1 **Effect of salinity on the cotton cultivation and introduction of**
2 ***Amaranthaceae* halophytes in the Yellow River Delta, China**

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5 Hiroshi Takagi^{1,2} and Satoshi Yamada¹

6
7 Corresponding author

8 E-mail, hiroshi.takagi@wsu.edu; Tel, (509) 335-3896; Fax, (509) 335-4848

9
10 ¹ Faculty of Agriculture, Tottori University, 4-101 Koyama Minami, Tottori 680-8553,
11 Japan

12
13 ²Present address: School of Biological Sciences, Washington State University, Pullman, WA
14 99164, USA

15
16 ORCID ID of Hiroshi Takagi: <https://orcid.org/0000-0003-0321-0284>

Abstract

Cotton is a main cash crop in the Yellow River Delta in China. Although cotton is known for its high salt tolerance, cotton yield is severely affected by excessive salt accumulation in soil. A large amount of the Yellow River water is introduced annually to leach surface salts; however, it has limited effects due to poor soil physical quality. In this study, we aimed to investigate the impact of soil salinity on cotton growth and the viability of *Amaranthaceae* halophytes as alternative crops. Cotton and *Amaranthaceae* plants, including *Suaeda salsa*, *Kochia scoparia*, swiss chard, table beets and spinach, were planted in a large field in the Yellow River Delta that had spatial differentiation in terms of soil electrical conductivity (EC). Our analysis on soil revealed that Na^+ was the major cause of high EC; however, soil alkalization was not observed in highly salinized areas. Cotton biomass showed a strong negative correlation with soil EC. Although all tested *Amaranthaceae* plants also decreased biomass in high EC areas, this effect was clearly less pronounced in *S. salsa* and *K. scoparia*. To our surprise, levels of major (K^+ , Ca^{2+} and Mg^{2+}) or minor (Fe^{2+} , Mn^{2+} , Zn^{2+})

32 and Cu^{2+}) essential elements were not significantly affected by soil EC in all plant species,
33 suggesting that ion imbalance was not the main factor of growth reduction. All
34 *Amaranthaceae* halophytes absorbed more Na^+ but less Ca^{2+} than cotton, thus it would be
35 possible that *Amaranthaceae* plants function better than cotton in terms of maintaining soil
36 quality.

37

38 **Key words:** cotton, *Amaranthaceae*, salinity, Yellow River, soil electrical conductivity,
39 phytoremediation

1. Introduction

Salinity and sodicity are the major agricultural problems that lead to severe economic loss. Excessive Na^+ accumulation in soils is harmful for non-salt tolerant glycophytes since it not only creates an abnormal plant physiology such as ion imbalance and osmotic shock but also diminishes the physical and chemical quality of soils (Bernstein 1975; Bohnert et al. 1995; Munns 2002; Dodd et al. 2009). Throughout the world, large farming lands have already been salt-affected, and climate change is expected to accelerate soil salinization (Jesus et al. 2015). Thus far, hydraulic, physical, chemical and biological practices have been developed to protect productive soils from excessive salt accumulation. Leaching and chemical amendments are the most commonly used techniques to desalinize soils. Leaching is, however, subject to the limitation of quantity and quality of water since it requires large amounts of non-salinized water to drain excessive salt from fields. In arid and semiarid zones, the shortage of good quality water is the bottleneck for this approach (Rabhi et al. 2010). Although chemical amendments such as gypsum are also effective at reducing the

soil $\text{Na}^+:\text{Ca}^{2+}$ ratio and improving soil quality, the increasing price of these amendments has made such treatment problematic, especially in some developing countries (Qadir et al. 2002; Rabhi et al. 2009; Rabhi et al. 2010). Phytoremediation is an alternative desalinization method that is simply defined as cultivating salt-accumulating or salt-tolerant plants (Jesus et al. 2015). Phytoremediation is relatively easy, cheap and environmentally friendly, and positive impacts of salt uptake of halophytic plants on soil quality have been reported (Rabhi et al. 2009; Rabhi et al. 2010).

The Yellow River Delta in China is a coastal delta that has experienced remarkable economic and industrial development (Fang et al. 2005). Cotton (*Gossypium hirsutum* L.) is one of the Delta's main cash crops; however, its production is severely affected by the accumulation of salt in soil, despite cotton's identity as a plant species that is relatively tolerant to both salinity and sodicity (Maas and Hoffman 1977; Abrol and Bhumbla 1979). Despite a massive economic loss, the mechanism of cotton growth reduction in the Yellow River Delta is, so far, poorly understood. In many cases, soil salinity and sodicity problems are caused by inappropriate irrigation and water evaporation from the soil surface; however,

in the Yellow River Delta, soluble salts mostly come from seawater intrusion during high tides and coastal storms since this delta is low-lying enough to be flooded and the poor drainage of alluvial soils accelerates soil salinization (Fang et al. 2005; Meng et al. 2016). Interestingly, salinity levels are highly diversified within a narrow scope in the Yellow River Delta (Meng et al. 2016); thus, farming lands often show dotted patterns of salt-affected zones. To prevent continual salt accumulation, a large amount of the Yellow River water is introduced to leach excessive surface salts from the soil every year before new cultivation starts; however, the effect of leaching on soil quality is not sufficient to fundamentally improve cotton yields. Moreover, it is becoming difficult to use enough freshwater from the Yellow River due to the limited water resources and large expansion of agricultural land (Mao et al. 2016).

Although Na^+ is generally a toxic element for most plants, its growth-promoting effects on *Amaranthaceae* halophytes has been reported (Wang et al. 2001; Mori et al. 2006; Takagi and Yamada 2013; Kaburagi et al. 2014; Kaburagi et al. 2015; Yamada et al. 2015). Some *Amaranthaceae* halophytes have good nutrient values and are widely consumed as

85 food and animal feed (Ninfali and Angelino 2013). For instance, *Suaeda salsa* is the
86 pioneer halophyte in the Yellow River Delta that is consumed as a popular vegetable (Zhao
87 et al. 2005; Wu et al. 2011).

88 In this study, we performed a large-scale field analysis in Dongying, one of the most
89 intensively developed cities in the Yellow River Delta, to investigate the soil characteristic
90 and the mechanism of cotton growth reduction by soil salinization, and the viability of
91 *Amaranthaceae* halophytic plants as alternative crops.

2. Materials and Methods

2.1 Field design and plant cultivation

To design the experimental field, a preliminary survey was carried out on a severely salt-affected cotton field located in Dongying, Shandon, China (approximately 37°N, 118°E) on November 20th, 2010, and we tracked the Global Positioning system (GPS) information using a Garmin eTrex GPS (Garmin Ltd., Kansas, USA) (Fig. S1). In the following year, a large experimental field was set up based on the GPS data (Fig. 1 and Fig. S1).

We made our experimental field and sowed the seed in the end of April 2011. After leaching water was drained from the field, the surface soil was tilled with a tractor (depth = 10 cm), and 44 small (3 m×4 m) and 40 large plots (3 m×9 m) were created (Fig. 1). Each plot was circled with small banks (20 cm height) to minimize the interference from other plots, subsequently fertilized with 22.5 kg N 10a⁻¹ as urea, 32 kg P₂O₅ 10a⁻¹ as calcium superphosphate, and 15 kg K₂O 10a⁻¹ as potassium sulfate. Cotton, *S. salsa*, swiss chard (*Beta vulgaris* L. var. *cicla*), table beets (*Beta vulgaris* L. var. *rubra*) and spinach (*Spinacia*

107 *oleracea* L.) and *Kochia scoparia* (L.) were randomly assigned to each plot (Fig. 1). Planting
108 densities were determined based on our expectation of plant sizes; 15 cm×20 cm for spinach,
109 40 cm×40 cm for cotton, *S. salsa*, swiss chard and table beets; 40 cm×60 cm for *K. scoparia*.
110 The number of seeds per planting hole was four for cotton, table beets and spinach, five for
111 swiss chard, and one pinch for *S. salsa* and *K. scoparia*. To prevent dryness, each plot was
112 covered with clear plastic mulch immediately after seeding. In the middle of May, the plastic
113 mulch was broken to create small holes for the seedlings to grow out. However, all plants
114 (and especially those planted in highly salinized areas) showed too low germination rates at
115 this point to continue further experiments (Fig. S2). Therefore, from May 28–June 6th, we
116 transplanted excess seedlings of cotton, *S. salsa*, swiss chard, spinach and table beets grown
117 in moderately salinized area and seedlings of *K. scoparia* grown in a greenhouse to
118 complement the sparsity of plants in the field. It should be noted that seedlings of *K. scoparia*
119 from the greenhouse were at a similar developmental stage as those germinated in the field.
120 To protect the seedlings from herbivore attacks, the entire experimental field was covered
121 with large bird nets until the middle of July 2011.

122

123 ***2.2 Electrical conductivity measurements in the field***

124 We determined the soil electrical conductivity (EC) levels of all plots using a WET sensor
125 (WET-2, Delta-T Devices, Cambridge, UK). In small plots, soil EC was measured in at
126 least three spots, and in large plots, measurements were taken in at least six spots. The
127 mean of the EC measurements from a plot was regarded as the EC values of that plot.

128

129 ***2.3 Chemical analyses of leaching water***

130 Before we launched the experimental field, a large amount of the Yellow River water was
131 introduced to wash excessive salt from the soil, following the practice of local farmers (Fig.
132 S3). Standing water in the flooded field was collected on March 25th, 2011, and its ion
133 contents, pH and EC were measured. Cation and anion contents in the flood water were
134 determined with an atomic absorption spectrophotometer (Z-2310, Hitachi, Tokyo) and ion
135 chromatography (LC-10A, Shimazu, Kyoto, Japan), respectively. The sodicity hazard of the
136 water was indicated by the sodium adsorption ratio (SAR):

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}}$$

where $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are concentrations in mmol_c L⁻¹.

2.4 Chemical analyses of surface soils

Prior to the application of fertilizer, top soils (20 cm depth) were collected from three locations in every small plot and from five locations in every large plot, and were mixed homogeneously on April 26th, 2011. Saturated paste extracts were obtained following the methods of Endo et al. (2014). Air-dried soil samples were passed through 2-mm sieve, and distilled water was added until soils were saturated. Saturated pastes were kept under 25°C for more than 2 h and vacuumed to obtain paste extracts. Saturated paste extracts were used for pH, EC (hereafter we use EC_e to specify EC of saturated paste extracts), cation and carbonate alkalinity measurements. Cation contents in paste extracts were determined with an atomic absorption spectrophotometer (Z-2310, Hitachi, Tokyo). Carbonate alkalinity was determined by titration using 0.01 N H₂SO₄ that was oriented by 0.02 N NaOH. The sodicity hazard of soils was indicated by SAR.

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153 **2.5 Plant biomass and mineral contents**

154 Aerial parts of cotton, *S. salsa*, *K. scoparia*, and swiss chard, as well as tuberous roots and
155 aerial parts of table beets, were harvested from July 14–18th, 2011. After measuring the
156 fresh weights of the plant parts, the samples were cut into small pieces and left in an 80°C
157 fan-forced oven due to the limited size and capacity of the oven. The dried samples were
158 used to determine water contents and cation measurements. The dry weights of whole
159 shoots and tuberous roots were estimated using the fresh weights and water contents. Since
160 the number of plants per planting spot was not equal, dry weight was indicated with gram
161 per hill.

162 Plant cation contents were determined by following the methods of Takagi and Yamada
163 (2013). Dried powdered samples were digested in an acidic mixture on a 350°C plate. All
164 cation contents were measured with an atomic absorption spectrophotometer (Z-2310,
165 Hitachi, Tokyo).

3. Results

3.1 Elemental contents, pH and EC of water for leaching

Every year, local farmers in Dongying introduce a large amount of water from the Yellow River to remove excessive salt from the soil (Fig. S3). We tested if the quality of leaching water is sufficient for soil amelioration. Our results show that water introduced to the field is available for leaching (Table 1). Although Na^+ was the most abundant cation, the levels of EC and SAR were lower than the hazardous levels of salinity and sodicity ($\text{EC} > 4$ and $\text{SAR} > 13$, respectively). Cl^- and SO_4^{2-} were enriched in this water. This tendency was observed in tsunami-affected soils (Raja et al. 2009; Changué-Goff et al. 2012), suggesting that the source of salt in leaching water is originated from seawater.

3.2 Characteristics of soils in the research field

We prepared experimental field after leaching water was completely drained (Fig. 1), and surface soil samples were collected from each plot before the application of fertilizer.

Subsequently, soil samples from 69 independent plots were randomly selected from 84 plots and used for the saturation paste extraction. The levels of ECe ranged from 1.97 to 36.8 dS m⁻¹. We also tested the pH of the paste extracts since high salinity often accompanies high pH due to the effect of bicarbonate (Dodd et al. 2009). To our surprise, ECe was negatively correlated with pH (Fig. 2A). This result suggests that pH is not a major factor in impaired cotton growth. Soil alkalinity (CO₃²⁻ and HCO₃⁻ concentration) was not correlated with soil ECe (Fig. 2B). This unclear relationship between soil alkalinity and ECe is consistent with the reported characteristics of soils in the Yellow River Delta (Weng et al. 2010). Data from this and previous studies suggest that the majority of Na⁺ in the soil is derived from NaCl but not Na₂CO₃. Next, we measured Na⁺, Mg²⁺ and Ca²⁺ contents in 22 randomly selected paste extracts. Our results indicate that Na⁺, not Mg²⁺ or Ca²⁺, is the major cause of high salinity (Fig. 2C). Our results also showed that, in many cases, soil salinity and sodicity are higher than hazardous levels (ECe > 4 and SAR > 13, respectively; Fig. 2D).

3.3 Soil EC tested by a WET sensor

We measured soil EC with a WET sensor on May 12th, 2011. Our results show that the south part of the research field tended to contain soil with high EC levels. Moreover, the northwest parts (plot no. 47–61) exhibited higher EC levels than the northeast parts (plot no. 70–84). This distribution pattern of soil salinity resembles the pattern originally observed in November 2010, before the experiment was initiated (Fig. 3 and Fig. S1). These data suggest that the effect of leaching is not sufficient to improve soil quality.

3.4 Plant biomass

We harvested plants from July 14–18th and measured their dry weights (Fig. 4). Unfortunately, none of the spinach plants survived in our experimental field, likely due to the low salt tolerance exhibited by spinach. We found a strong negative correlation between cotton dry weight and soil EC measured with a WET sensor on May 12th, suggesting that cotton growth in July can be predicted by simple soil EC measurements in May. The degree of growth reduction was, however, different among plant species. Cotton showed the most

prominent growth reduction rates, and *S. salsa* and *K. scoparia* exhibited better biomass production even in high EC plots.

3.5 Plant mineral contents and sodium uptake capacity

Cation contents were quantified using plants collected from July 14–18th. Our results showed that cotton absorbed more Ca^{2+} than Na^{+} (Fig. 5), suggesting that cotton cultivation may enhance the soil Na^{+} : Ca^{2+} ratio, thereby creating a poor soil physical property that limits the effects of leaching. Conversely, all *Amaranthaceae* plants, especially *S. salsa*, contained more Na^{+} than Ca^{2+} (Fig. 5), suggesting that these types of plant species might improve the Na^{+} : Ca^{2+} ratio in soils.

It was previously reported that a Na^{+} rich environment suppresses the uptake of other elements in cotton and *Amaranthaceae* plants (Ahmad et al. 2002; Takagi and Yamada 2013). To our surprise, levels of neither major (K^{+} , Ca^{2+} and Mg^{2+}) or minor (Fe^{2+} , Mn^{2+} , Zn^{2+} and Cu^{2+}) essential elements were significantly affected by high EC in all plant species. The levels of Fe^{2+} in table beets were the highest at the lowest EC plot; however,

226 we could not find a clear correlation between Fe^{2+} levels and plant dry weight. These
227 results suggest that tested plants demonstrated higher ion homeostasis than laboratory
228 conditions, and ion imbalance was not the main factor of growth reduction in highly
229 salinized soils.

4. Discussion

To test the effect of salinity on cotton growth and the possibility of *Amaranthaceae* halophytes as alternative crops, we conducted field research in the Yellow River Delta. The experimental field had a wide range of salinity levels and could be used to test the effects of different salinity levels on plant growth (Fig. 3).

Analysis of leaching water revealed that it was of sufficient quality for desalinization (Table 1). This suggests that poor drainage and soil physical condition limited the effect of leaching and other desalinization methods need to be introduced to improve soil quality. We investigated the soil characteristics using saturated paste extracts. Our results clearly indicated that Na^+ , not Mg^{2+} or Ca^{2+} , is mostly responsible for high soil ECe (Fig. 2C and 2D). This tendency is consistent with a previous report about soils characteristics in the Yellow River Delta (Weng et al. 2010). We also tested the relationship between soil pH and ECe, since alkalization is frequently observed in salinized soil, and its adverse effect on cotton yield is reported (Dodd et al. 2009). In our soil samples, however, pH was negatively

correlated with ECe (Fig. 2A), and bicarbonate seemed to have a limited impact on soil pH (Fig. 2B). These results support the idea that the process of soil salinization in the Yellow River Delta is different from that in typical calcareous soils (Fang et al. 2005; Meng et al. 2016). Overall, our results indicated that plant growth reduction in high EC areas is irrelevant to bicarbonate and soil alkalization.

To investigate the effect of salinity on plant growth, seeds of cotton and *Amaranthaceae* plants were directly sown on the research field. Although the germination was severely affected by soil salinity (Fig. S2), we could still harvest plants after transplanting, except for spinach, which was nonviable (Fig. 4). It is generally thought that plants at early growth stages are more sensitive to excessive salts than those at later developmental stages (Wilson et al. 2000). Therefore, we think that transplanting is needed to maximize yields in high EC areas. We harvested plants in July 2011 and measured their dry weights (Fig. 4). A clear negative correlation between plant biomass and EC was observed in cotton. This result suggests that cotton growth can be well predicted with simple EC measurements in taken in the middle of May and perhaps earlier. All *Amaranthaceae* plants also decreased in biomass

when grown in high EC plots; however, the adverse effect of salinity was less pronounced in *S. salsa* and *K. scoparia*.

We previously showed that the supplementation of NaCl in hydroponic solution decreased the levels of essential elements such as K^+ , Ca^{2+} and Mg^{2+} in *S. salsa*, *K. scoparia* and Swiss chard (Takagi and Yamada 2013). It was also shown that NaCl treatments decreased K^+ , Ca^{2+} and Mg^{2+} contents in cotton in a dose-dependent manner (Zhang et al. 2014). In this study, however, EC levels barely affected the levels of major and minor essential elements in cotton and *Amaranthaceae* plants (Fig. 5). Moreover, the limited impact of soil EC on Fe^{2+} and Zn^{2+} contents supports the idea that soil pH is not responsible for growth reduction, because bicarbonate and high pH often cause the deficiency of these minerals (Hajiboland et al. 2003; Fodor et al. 2012). Taken together, our results suggest that plant growth impairment in high EC soils is not attributed to ion imbalance. It is possible that plant growth reduction in the Yellow River Delta is mainly attributed to osmotic stress and poor soil physical states that attenuate root elongation and function, since salinized soils in the Yellow River Delta are extremely fine and often cause waterlogging problems (Mao et

al. 2016). However, detailed mechanism of growth reduction requires further investigation.

Jesus et al. (2015) classified the surviving strategies of plants in salinized environments into three groups: excluder, accumulator and conductor. Excluder plants prevent salts from entering their tissues; accumulator plants absorb and accumulate salts; and conductor plants absorb salts and excrete them through salt glands. In this study, cotton showed very little Na^+ uptake, indicating that cotton is a typical excluder-type plant. Moreover, cotton's demand for Ca^{2+} was relatively high. In fact, it is reported that Ca^{2+} plays an important role in the early stages of fiber elongation (Tang et al. 2014), suggesting that sufficient Ca^{2+} uptake is necessary for cotton fiber quality. Given the Na^+ and Ca^{2+} contents of cotton, long-term cotton cultivation might enhance the soil $\text{Na}^+ : \text{Ca}^{2+}$ ratio, leading to poor soil physical conditions and low efficiency of leaching. *Amaranthaceae* halophytes, which showed characteristics of accumulator-type plants, accumulated higher Na^+ and lower Ca^{2+} than cotton (Fig. 5), suggesting that they are the better option to reduce the soil $\text{Na}^+ : \text{Ca}^{2+}$ ratio. It would be interesting to test the long-term effect of *Amaranthaceae* halophyte cultivation on soil quality.

290 In summary, we conducted a large field research in the Yellow River Delta and found that
291 cotton growth was severely affected by soil salinity and the growth reduction rates correlate
292 with the EC levels determined by the WET sensor. It appears that soil alkalization and ion
293 imbalance were not the main reason of the plant growth impairment. We also found that
294 *Amaranthaceae* halophytes *S. salsa* and *K. scoparia* had better salt tolerance than cotton.
295 All tested *Amaranthaceae* halophytes absorbed more Na^+ and less Ca^{2+} compared with
296 cotton, thus it would be possible that long-term cultivation of *Amaranthaceae* halophytes
297 improves soil quality in the Yellow River Delta.

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References

- Abrol I, Bhumbla D (1979) Crop response to differential gypsum application in a highly sodic soil and the tolerance of several crops to exchangeable sodium under field conditions. *Soil Sci* 127:79–85.
- Ahmad S, Khan N-I, Iqbal MZ, Hussain A, Hussan M (2002) Salt Tolerance of Cotton (*Gossypium hirsutum* L.). *Asian J Plant Sci*. 1:715–719. doi:10.3923/ajps.2002.715.719
- Bernstein L (1975) Effects of salinity and sodicity on plant growth. *Annu Rev Phytopathol*. 13:295–312.
- Bohnert HJ, Nelson DE, Jensen RG (1995) Adaptations to Environmental Stresses. *Plant Cell* 7:1099–1111. doi:10.1105/tpc.7.7.1099.
- Chagué-Goff C, Niedzielski P, Wong HKY, Szczuciński W, Sugawara D, Goff J (2012) Environmental impact assessment of the 2011 Tohoku-oki tsunami on the Sendai Plain. *Sediment Geol* 282:175–187. doi:10.1016/j.sedgeo.2012.06.002
- Dodd K, Guppy C, Lockwood P, Rochester I (2009) The effect of sodicity on cotton: plant response to solutions containing high sodium concentrations. *Plant Soil* 330:239–249. doi:10.1007/s11104-009-0196-6.
- Endo T, Kubo-Nakano Y, Lopez RA, Serrano RR, Larrinaga JA, Yamamoto S, Honna T (2014) Growth characteristics of kochia (*Kochia scoparia* L.) and alfalfa (*Medicago sativa* L.) in saline environments. *Grassl Sci* 60:225–232. doi:10.1111/grs.12061
- Fang H, Liu G, Kearney M (2005) Georelational analysis of soil type, soil salt content,

landform, and land use in the Yellow River Delta, China. *Environ Manage* 35:72–83.
doi:10.1007/s00267-004-3066-2.

Fodor F, Kovács K, Czech V, Solti Á, Tóth B, Lévai L, Bóka K, Vértés A (2012) Effects of short term iron citrate treatments at different pH values on roots of iron-deficient cucumber: A Mössbauer analysis. *J Plant Physiol* 169:1615–1622. doi:10.1016/j.jplph.2012.04.012.

Hajiboland R, Yang XE, Römheld V (2003) Effects of bicarbonate and high pH on growth of Zn-efficient and Zn-inefficient genotypes of rice, wheat and rye. *Plant Soil* 250:349–357. doi:10.1023/A:1022862125282

Jesus JM, Danko AS, Fiúza A, Borges M-T (2015) Phytoremediation of salt-affected soils: a review of processes, applicability, and the impact of climate change. *Environ Sci Pollut Res* 22:6511–6525. doi:10.1007/s11356-015-4205-4. PMID: 25854203

Kaburagi E, Morikawa Y, Yamada M, Fujiyama H (2014) Sodium enhances nitrate uptake in Swiss chard (*Beta vulgaris* var. *cicla* L.). *Soil Sci Plant Nutr* 60:651–658. doi:10.1080/00380768.2014.938595

Kaburagi E, Yamada M, Fujiyama H (2015) Sodium, but not potassium, enhances root to leaf nitrate translocation in Swiss chard (*Beta vulgaris* var. *cicla* L.). *Environ Exp Bot* 112:27–32. doi:10.1016/j.envexpbot.2014.11.007

Mass E, Hoffman G (1977) Crop salt tolerance—current assessment. *ASCE J Irrig Drain Div* 103:115–134.

Mao W, Kang S, Wan Y, Sun Y, Li X, Wang Y (2016) Yellow river sediment as a soil amendment for amelioration of saline land in the Yellow River Delta. *Land Degrad Develop* 27:1595–1602. doi:10.1002/ldr.2323

370 Meng L, Zhou S, Zhang H, Bi X (2016) Estimating soil salinity in different landscapes of the
 371 Yellow River Delta through Landsat OLI/TIRS and ETM+ Data. J Coast Conserv 20:271–
 372 279. doi:10.1007/s11852-016-0437-9
 373
 374 Mori S, Yoshiba M, Tadano T (2006) Growth response of *Suaeda salsa* (L.) Pall to graded
 375 NaCl concentrations and the role of chlorine in growth stimulation. Soil Sci Plant Nutr 52:
 376 610–617. doi:10.1111/j.1747-0765.2006.00076.x
 377
 378 Munns R (2002) Comparative physiology of salt and water stress. Plant Cell Environ 25:239–
 379 250. doi:10.1046/j.0016-8025.2001.00808.x.
 380
 381 Ninfali P, Angelino D (2013) Nutritional and functional potential of *Beta vulgaris cicla* and
 382 *rubra*. Fitoterapia 89:188–199. doi:10.1016/j.fitote.2013.06.004.
 383
 384 Rabhi M, Ferchichi S, Jouini J, Hamrouni MH, Koyro HW, Ranieri A, Adbelly C, Smaoui A
 385 (2010) Phytodesalination of a salt-affected soil with the halophyte *Sesuvium portulacastrum*
 386 L. to arrange in advance the requirements for the successful growth of a glycophytic crop.
 387 Bioresour Technol 101:6822–6828. doi:10.1016/j.biortech.2010.03.097.
 388
 389 Rabhi M, Hafsi C, Lakhdar A, Hajji S, Barhoumi Z, Hamrouni MH, Abdelly C, Smaoui A
 390 (2009) Evaluation of the capacity of three halophytes to desalinize their rhizosphere as grown
 391 on saline soils under nonleaching conditions. Afr J Ecol 47:463–468. doi:10.1111/j.1365-
 392 2028.2008.00989.x
 393
 394 Raja R, Ghoshal Chaudhuri SS, Ravisankar N, Swarnam TP, Jayakumar V, Srivastava RC
 395 (2009) Salinity status of tsunami-affected soil and water resources of South Andaman, India.
 396 Curr Sci 96: 152–156.
 397
 398 Qadir M, Qureshi RH, Ahmad N (2002) Amelioration of calcareous saline sodic soils through
 399 phytoremediation and chemical strategies. Soil Use Manag 18:381–385.

doi:10.1079/SUM2002149

Takagi H, Yamada S (2013) Roles of enzymes in anti-oxidative response system on three species of chenopodiaceous halophytes under NaCl-stress condition. *Soil Sci Plant Nutr* 59:603–611. doi:10.1080/00380768.2013.809600

Tang W, Tu L, Yang X, Tan J, Deng F, Hao J, Guo K, Lindsev K, Zhang K (2014) The calcium sensor GhCaM7 promotes cotton fiber elongation by modulating reactive oxygen species (ROS) production. *New Phytol* 202: 509–520. doi: 10.1111/nph.12676.

Wang B, Lu U, Ratajczak R (2001). Effects of salt treatment and osmotic stress on V-ATPase and V-PPase in leaves of the halophyte *Suaeda salsa*. *J Exp Bot* 52:2355–2365. doi: 10.1093/jexbot/52.365.2355.

Weng Y-L, Gong P, Zhu Z-L (2010) A Spectral Index for Estimating Soil Salinity in the Yellow River Delta Region of China Using EO-1 Hyperion Data. *Pedosphere* 20:378–388. doi:10.1016/S1002-0160(10)60027-6

Wilson C, Lesch SM, Grieve CM (2000) Growth Stage Modulates Salinity Tolerance of New Zealand Spinach (*Tetragonia tetragonioides*, Pall.) and Red Orach (*Atriplex hortensis* L.). *Ann Bot* 85:501–509. doi:10.1006/anbo.1999.1086

Wu H, Liu X, You L, Zhang L, Zhou D, Feng J, Zhao J, Yu J (2011) Effects of salinity on metabolic profiles, gene expressions, and antioxidant enzymes in halophyte *Suaeda salsa*. *J Plant Growth Regul* 31:332–341. doi:10.1007/s00344-011-9244-6

Yamada M, Kuroda C, Fujiyama H (2016) Function of sodium and potassium in growth of sodium-loving Amaranthaceae species. *Soil Sci Plant Nutr* 62:20–26. doi:10.1080/00380768.2015.1075365

430 Zhang L, Ma H, Chen T, Pen J, Yu S, Zhao X (2014) Morphological and physiological
431 responses of cotton (*Gossypium hirsutum* L.) plants to salinity. Plos ONE 9:e112807.
432 doi:10.1371/journal.pone.0112807
433
434 Zhao KF, Fan H, Song J, Sun MX, Wang BZ, Zhang SQ, Ungar IA (2005) Two Na⁺ and Cl⁻
435 hyperaccumulators of the Chenopodiaceae. J Integr Plant Biol 47:311–318.
436 doi:10.1111/j.1744-7909.2005.00057.x
437

Table 1. Characteristics of water for leaching.

Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	NO ₂ ⁻	NO ₃ ⁻	SO ₄ ²⁻	pH	EC	SAR
				mmol _c L ⁻¹						
									dS m ⁻¹	mmol _c L ⁻¹
6.01	0.98	3.33	3.36	5.19	0.10	1.03	3.91	8.30	1.40	3.28

Water was collected from the research field in March 2011. EC, electrical conductivity;
SAR, sodium absorption ration.

Fig. 1 Schematic diagram of the research field. This field consists of 40 large plots (9 m×3 m) and 44 small plots (4 m×3 m). Colors of plots indicate tested plant species.

Fig. 2 Relationships between electrical conductivity of saturated paste extract (ECe) and pH (A), carbonate alkalinity (B), cation contents (C) and sodium absorption ratio (SAR; D). Saturated paste extracts were obtained from air-dried top soils (depth = 20 cm). Asterisks denote significant correlation ($***P < 0.001$ by *Pearson* test).

Fig. 3 Soil electrical conductivity (EC) measured by a WET sensor on May 2011. The distribution pattern of soil EC measured with a WET sensor. The values of EC (dS m^{-1}) were represented by a boxed color on the blue-yellow-red gradient scale.

Fig. 4 Effect of soil salinity on plant growth. Data of electrical conductivity (EC) were taken from Fig. 3. Asterisks denote significant correlation (* $P < 0.05$, ** $P < 0.01$ by Pearson test).

Fig. 5 Effect of soil salinity levels on Na⁺, K⁺, Mg²⁺, Ca²⁺, Fe²⁺, Mn²⁺, Zn²⁺ and Cu²⁺ contents in cotton and *Amaranthaceae* halophytes harvested in July 2011. In table beets, the shoots and tuberous roots were used; in other plants, only the shoots were used for elemental measurements. Data of electrical conductivity (EC) were taken from Fig. 3.

Fig. S1 Preliminary field survey. GPS information of the salinized cotton field tracked using a Garmin eTrex GPS in November 2010. Dead indicates the areas with no cotton growth. The experimental field was designed to create spatial variations in soil salinity levels.

482 **Fig. S2 Distribution pattern of germination rate.** Germination rates were roughly
 483 categorized into orange (0%), gray (more than 0%, less than 25%), light green (25% or more,
 484 less than 50%) and green (50% or more).

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Fig. S3 The picture of the experimental field flooded with the Yellow River water for leaching in March 2011.