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Soil salt distribution under mulched drip irrigation in an arid area of northwestern China☆

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ABSTRACT

Mulched drip irrigation (MDI) has now become popular in arid and semi-arid areas, under which, however, salts are likely to build up in the surface soil due to deficient leaching water. To explore this new kind of secondary salinization issue, a 3-year experiment was conducted in an arid area in Xinjiang, northwestern China from 2008 to 2011. Over 15,000 soil samples were collected during the experimental years. The patterns of soil salinity distribution under MDI along the horizontal direction as well as vertical direction have been explored. Our results indicate that soil particle size distribution has great impact on soil salt migration and distribution. The salt will build up above the relatively impermeable layer along the soil profile. The zone below drip pipe obtains the lowest salinity level and the salt accumulates in the inter-film zone at the end of growth period. The salinity in the inter-film zone is 1.24–2.34 times the value in the zone below drip pipe within 50 cm soil depth, according to the soil texture. Furthermore, our analysis suggests that surface salinity distribution is dominated by MDI while the influence of MDI on salinity distribution is decreasing with the downward distance from ground surface.

1. Introduction

The secondary salinization induced by improper irrigation has been presented as a crucial threat to agriculture all over the world, especially in arid and semi-arid areas (Dong et al., 2009; Oster, 1994; Scanlon et al., 2010; Wang et al., 2012). Traditionally, the secondary salinization is caused by flooding irrigation, i.e. too much irrigation water induces water table rising and the succeeding intense phreatic evaporation leads to the upward moving of salt from groundwater and accumulating in the ground surface (Runyan and D'Odorico, 2010; Vlek et al., 2008). Recently, a new form of secondary salinization calls attentions, which is caused by deficient leaching water under micro-irrigation condition. Particularly in drip irrigation, the distribution of dissolved salts in the soil profile follows the pattern of the water flux with the tendency for accumulation at the periphery of the wetted soil mass, and the salt accumulation is much greater near the surface than at the deeper layers and increases with distance from the emitters (Palacios-Diaz et al., 2009; Phocaides, 2007; Wang et al., 2011). In fact, salinization under drip irrigation condition has occurred in many arid and semi-arid areas, including Israel, Egypt, USA, Lebanon and other places (see Burt et al., 2003; Chen et al., 2010; Christen et al., 2007; Darwish et al., 2005; Feng et al., 2005 for details).

Mulched drip irrigation (MDI), as a new micro-irrigation approach incorporating surface drip irrigation method and film mulching technique, has been widely applied in Xinjiang Province of China since 1990s (Chen et al., 2010; Hu et al., 2009; Wang et al., 2011; Zheng et al., 2009). It has several advantages such as (1) increasing water use efficiency by delivering water precisely to root zone and eliminating most useless soil evaporation by mulching; (2) improving soil thermal conditions for crop germination and seedling growing during early spring when the frozen injury occurs frequently; (3) decreasing labor input by applying fertilizer and pesticide automatically with water. The mulched drip irrigation has now become popular in other arid and semi-arid areas of China (Dou et al., 2011; Hou et al., 2010; Kang et al., 2010; Wan et al., 2010), and it is also potentially applicable to other Central Asia regions with similar climatic and farming conditions (O'Hara, 1997). However, under current MDI practice, irrigation water can only penetrate into the soil above 50–60 cm depth due to limited water supply. Salts from irrigation water, soil parent material, and groundwater are likely to build up on the surface of the cultivated

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soil by evaporation (Gowing et al., 2009; Isidoro and Grattan, 2011). Salt accumulation and specific management techniques, therefore, become the special concern for MDI in arid and semi-arid areas.

The proper design and management of MDI systems require a fully understanding of salt distribution and accumulation patterns, which has, however, not been well understood. The difficulty comes principally from the strong heterogeneity of soil salinity both at temporal and spatial (horizontal as well as vertical) scales. The larger number of soil samples could overcome such variability to some extent and provide more accurate salinity appraisal (Richards, 1954), which is, however, laboring and time-consuming and thus has rarely been implemented in the existing studies. Additionally, the salt distribution and accumulation results are seldom reported for cotton field although the corresponding water distribution results have been frequently published (Dagdelen et al., 2009; Ibragimov et al., 2007; Karam et al., 2006). Cotton is one of the most important fiber/cash crops and grown worldwide including Xinjiang Province of China (Tang et al., 2010). Although cotton is known as a salt-tolerant crop (Ashraf, 2002), the yield will sharply decrease as the soil salinity expressed by saturated extract of electrical conductivity exceeds 7.7 dS m^{-1} (Maas and Hoffman, 1977). In few researches about soil salinity in the cotton field under MDI condition, the authors focused on the gross status of salinity accumulation. For example, Chen et al. (2010) show that average salinity in the 1.0 m soil profile increases by 236 percent and 447 percent respectively for moderate and high saline water irrigation based on 4000 sampling measurements in a 3-year field experiment, while Wang et al. (2011) indicate a decreasing trend of salinity in 1.1 m soil profile by 73 percent for fresh water irrigation based on 3000 sampling measurements also in a 3-year field experiment. Also, Zheng et al. (2009) show that soil salinity increases during the pre-irrigation period and decreases during the drip-irrigation period based on 1800 sampling measurements in a 1-year field experiment.

The purpose of this study is to investigate the specific pattern of salt distribution associated with MDI in a cotton field in northwestern China. As mentioned above, the difficulty with such exploration lies with the strong heterogeneity of soil salinity at the field scale and the destructive salinity measurement method. To the authors' knowledge, the state-of-the-art equipment as Hydra Probe® Soil Sensor (Stevens Water Monitoring Systems, Inc., U.S.A., it has been equipped in this study area) can't meet the accuracy demand of soil salinity measurement under dry and high salinity condition (Jones et al., 2002), and the researchers still rely heavily on traditional sampling and paste extracting method. In addition, the sampling method is destructive and thus we could not make the continuous salinity measurement at a specific site. To deal with this problem, we used a large number of samples to get the average status to analyze salt distribution and introduced a statistical dimensionless index (M) to quantify the special qualitative pattern associated with MDI.

2. Method and material

2.1. Experimental site and plot layout

The experimental site is located on the northeast edge of Taklimakan Desert, belong to Bayangol Prefecture of Xinjiang Province in northwestern China (86°12′E, 41°36′N, 886 m a.s.l., see Fig. 1). The field experiment was conducted from 2008 to 2011 in a cotton field with 0.53 ha area. The study area is characterized by a typical inland arid climate with strong diurnal temperature fluctuation and rarely mean annual precipitation of approximately 60 mm. The annual mean temperature is 11.48 °C and annual total sunshine is 3036 h, which is favorite for cotton growth. The mean annual potential evaporation measured by Φ20 evaporation pan is rather high to 2788 mm. During the experimental years (2008–2011), the average relative humidity in the growth period is 37.62%, and the groundwater table varies from 1.4 m to 4.1 m (shallow in autumn and deep in spring). The average electrical conductivity (EC) of groundwater is 3.9 dS m^{-1} while it is 0.9 dS m^{-1} for irrigation water from the Kuta canal originating from Kongqi River.

Generally the main soil types in the study area are loamy sand and sandy loam. The soil bulk density varies from 1.58 to 1.74 Mg m^{-3} in the 1.5 m soil profile and the saturated volumetric water content is approximately 0.42. The previous study shows that soil particle size distribution (PSD) has great impacts on soil salinity (Hu et al., 2011), and therefore, we set up three fields in the experimental site (see Fig. 1) according to the soil texture characterized by PSD to explore the influence of MDI on salt distribution and accumulation. As shown in Fig. 2, Field #1 has the lowest clay and silt (hereafter as finer particle) content and the PSD is relatively uniform along vertical direction. Field #2 and #3 have similar

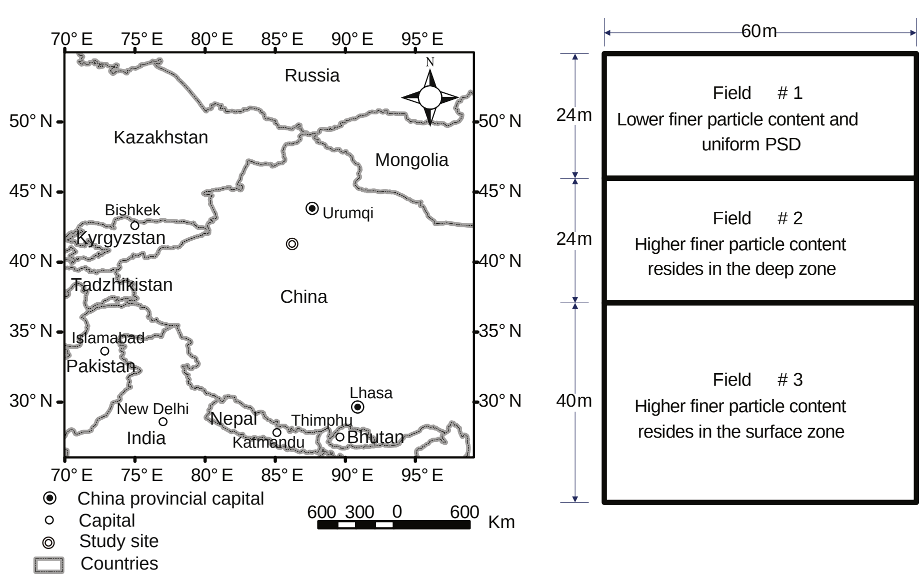

Fig. 1. Geographic location of study site and field layout.

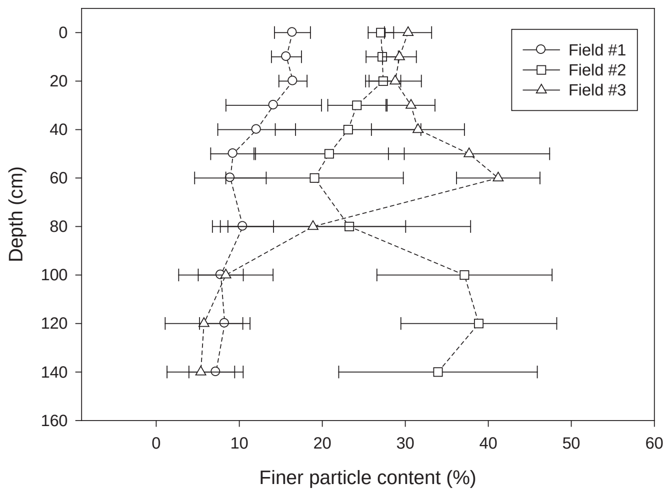

Fig. 2. Profile of soil particle size distribution (PSD) in different fields (Finer particle includes clay and silt parts whose particle size is less than 50 μm; The data shown is the mean value of 9 samples, and error bar represents the standard deviation).

higher finer particle content than Field #1 but present totally different layered feature. The finer particle layer resides in the deep zone in Field #2. Conversely in Field #3, the finer particle layer resides in the surface zone and soil texture becomes sandy when moving downwards. Moreover, three sub-fields were designed in each experimental field, which can be regarded as the replicators for each field.

2.2. Cotton planting and field management

The cotton (*Gossypium hirsutum L.*) was planted on April and harvested from September during the experimental period. The seeds were sown at 0.1 m intervals in the row to yield a population of 260,000 plants ha^{-1}, and the emergence rates were about 60% and the actual plant density was 160,000 plants ha^{-1}. There are two different styles of cotton planting and drip pipe arrangement. The principal style is named "one pipe, one film and four rows of cotton arrangement" (OPA) (Gao et al., 2010), which means that one drip pipe beneath the mulched film is in the middle of four rows of cotton (see Fig. 3(a)). The width of the film is 110 cm and the inter-film zone is 40 cm. The other style is named "two pipe, one film and four rows of cotton arrangement" (TPA) (see Fig. 3(b)), which was applied for Field #1 and #2 in 2010 only. For convenience, the three terms, i.e., wide-row zone (WRZ), narrow-row zone (NRZ), and inter-film zone (IFZ) are defined separately for OPA and TPA as shown in the Fig. 3.

The experimental site has a long history of cotton planting with flood irrigation prior to drip irrigation installation in 2008. The investigation shows that the groundwater table was as shallow as 1 m before 2008. The initial high soil salinity at the beginning of 2008 should be induced by previous flood irrigation practice. The volume of annual irrigation water was not exactly identical for the three fields in the experimental years, which is shown in Table 1. Irrigation schedules adopted by local farmers are summarized in Table 2. The amount of irrigation water for different cotton growth stages was obtained by multiplying the annual irrigation volume in Table 1 by the percentage value in Table 2. To meet the plant requirement for nutrient, 225 kg/ha compound fertilizers (14% N, 16% P_2O_5, 15% K_2O) and 225 kg/ha urea (46% N) were applied as the basic fertilizer before plowing. During the growth period approximately 525 kg/ha urea (46% N) was applied as the supplement fertilizer by fertigation method.

2.3. Data collection

Soil samples were collected two times a week in cotton growth period using an auger (model Auger Edelman combination 5 cm, Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) from the boreholes for moisture and salinity measurements. Growth period is from May to September. The samples were obtained from WRZ, NRZ and IFZ (see Fig. 3) respectively at varied depths, i.e., 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–80,

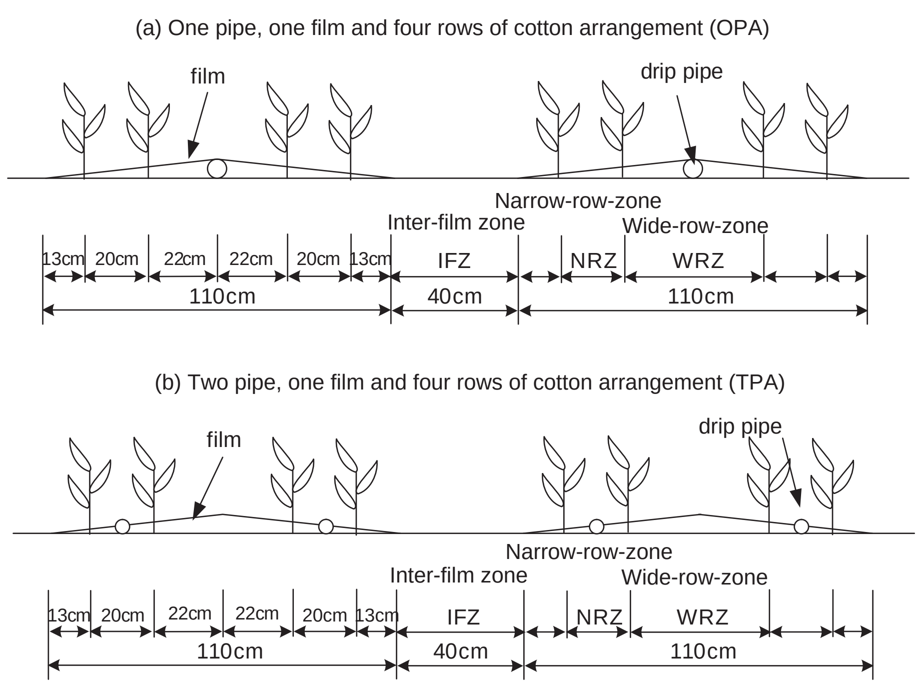

Fig. 3. Styles of cotton planting and drip pipe arrangement.

Table 1
Annual irrigation volume of different fields during 2008–2010 (Unit: mm).

	2008	2009	2010
Field#1	437	415	400
Field#2	572	561	450
Field #3[a]	434	518	–

[a] The soil sample measurement and irrigation volume data are absent for Field #3 in 2010.

80–100, 100–120, 120–150 cm depth beneath ground surface. More than 15,000 soil samples were collected throughout the experimental years.

Prior to soil salinity measurement, the volumetric water content for the same soil sample was determined using the gravimetric method. Soil electrical conductivity (EC) is a popular criterion to define soil salinity (Li et al., 2007; Richards, 1954), and can be used to calculate total dissolved salt (TDS) (Corwin and Lesch, 2003; Dou et al., 2011; Steppuhn et al., 2005). In this study, the soil samples were crushed and passed through a 2 mm sieve after drying at 105 °C for 8 h. Then the $EC_{1:5}$ was measured in the paste extracts with soil/water ratio of 1:5 (weight) by a conductivity meter (DDS-307, Shanghai Precision & Scientific Instrument Inc., China). For simplicity, the term $EC_{1:5}$ is abbreviated as EC hereafter. In order to convert EC to TDS, the relationship between TDS and EC was determined through the laboratory experiments with 80 soil samples from the experiment fields. The TDS of soil sample was defined by summing up the dominant cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}) (Yao and Yang, 2010) of 1:5 soil water extract. The linear regression between TDS (g kg^{-1}) to EC (dS m^{-1}) is shown in Fig. 4.

2.4. Statistical analysis

The classic statistic method was applied to analyze the variability among the data and to explore the spatial and temporal salt distribution under MDI using the statistic package of MATLAB and EXCEL. Specifically, space-weighted mean salinity for a soil profile is calculated by the weighted mean method (Dou et al., 2011) as following

$$EC = \frac{\sum\limits_{\substack{j = 0-10,\ldots,120-150 \\ k = 0,30,65}} EC(j,k)*S(j,k)}{\sum\limits_{\substack{j = 0-10,\ldots,120-150 \\ k = 0,30,65}} S(j,k)}$$

where, *EC(j,k)* is EC (dS m^{-1}) for the soil sample collected at *j* cm beneath ground surface and *k* cm to the film center along the horizontal direction, and *S(j,k)* is the represented volume of *EC(j,k)*.

Most results have been analyzed for the root zone in this study for two reasons, i.e., (1) the soil salinity and moisture conditions of root zone impose direct impacts on plant growth and fiber yield, and (2) the root zone is the highly active zone influenced by infiltration and evapotranspiration processes. According to the measurement data, the root zone of cotton in this study is within depth of 50 cm, which agrees with the result in drip irrigated cotton field by Hu et al. (2009) and Wang et al. (2011).

Many theoretical and experimental researches suggest that there exists a special qualitative pattern (SQP) of salt distribution associated with MDI, i.e., salt content is lowest in the WRZ while highest in the IFZ under OPA arrangement, or it is higher in both IFZ and WRZ than NRZ under TPA arrangement due to the tendency for accumulation at the periphery of wetted soil mass. The strong heterogeneity of soil salinity, however, makes it difficult to recognize such pattern by the date obtained from destructive experiment. This difficulty is partly solved by introducing a statistical dimensionless index (*M*) by Hu et al. (2011), which was adopted with modifications in this study as following:

$$M_j = \frac{N_j^{SQP}}{K}$$

where M_j is the statistical dimensionless index representing the SQP of salt distribution associated with MDI, the M_j is calculated on the basis of a specific soil layer *j*. Here the three concurrent salinity measurements, conducted respectively in IFZ, NRZ, and WRZ but at the same layer *j* (noted as EC_{IFZ}, EC_{NRZ}, EC_{WRZ}), are considered as one sample group, and *K* is the total number of sample groups measured at layer *j*. N_j^{SQP} is the number of sample groups that present the SQP of salt distribution associated with MDI described above. There are 6 permutations of the set {EC_{IFZ}, EC_{NRZ}, EC_{WRZ}} by the order of EC magnitude under the completely random condition, namely (EC_{IFZ}, EC_{NRZ}, EC_{WRZ}), (EC_{IFZ}, EC_{WRZ}, EC_{NRZ}), (EC_{NRZ}, EC_{IFZ}, EC_{WRZ}), (EC_{NRZ}, EC_{WRZ}, EC_{IFZ}), (EC_{WRZ}, EC_{IFZ}, EC_{NRZ}), (EC_{WRZ}, EC_{NRZ}, EC_{IFZ}), in which the first number in the parentheses is biggest and the last one is smallest. Hu et al. (2011) categorized (EC_{IFZ}, EC_{NRZ}, EC_{WRZ}), (EC_{IFZ}, EC_{WRZ}, EC_{NRZ}) and (EC_{NRZ}, EC_{IFZ}, EC_{WRZ}) as the SQP of salt distribution under OPA. In our study we re-define more strictly that only (EC_{IFZ}, EC_{NRZ}, EC_{WRZ}) permutation can be considered as SQP under OPA. We also extend this definition to TPA, i.e., two permutations including (EC_{IFZ}, EC_{WRZ}, EC_{NRZ}) and (EC_{WRZ}, EC_{IFZ}, EC_{NRZ}) are considered as SQP under TPA. Therefore, we can expect that *M* equals to 1/6 under OPA and 1/3 under TPA if soil salt distributes completely randomly along the horizontal direction. The *M* value should be equal to its maximum value 1.0 for both arrangements if salt distribution is completely dominated by MDI. In most cases impacted by both MDI and random, the *M* value should be 1/6–1.0 under OPA and 1/3–1.0 under TPA.

3. Results and discussions

3.1. Soil salt distribution along the horizontal direction

Perpendicular to drip pipe, the soil profile can be divided along the horizontal direction into three zones including IFZ, NRZ, and

Table 2
Typical irrigation schedule adopted for experiments during 2008–2010.

Year	Cotton growth stage							
	Squaring stage (Jun 15 – Jul 3)		Flower stage (Jul 4 – Jul 28)		Bolls stage (Jul 29 – Aug 18)		Boll opening stage (Aug 19 – Sep 1)	
	Percentage	Events	Percentage	Events	Percentage	Events	Percentage	Events
2008	14%	2	32%	3	35%	3	19%	2
2009	20%	3	44%	4	27%	3	9%	2
2010	20%	3	44%	4	27%	3	9%	2

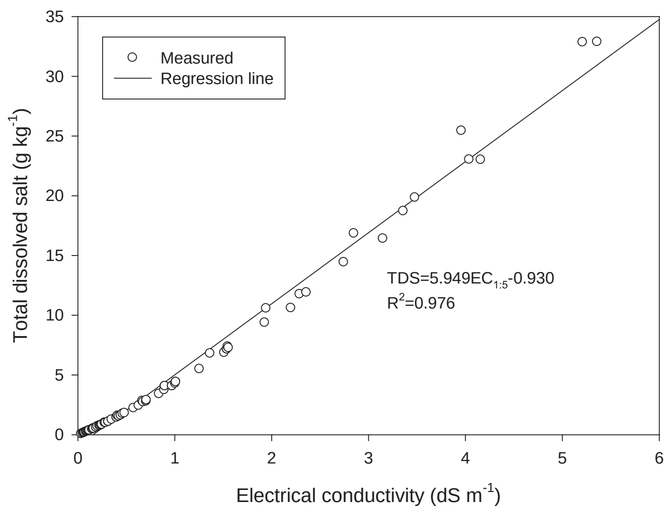

Fig. 4. The linear relationship between total dissolved salt (TDS) and electrical conductivity ($EC_{1:5}$).

WRZ as dictated in Fig. 3. Under MDI condition, soil salt distribution follows the pattern of the water flux with the tendency for accumulation at the periphery of the wetted soil mass. In general, the zone below drip pipe owes the lowest salinity level and forms a desalinization zone. Correspondingly, soil salinity will accumulate in IFZ under OPA and accumulate in both IFZ and WRZ under TPA.

To explore the salt build-up process, we propose a horizontal salinity distribution ratio which is defined as the proportion of salt content in a specific horizontal position occupying the sum of whole profile. The Fig. 5 shows the salt build-up process from the irrigation beginning to the end of growth period. When cotton are sown in late April, the mean horizontal salinity distribution ratios are almost equal to 0.33 in IFZ, NRZ and WRZ (not shown in Fig. 5), and as time goes by, the ratios change associated with soil salt migration. In 2008, the ratio of Field #1 is 0.45 and 0.23 for IFZ and WRZ in early July, while the ratio changed to 0.53 and 0.21 in late August, which indicates that the salt is redistributed and accumulated towards the IFZ. For Field #2 in 2009, the mean horizontal salinity distribution ratio is 0.39 and 0.28 for IFZ and WRZ in late June, and 0.46 and 0.26 in late August with the same trend as in Field #1.

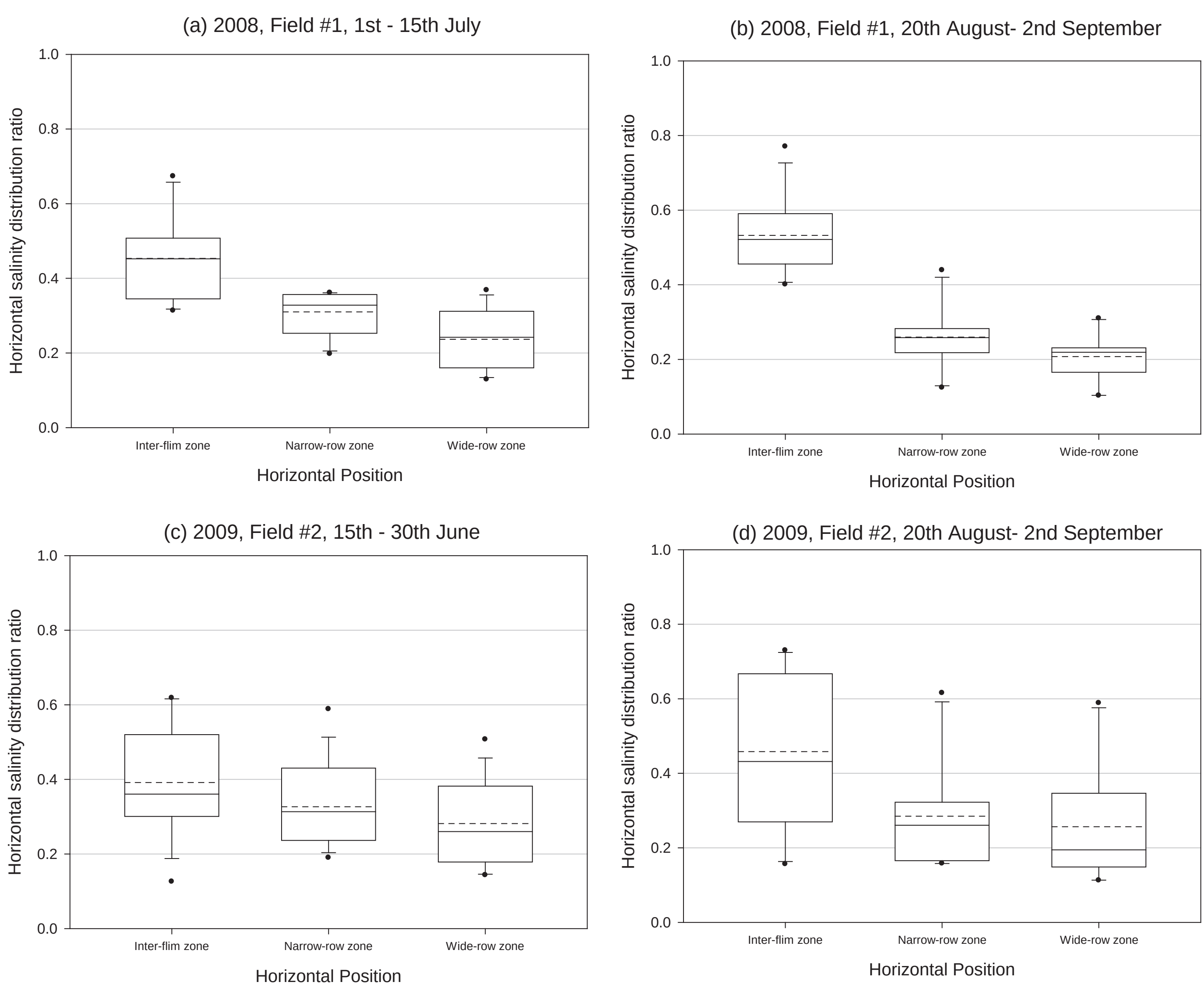

Fig. 5. The soil salt build-up process along the horizontal direction for 0–50 cm depth in growth period (On each box, the central solid line is the median, dash line is the mean, the edges of the box are the 25th and 75th percentiles, the whiskers extent to the most extreme data points, and the outliers are plotted individually as solid circle dot).

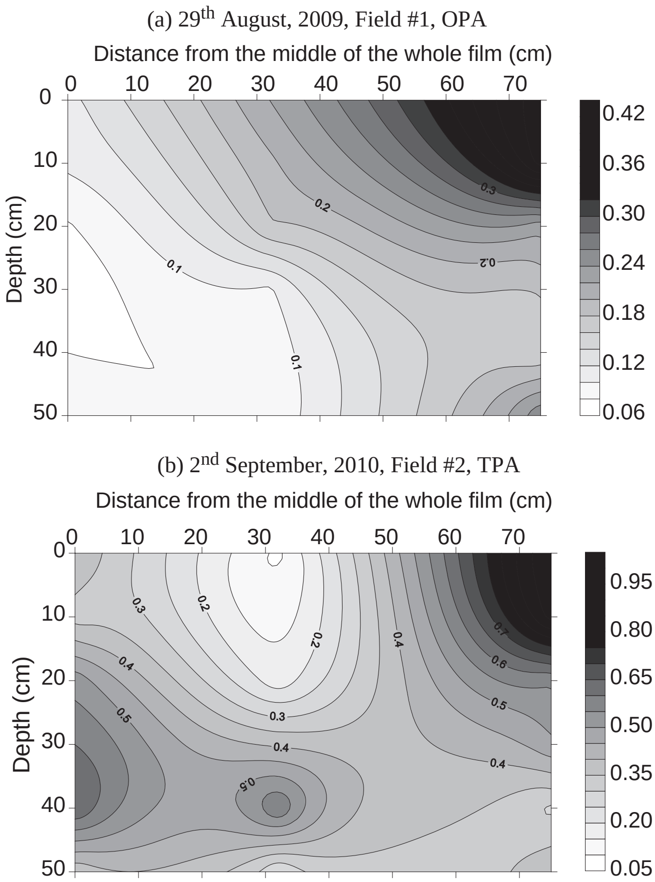

Fig. 6. Typical salinity contour in the vertical transect perpendicular to the drip pipe (Unit: dS m^{-1}).

The desalinization zone and salt distribution pattern can be easily observed through the typical salinity contour in the vertical transect perpendicular to the drip pipe (Fig. 6). Salt content is lowest in the WRZ while highest in the IFZ under OPA arrangement, and it is higher in both IFZ and WRZ than NRZ under TPA arrangement. The root distribution data indicates that the majority of active root exists in desalinization zone. Since the soil salinity mainly accumulates at the periphery of the wetted soil mass, i.e., the inter-film zone, the relatively low soil salinity in desalinization zone provides a favorable environment for plant root growth and water uptake (Bui, 2013).

The results shown in Fig. 7 confirm the pattern of soil salt distribution along the horizontal direction. For example, in Field #1 the mean EC value in IFZ is 0.97 dS m^{-1} which is 2.41 times the value in WRZ in 2008. The similar distribution of salt content can also be observed in 2009 in Field #1 and the EC value in IFZ is 2.26 times the value in WRZ. The ratios of EC in IFZ over that in WRZ are also calculated for Field #2 and #3, which gives 1.73 for 2008 and 1.82 for 2009 in Field #2, and 1.22 for 2008 and 1.26 for 2009 in Field #3. We can see from the results that the ratio values are biggest in Field #1 and smallest in Field #3 in spite of their absolute values of EC. Recall that the surface soil is more sandy in Field #1, the above results imply that associated with the higher active movement of water flux, soil salt would transport to and accumulate in the IFZ more easily for sandy soil than clay soil along the horizontal direction.

Due to the application of TPA in 2010, the soil salt accumulates to both the IFZ and WRZ. The soil salt of the mulched zone (including WRZ and NRZ) contribute 70.7% and 60.7% to that of the whole profile within the 50 cm soil depth in Field #1 and Field #2, respectively (Fig. 7(c) and (f)). However, the ratios are 50.7% and 56% under OPA in the Field #1 and Field #2. Since the total irrigation volumes are similar under OPA and TPA, the volume for each emitter under TPA will decrease to the half value of OPA, leading to the weak leaching effects. Therefore, the soil salt of the mulched zone is higher under TPA than OPA.

3.2. Soil salt distribution along the vertical direction

Natural soils are usually stratified which consist of layers of different soil texture with different soil particle size distribution (PSD), as shown in Fig. 2 for soil profiles in our study area. The previous research suggests that soil PSD is of great importance for soil water movement, soil erosion and soil solute migration (Hu et al., 2011). For the soil salt distribution under MDI condition, this research further suggests that layered pattern of soil PSD dominates the vertical distribution pattern of soil salinity. The Fig. 8 shows the vertical distribution of averaged EC for the three fields. For convenience, the finer particle content (<50 μm) in Fig. 2 is repeatedly plotted in Fig. 8. As we can see from this figure, the averaged EC profiles present quite unique patterns for the three fields associated with layered pattern of soil PSD. Soil salt tends to build up above the relatively impermeable layer where the soil texture changes rapidly from sandy to clay. For example, in Field #2 the finer particle content reaches its peak value (40%) at the depth of about 100 cm and soil salt accumulates at the depth of 60–80 cm where the average EC (0.85 dS m^{-1}) is 1.6 times the whole profile average value. Also in Field #3, the peak finer particle content (41%) occurs at the depth of 60 cm, and correspondingly, salt builds up at the depth of 10–40 cm, where the average EC (1.56 dS m^{-1}) is 1.5 times the whole profile average value. In field #1, however, the soil PSD is relatively uniform and no distinct salt build-up occurs.

Previous research (e.g., Yu et al., 2011) shows that in the region with shallow groundwater table the finer soil particle layer with low permeability will prevent groundwater going up to the surface soil and thus can alleviate the surface soil salinization caused by phreatic evaporation. For the MDI area, however, the upward trend of salt from groundwater to ground surface driven by phreatic evaporation is replaced by the downward trend from irrigation water to periphery of wetted soil mass due to the relative deep groundwater table and limited leaching effect. Therefore, soil salt will accumulate above the finer particle layer as shown in Fig. 8, which is opposite compared to the shallow groundwater table case.

Another interesting result is the different patterns of relationship between soil texture and soil salinity at different depths. For the root zone, the Fig. 9(a) shows the exponential relation between EC and finer particle content. While for the deep layer at the depth of 80–150 cm, the EC values remain in low level for all range of soil particle size as shown in Fig. 9(b). This should be due to the small amount of irrigation water and the lower groundwater table, which means rare percolation from top and limited phreatic evaporation from bottom. Therefore, soil salt can't move without water mobilization in the deep zone. Also, the relationship between soil texture and salinity for sandy soil layers is plotted in Fig. 10, of which the soil texture and salinity data for 0–50 cm depth are the same with the corresponding data in Fig. 9(a). Because coarser sand particles possess much smaller specific surface area than finer clay and silt particles, and the soil salt can easily move into groundwater with irrigation water flux due to the high permeability of sandy soil, the salt would not be readily accumulated in the sandy soil layer regardless of its position (e.g., neither at root layer nor at deep layer, as shown in Fig. 10). This indicates that secondary salinization would be inclined to occur in the clay soil under MDI condition.

The *M* index defined in Section 2.4 for the three fields is shown in Fig. 11(a). As we see from the figure, the *M* index profiles present

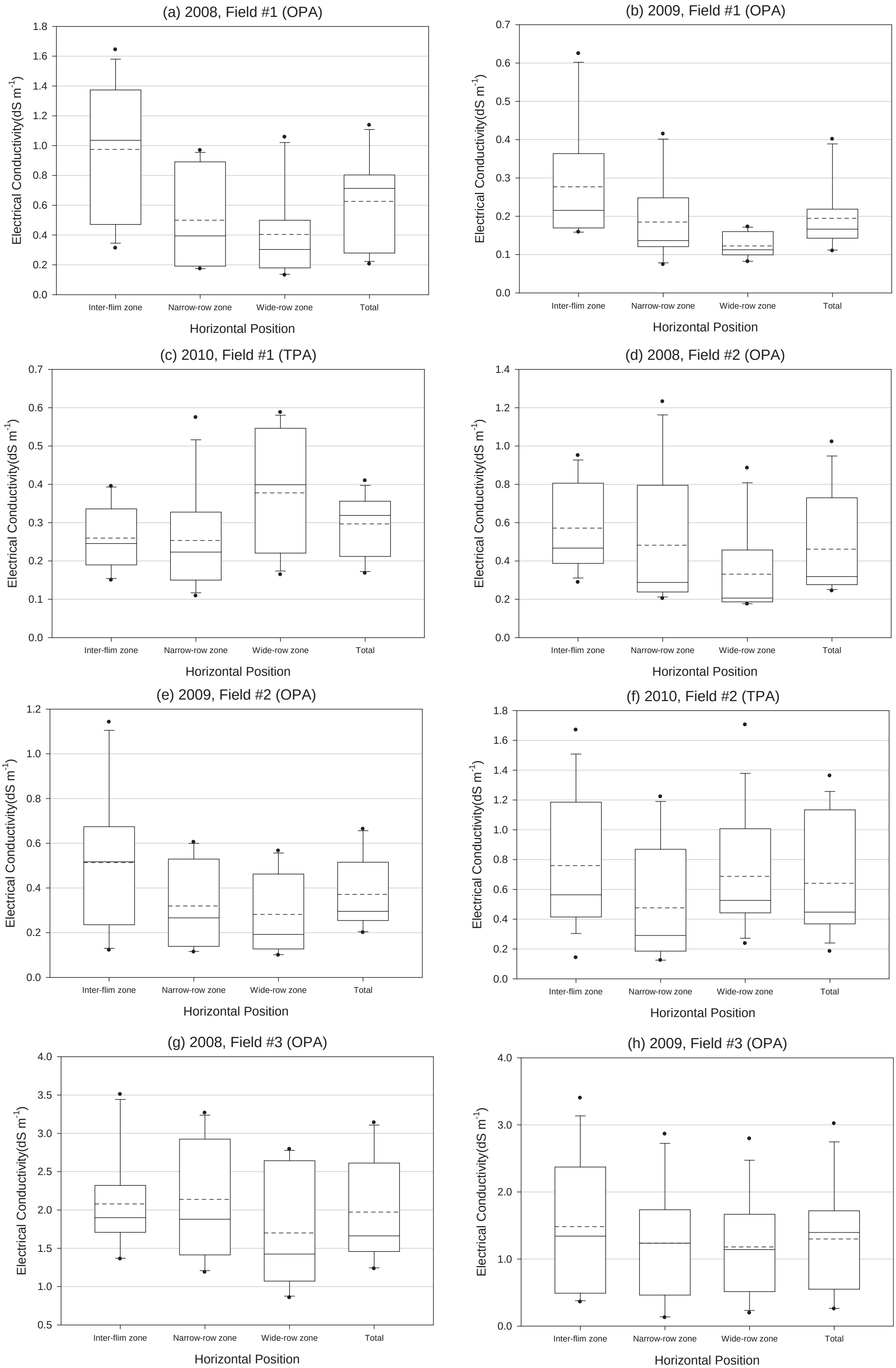

Fig. 7. Horizontal distribution of soil salinity for 0–50 cm depth at the end of irrigation period (The EC value was obtained by averaging the measurement on 1440 soil samples collected from 20th August to 2nd September from ground surface to 50 cm depth in different zones each year. See Fig. 5 for more legend explanation).

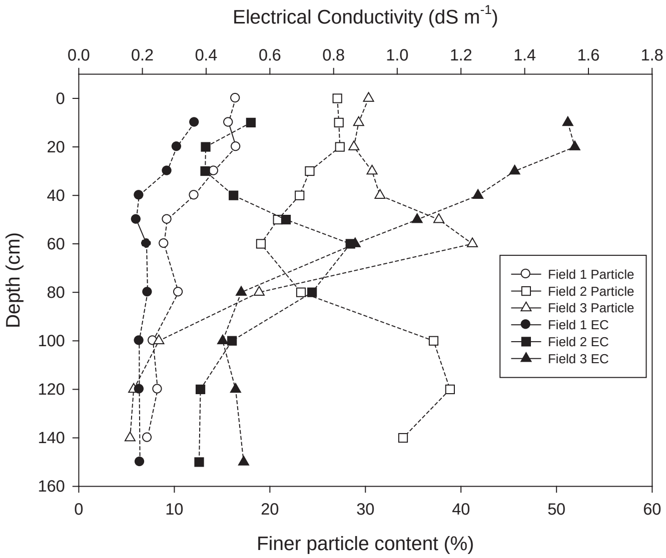

Fig. 8. Vertical distributions of average EC in soil profiles (The EC value was calculated by averaging all soil sample measurements including WRZ, NRZ and IFZ for 2 years, i.e., 2009 and 2010. Sample numbers are 4704 in Field #1 and #2, and 1584 in Field #3).

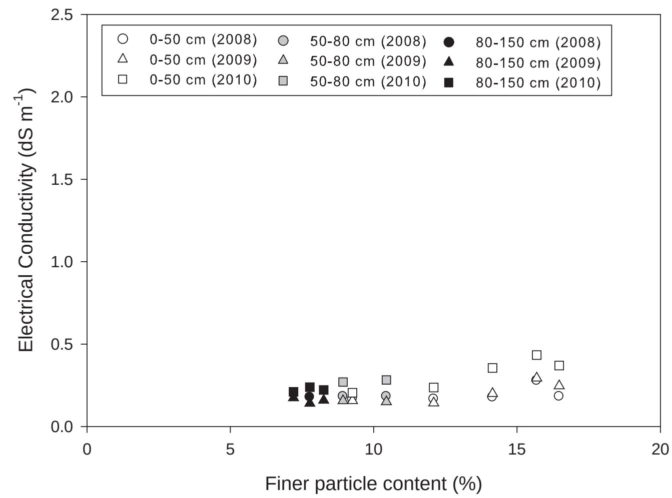

Fig. 10. The EC values varied with different layers in sandy soils (The EC value was calculated by averaging soil sample measurements at different depth in each plot of Field 1 throughout the whole growth period).

the similar patterns despite the distinct differences of soil texture and salt content among the three fields. As a comparison, we plot the vertical distribution of absolute EC value in the Fig. 11(b), which shows the totally different distribution pattern of absolute EC values among the three fields and it is hard to identify the similarity of the three profiles although they are observed at the same time under similar mulched drip irrigation schedule. We can also see from Fig. 11(a) that the *M* index is high at the surface soil layer, which indicates that surface salinity distribution is dominated by MDI; and the *M* index shows a decreasing trend toward the deeper layer, which indicates that the influence of MDI is decreasing with the downward distance from ground surface. The random plays more roles on the salinity distribution in deep layer. Furthermore, the *M* index of surface layer is higher in Field #1 than in Field #3, which can be, again, explained by the texture discrepancy between the two fields as we have already showed in the part of Section 3.1. Since Field #1 is sandier than Field #3, the movement of water flux is easier in Field #1 due to higher permeability. Therefore, the redistribution of soil salinity is more obvious in Field #1 than in Field #3. However, the general redistributed patter of *M* index which is characterized by high value at the surface and decreased trend from surface to deep zone is similar among the three fields.

The *M* index in Fig. 11(a) is calculated at the end of cotton growth period. To find out the evolution pattern of *M* index profile throughout the growth period, we first checked the initial profile of average *M* index for the three fields just after sowing (Fig. 12). The results show clearly that the initial *M* index along the profile present totally random feature with mean value around 1/6. Then the *M* index profiles at different time throughout the growth period are plotted in Fig. 13, which indicates that the MDI dominated pattern of *M* index profile is formed rather quickly after irrigation starts.

4. Summary and conclusion

Soil salt distribution under mulched drip irrigation (MDI) was analyzed based on the 3 years field experiment conducted in a cotton field of Xinjiang, northwestern China. In order to explore the

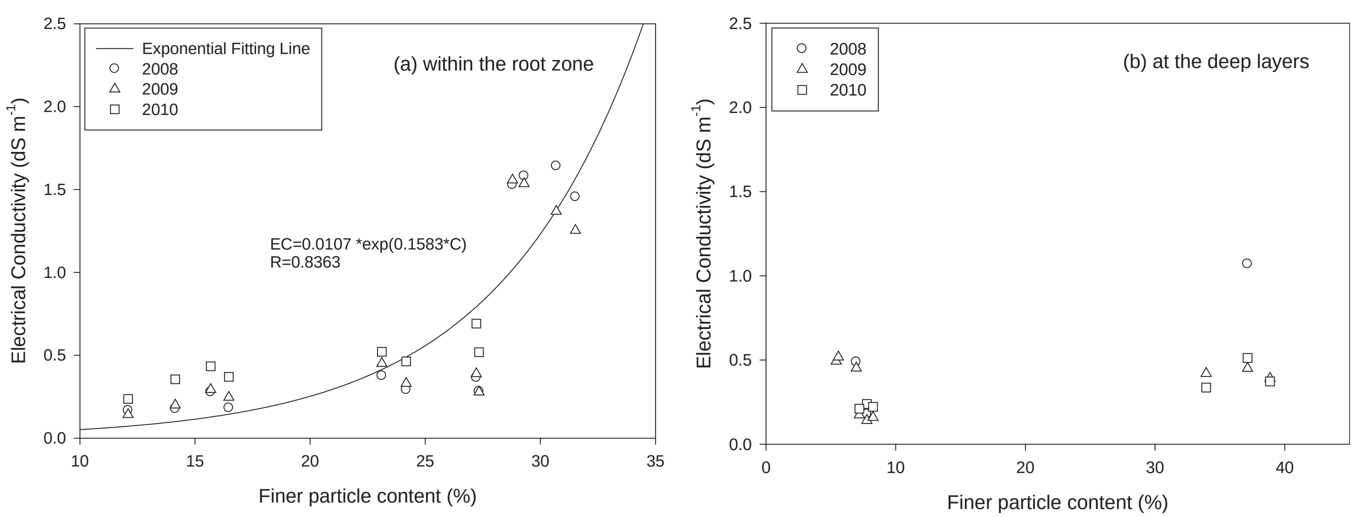

Fig. 9. Relationship between EC and finer particle content (a) within the root zone (The EC value was calculated by averaging soil sample measurements at different depth above 50 cm in each plot of all fields throughout the whole growth period); (b) at the deep layers (The EC value was calculated by averaging soil sample measurements at different depth from 80 cm to 150 cm in each plot of all fields throughout the whole growth period).

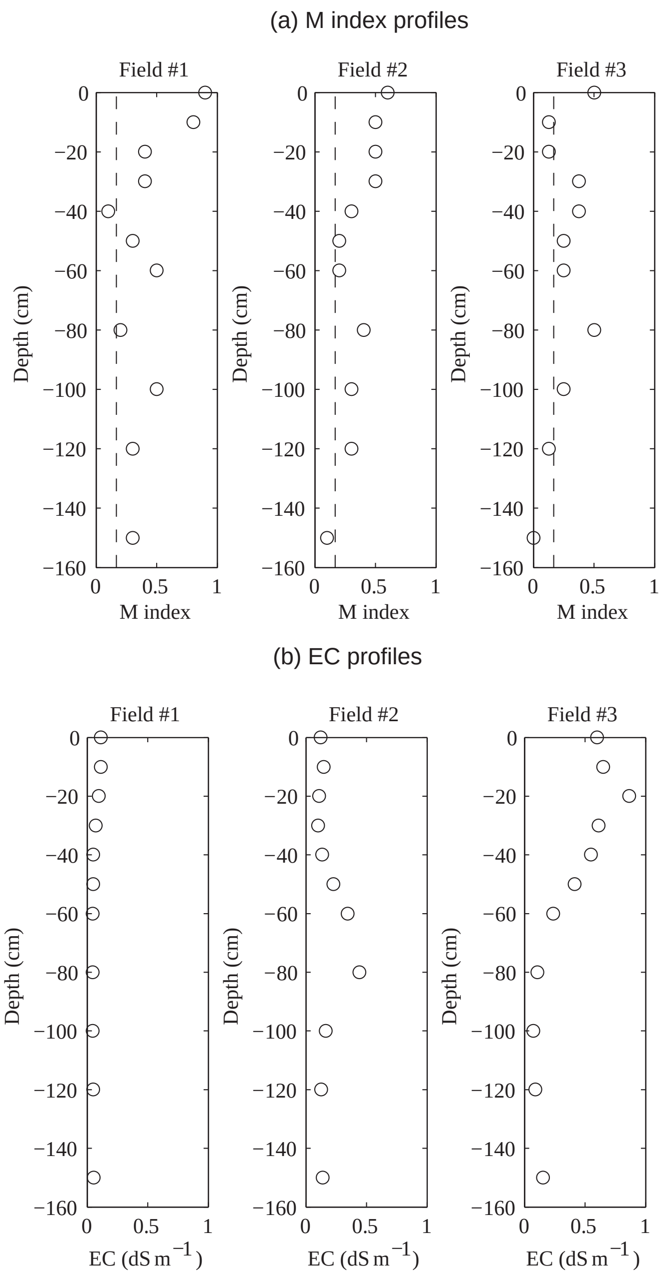

Fig. 11. Profiles for the three fields in 2009 (a) *M* index profiles (The dash line is the 1/6 line, and the *M* value was calculated by averaging soil samples collected from 20th August to 2nd September in each field; The number of sample groups K was 15 for each field); (b) EC profiles (The EC value was calculated by the same data as Fig. 11(a)).

effects of soil particle size distribution (PSD) on soil salinity three fields with three replications (9 plots) were set up according to different soil texture characterized by particle size distribution. The three fields have the distinct soil particle size distribution features, in which one field (Field #1) has the lowest clay and silt content and the PSD is relatively uniform along vertical direction, while the other two fields (Field #2 and #3) have similar higher clay and silt content but different stratified feature. The clay and silt particle layer resides in the deep zone in Field #2. Conversely, the clay and silt particle layer resides in the surface zone in Field #3. More than 15,000 soil samples were collected and tested throughout the experimental years. To deal with the strong heterogeneity of soil salinity at the field scale, we adopted a statistical dimensionless index *M* defined by Hu et al. (2011) with slight modifications in this

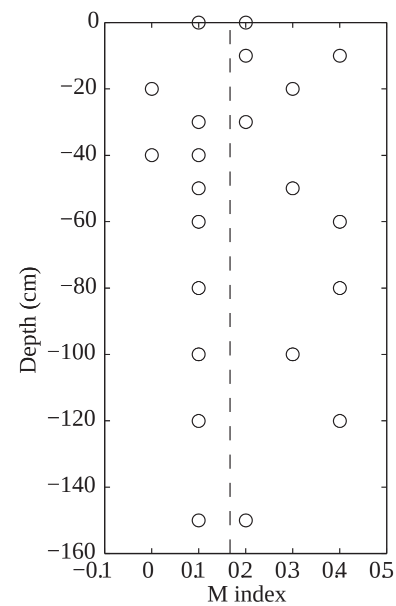

Fig. 12. Initial *M* index profile after sowing (The total number of sample groups K was 20 for this figure).

study to explore the special qualitative pattern (SQP) of salt distribution associated with MDI.

Our results show that soil particle size distribution has great influence on soil salt migration and distribution. There is a surprising exponential relationship between soil EC and clay\silt particle content in the root zone and the soil salinity increases sharply when the soil owes more clay\silt particle content. For the sandy soil, however, salt would not accumulate in both root zone and deep zone because the salt can be easily leached into groundwater due to the high permeability of soil. In the deep zone of soil profile, however, the salt content remains at lower level for all range of soil particle size due to the small amount of irrigation water and the lower groundwater table under MDI condition.

Soil salt distribution along horizontal direction follows the pattern of the water flux and tends to accumulate at the periphery of the wetted soil mass. At the end of growth period, the zone below drip pipe is at the lowest salinity level and forms a desalinization zone. Meanwhile, the salt migrates to the inter-film zone and accumulates significantly. The salinity in the inter-film zone is 1.24–2.34 times the value in the zone below drip pipe within 50 cm soil depth, according to the soil texture. Soil salt would easier transport to and accumulate in the IFZ for sandy soil than clay soil associated with the higher active movement of water flux in sandy soil.

Therefore, the soil salinization tends to be severe when the clay/silt particle content is high, whereas the redistribution along the horizontal direction may be weak under this situation due to the inactive water movement, and the MDI influence depth will be shallow. In contrast, for sandy soil, the salinization will be mild in the surface zone but the redistribution along the horizontal direction tends to be intense, and the MDI influence depth will be deeper when compared with the clay/silt soil situation.

For the common stratified natural soil profile, the relatively impermeable clay/silt layer will prevent groundwater going up to the surface soil and thus can alleviate the surface soil salinization caused by phreatic evaporation under flood irrigation condition (usually with shallow groundwater table). However, in the MDI area (usually with deep groundwater table) the upward trend of salt from groundwater to surface driven by phreatic evaporation is

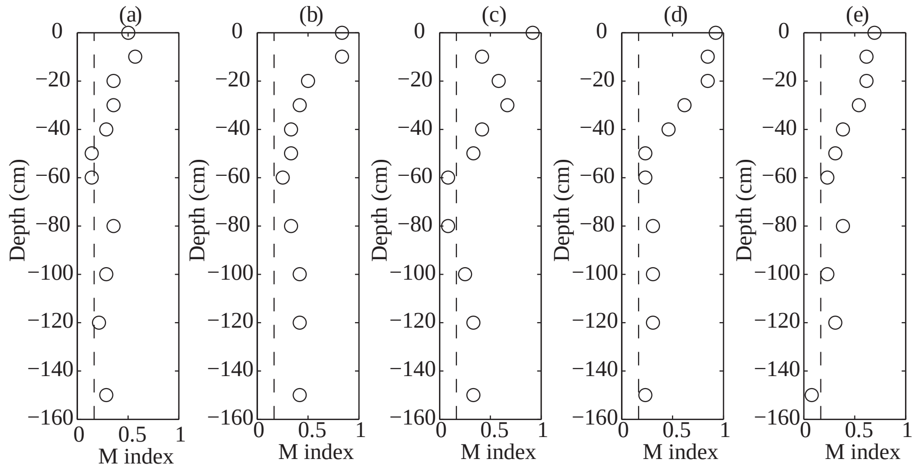

Fig. 13. The evolution of *M* index profile from June to August in 2009 in Field #2 ((a) The second half of June; (b) The first half of July; (c) The second half of July; (d) The first half of August; (e) The second half of August; The number of sample groups K was 15 for each sub-figure).

replaced by the downward trend from irrigation water to periphery of wetted soil mass. Therefore, soil salt will accumulate above the relatively impermeable layer, which is opposite compared to the flood irrigation situation.

The statistical dimensionless index *M* proposed by Hu et al. (2011) was improved in this study, which can overcome the difficulties associated with strong heterogeneity of soil salinity to recognize salt distribution pattern when using the absolute salinity value. When the soil salinity changes sharply along the vertical direction in stratified soil profile together with the strong heterogeneity, the traditional statistic methods such as weighted averaging method can hardly capture the underlying principles of salinity distribution. By using *M* index, the patterns of soil salinity distribution under MDI along the horizontal direction as well as vertical direction have been revealed in this study. The soil salt is uniformly distributed along the horizontal direction at the beginning of cotton growth period, and the salt is accumulating and the specific pattern of salt distribution will be formed gradually after irrigation begins. The *M* index results clearly show that surface salinity distribution is dominated by MDI. While the influence of MDI on salinity distribution is decreasing and the random factor dominates more when we move downward.

In this study we focus on the soil salinity distribution under mulched drip irrigation. As salts are likely to build up on the surface of cultivated soil under current MDI practice, long-term salt accumulation should be another important concern for MDI management in arid and semi-arid areas. This would be the topic in our future studies.

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