seed emergence and plant growth

The enhancement of salinity in the surface soil suggests that application of biochar can be detrimental to seed germination and sprout well-being if not managed properly. This is proved by the results of cotton planting, which sprouted sparsely in the biochar-mixed mellow soil with about half of the seedlings survived the first month (Fig. 5a). Despite the disadvantage at the surface, however, the seedlings grew lushly 3 months later (Fig. 5b), suggesting that the reduced salinity in the subsoil is favorable to the growth of the plant. Statistical results further indicated that, compared to the control, the average height was increased by 10% at the time of the plant topping, average number of boll-bearing branch per plant increased by 13% and final net productivity by 23% (Wang et al., 2014)..The problem caused to the surface soil was resolved successfully after removal of the top 2 cm of soil. The seeds sowed afterwards germinated well without noticeable lack of seedlings, nor withering in the following month, contrasting sharply to the previous year (Fig. 5c cf. a).

3.2. Laboratory experiments

The highly-controlled laboratory experiments allowed us to unravel the mechanism of the behavior observed in the field. The application of biochar at the weight ratio of 0%, 5% and 10% resulted in soil column height of 19.9 cm, 26.7 cm and 33.3 cm, bulk density of 1.26 g/cm^3, 0.92 g/cm^3 and 0.76 g/cm^3 and water holding capacity of 26.4%, 44.8% and 57.2%, respectively, and affected different features as showed below.

3.2.1. Variations of salts and nutrients in leaching

Leaching reduced Cl^-, Na^+ and K^+ concentration to almost zero in the entire soil columns, as well as NO_3^- below 5 cm deep (Fig. 6). Above 5 cm, NO_3^- increased progressively. The total NO_3^- left in the soil, however, only accounts for 6%-18% of the nitrogen applied at the beginning of the experiment, indicating the severity of nutrient loss incurred in soil leaching. The watering of the soil, however, is not enough to leach out the dominant ion, SO_4^{2-}, leaving a considerable amount in the lower part of the soil column. It was suppressed below 3 cm depth to nearly 10 mg/g and 9 mg/g in terms of the maximum concentration for 0% and 1% of biochar, respectively, while below 6 cm to about 8 mg/g and 6 mg/g for 5% and 10% of biochar, respectively. These results showed that biochar application strengthens salt leaching.

3.2.2. Variations of salts and nutrients in evaporation

The following air-drying (evaporation) of the leached soil columns caused upward migration of SO_4^{2-}, which accumulated consequently in the top soil to as much as 1.4 and 2.1 times the control for 5% and 10% of biochar, respectively (Fig. 6). The evaporation, however, is not strong enough as to drive the low-concentration ions such as K^+, Na^+, Cl^- up to a noticeable accumulation in the top soil. This was shown in the intended evaporation experiments. As shown in Fig. 7, K^+,

Na^+, Cl^-, SO_4^{2-} and NO_3^- were all driven up, concentrating increasingly with biochar application rate at the top in both evaporation periods. The watering at the end of the 7th week showed, once more, the increased leaching efficiency with biochar.

Leaching and evaporation drives the ions in opposite directions. In either case, however, biochar played a positive role. This suggests that amendment of biochar strengthens movement of ions in the soil. This mechanism, however, is complicated for cations due to electrical adsorption. Because biochar is negatively charged in electricity, it thwarts the movement of cations by the adsorption, making it move slower than the anions. This is exemplified by the upward migration of the ions in the soil amended with 10% of biochar, in which the concentration of Cl^-, SO_4^{2-} and NO_3^- was about to disappear while K^+ and Na^+ still high at the lower soil profile in the 9th week of the evaporation. Nevertheless, the vertical distribution of all the ions became similar again after the 10th week, suggesting that the adsorption is not important compared to the enhancement to the movement. Despite this, the slowed movement of the cations shed light on another mechanism, i.e., accumulation of salts at the top occurs at the expense of below. As shown by the distribution of the cations in the 9th week in comparison to the 8th, the concentration increase of K^+ and Na^+ at the top 8 cm is clearly offset by the reduction in the lower soil.

3.2.3. Loss of soil water in evaporation

Evaporation slowed down generally after the initial saturation during the first 14 weeks and increased sharply after the watering at the end of the 14th week (Fig. 8), which is consistent with the fact that evaporation increases with water content of soil. Application of biochar increased the weekly water evaporation by 9% and 37% for 5% and 10% of biochar, respectively, during this period. With further desiccation, the soil began cracking, increasing the surface area exposed to the air and, consequently, the evaporation. As proved by the control, the weekly water evaporation was increased by 77% during the 16^{th}-24^{th} weeks in comparison to the previous weeks without cracking. Biochar application lowered the soil bulk density, alleviating (at 5% biochar) or even preventing (at 10%) soil compaction and thus soil cracking, reducing the weekly water loss by 35% and 43%, respectively, in comparison to the control. The effect was strengthened further after the 2^{nd} watering at the end of the 21^{st} week, suggesting that application of biochar preserves more water from being lost in evaporation with further irrigation-evaporation cycles.

4. Discussion

4.1. How biochar works to cure soil salinization

Our data indicate that biochar application strengthens salt migration, consequently, more salts are leached down in watering or driven up during evaporation, the phenomena that were also observed by other studies (Huang et al., 2021; Sun et al., 2017; Yao et al., 2021). The former strengthens salt removal in irrigation or during the intended salt leaching while the latter the evacuation of salt out of the lower soil profile as an offset to the intensified salt accumulation in the surface. The resulted salt distribution facilitates desalinization through mechanical removal of the surface soil instead of leaching by excessive watering. In fact, removal of top soil has been adopted long time ago by local farmers to reclaim land lost to heavy salinization in Xinjiang. This technique, however, was hardly used to desalt the soil in cultivated land even at dearth of water supply. This is not due to short of technology since manual operation prevails in the management of the field. Our data show that the primary reason lies in the salinity of subsoil, which, unlike the biochar-amended, is unable to be lowered sufficiently for seeds and sprouts to develop satisfactorily.

The addition of salts from biochar may blur the offset in the lower soil profile as indicated by the results of the field experiments with MS and HS. In both cases, the plots were irrigated only once after biochar application. Limited leaching left in the soil a large portion of salts from biochar, these salts moved upwards in evaporation, obscuring the offset from the subsoil despite the several hundred percent enrichment in the surface soil (refer to EC in Table 3). By contrast, the salinity was reduced by 65% below surface of the biochar-amended mellow soil, which was subjected to 5 cycles of watering and evaporation before the mechanical desalting. It showed clearly the offset to the surface accumulation. Based on these observations, as well as on similar studies that high-frequency irrigation enhances salt leaching (Sun et al., 2019), we concluded that the salinity of the biochar-amended MS and HS would also be reduced in the entire subsoil after due cycles of irrigation and evaporation.

Capillary movement is the dominant approach for soil water evaporation (Lemon, 1956) and therefore the upward migration of salts (Li et al., 2013). Biochar application intensified evaporation before soil cracking, suggesting it increased the capillary effects. This is in agreement with recent observations that biochar application increases soil porosity (Fei et al., 2019), in the form of both macro-pores (Yao et al., 2021) and micro-pores, as well as their connectivity (Sun et al., 2021), thus boosting water holding capacity as found in this study and elsewhere (Allen, 2007; Cheng et al., 2006; Glaser et al., 2002; Jones et al., 2010; Karhu et al., 2011; Laird et al., 2010). The increase to the capillary pores is the root cause for biochar strengthening salt migration.

Among the reported mechanisms for biochar to ameliorate soil salinization, our results only confirmed the adsorption one, but only to the salts with positive charges in electricity. Even this mechanism is overwhelmed by the enhancement to salt migration though.

4.2. How biochar reduces water consumption

The increased water holding capacity by biochar application may improve the soil with the property of water provision but not water conservation due to enhancement to water loss in evaporation. This applies to a wide range of soil textures except the loamy sand (Phillips et al., 2020). Nevertheless, biochar application does conserve water as a whole. It derives in three ways: (i) reducing soil bulk density, which was reported in many similar studies (Yao et al., 2021), and thereby soil compaction and cracking, lowering evaporation significantly; (ii) promoting leaching efficiency, sparing water for salt removal through leaching; and (iii) boosting evacuation of salt from the subsoil in evaporation, facilitating removal of salts in a mechanical way. Our results indicate that these effects work well with the soil of up to 54.7% of sand.

4.3. Use of Biochar for desalinization at limited water resource and no-tillage: Practicability

Soil cracking is prevalent in irrigated land because of high content of clay and silt deposited by flooding and/or flushing irrigation (Wang et al., 2008), as well as of the calculated times of irrigation, which subject the soil to long time of desiccation. The cracking boosts water loss so substantially that its alleviation or prevention through biochar application has practical significance for water conservation.

The intended soil leaching before sowing consumes more than twice the amount of water used for the entire irrigations during the growing season. The substantial water resource can be spared by desalting the soil the mechanical way based on application of biochar. This is practical because farmland can be flattened very well nowadays using machineries assisted by computers, thus lending technology for removal of a specific depth of soil. The removed soil can be desalted through leaching using much smaller amount of water, and then returned to the field by various existing methodologies.

Newly-ploughed irrigation-silt soil has a bulk density as low as 0.8 g/cm^3 right after rotary tillage in our field experiment. This bulk density can be achieved roughly at 5% of biochar. Therefore, application of biochar can make the soil as loose as newly-ploughed, thus sparing tillage.

5. Conclusions

Our findings show that biochar aggravates soil salinization upon application due to addition of salts from itself as well as the enhanced accumulation of salts in the surface, i.e., 2 cm depth in our study. The latter is caused by increase to fine pores and thus capillary suction in the soil, promoting salt accumulation at the surface through evaporation. Application of biochar also strengthens salt leaching in irrigation. Together with the aggravated top accumulation, which draws more salts from the soil below, they create a plant-friendly salinity in the lower soil profile after due alternations of irrigation and evaporation. Based on the resulted salt distribution, removal of the top 2 cm soil rejuvenates the land very well. Adsorption of biochar slows down the migration of salts with positive electrical charges, this effect, however, is triavial relative to the strengthened movement. Biochar application promotes evaporation after irrigation due to enhanced water holding capacity and capillary movement. The increased water loss is reversed, however, once the soil cracks, a common phenomenon in irrigated farmland. Biochar application counteracts soil cracking due to reduction to soil bulk density and soil compaction. While facilitating non-tillage management, this mechanism reduces weekly net water evaporation by 35%

and 43% at 5% and 10% of biochar application rate, respectively. By improving leaching efficiency and facilitating mechanical desalinization instead of the intended leaching, biochar application provides a promising new water-efficient practice for sustainable agriculture in salt-affected land.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure captions

Fig. 1. Schematic of setup of the leaching (a) and evaporation (b) experiments.

Fig. 2. Major salts (Na^+, Cl^-, SO_4^{2-}), nutrients (K^+, NO_3^-) and EC measured at two sites (denoted as E and W in the graphs) in the field of mellow soil. a-b). Results in the control plot in July, 2014 (indicated as 201407). c-h). Results in the plot of 5% biochar in July, 2013 (201307), April, 2014 (201404) and July, 2014 (201407). Insert in panel e magnifies the variation of Na^+, Cl^-, K^+ and NO_3^- in the soil profile.

Fig. 3. Salts, nutrients and EC in the soil of high salinization (HS) (a, b) and medium salinization (MS) (c, d) in the field. a) and c) are the controls. b) and d) the plot amended with 5% biochar

Fig. 4. Mean EC in the field of mellow soil after two years of the experiment. Insert is the averaged results.

Fig. 5. Emergence of cotton seeds at different managements with the surface soil amended with 5% biochar (a, c) and the lush growth of the survived seedlings three months later (b). a). The seeds were sowed in the soil 2 days after mixed with biochar in early April, 2013; c) Seeds sowed without tillage after removal of the top 2 cm in the same plot next year.

Fig. 6. Change of salts and nutrients in the soil column in leaching experiment. a). The control with 0% biochar, b). Soil mixed with 1% biochar, c). Soil with 5% biochar, d). Soil with 10% biochar.

The inserts are close-up views of the vertical distribution of Cl^-, Na^+, K^+ and NO_3^-.

Fig. 7. Changes of the salts and nutrients in the evaporation experiments. The solid triangle and dash-line beneath indicate the occasion of simulated irrigation. 0%, 5% and 10% are the application rate of biochar.

Fig. 8. Water loss in evaporation in the laboratory experiment. The solid triangles and dash-lines indicate the occasion of watering, the blank triangle and the bold line denote the time of soil cracking.