Soil salinity management on raised beds with different furrow irrigation modes in salt-affected lands

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A B S T R A C T

Mismanagement of irrigation water and the ensuing secondary salinization are threatening the sustainability of irrigated agriculture especially in many dryland regions. The permanent raised-bed/furrow system, a water-wise conservation agriculture-based practice, is gaining importance for row- and high value-crops in irrigated agriculture. However, because of additional surface exposure and elevation, raised beds may be more prone to salt accumulation especially under shallow water table conditions. A field study was carried out in 2008 and 2009 in the Khorezm region, Central Asia, to investigate the effect of three furrow irrigation methods on salt dynamics of the soil and the performance of the cotton crop on the raised bed-furrow system. The irrigation methods compared included (i) Conventional furrow irrigation wherein every furrow was irrigated (EFI) at each irrigation event; (ii) Alternate skip furrow irrigation (ASFI) where one of two neighbouring furrows were alternately irrigated during consecutive irrigations events; and (iii) Permanent skip furrow irrigation (PSFI) during which irrigation was permanently skipped in one of the two neighbouring furrows during all irrigation events. For salinity management with PSFI a ‘managed salt accumulation and effective leaching’ approach was pursued.

The EFI method increased salt accumulation on the top of the raised beds. In contrast, the PSFI method allowed an effective salt leaching from the top of the raised beds. After leaching, salinity on top of the beds under PSFI was reduced to <3 dS m−1 compared to 5–6 dS m−1 under ASFI and EFI indicating an effective leaching with the PSFI method. Raw cotton (Gossypium hirsutum L., cv. Khorezm 127) yield was higher under the PSFI (2003 kg ha−1) method having yield increases of 984 kg ha−1 (96% higher) and 787 kg ha−1 (64% higher) than under EFI (1216 kg ha−1) and ASFI (1019 kg ha−1) methods, respectively. Better crop performance with PSFI was linked with the lesser salinization of the raised beds and a larger salt free root zone before the leaching events. In addition, the PSFI method reduced irrigation water demand contributed thus to minimizing secondary soil salinization. Thus, PSFI could be an effective method to manage the salt under raised beds in salt-affected irrigated arid regions.

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1. Introduction

The expansion of irrigated agriculture in Central Asia has increased the water demand and use up to 12000–14,000 m3 ha−1 yr−1 (Nazirov, 2005). But the productivity of the drylands in this region is still constrained by frequent water shortages and continuous deteriorations in water quality due to reduced water flows in the Syr- and Amu-Darya rivers and the steady increase in the volumes of drainage water discharged back into these river systems (Qadir et al., 2009). In turn, average salt accumulation rate (5.3 t ha−1 yr−1) in the Syr-Darya Basin is 5–10 times higher than in the Indus Basin (Qureshi et al., 2008). In addition to the deterioration in irrigation water quality and excessive water allowances for leaching soil salinity problems in the Syr-Darya basin are rooted in poor on-farm water management practices. Consequently, crop production in the lower reaches of the Syr-Darya Basin seriously suffers from secondary salinization and associated

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water logging problems due to a congestion of the field drainage networks.

Conservation agriculture (CA)-based practices, that involve minimal field traffic and tillage, adequate residue retention on the soil surface and economically diversified crop rotations, can significantly influence the upward transport of soluble salts and their re-distribution in the soil profile (Brady and Well, 2008). Amongst the CA practices, raised bed planting is gaining importance including for row crops (Sayre, 2007) also due to water savings of 25–30% and increased water use efficiencies (Sayre and Hobs, 2004; Hassan et al., 2005; Malik et al., 2005; Choudhary et al., 2008; Devkota et al., 2013).

Albeit residue retention in permanent raised beds has great potential to reduce soil salinity in salt-affected areas (Devkota, 2011; Devkota et al., 2015), crop residues are not always available in sufficient quantities for mulching in Central Asia due to the high demands as feed and biofuel (Kienzler et al., 2012). In the absence of sufficient crop residues, irrigation frequency, amount and method of irrigation are known to collectively determine the quantity, status, and distribution of salts in soils (El-Swaify, 2000). When irrigation water is applied to the furrows on every side of the bed, it allows salts to leach down from the furrows (Bakker et al., 2010). But the evaporation of water during the drying periods results in salt accumulation on the tops and side slopes of the raised beds (Richards, 1954). Such salt movement to the centre of the bed may damage (young) plants seeded there (Brady and Well, 2008). With the permanent skip furrow irrigation (PSFI) method, salts are ‘pushed’ across the bed from the irrigated side of the furrow, where plants are located, to the dry side without plants. This management of root zone salinity improves emergence, stand establishment and finally crop yields in saline fields (Meiri and Plaut, 1985). However, Holland et al. (2007) underlined that too rapidly advancing irrigation water in furrows, may reduce the time for salt dissolution and a consequent salt removal from the root zone compared to flood irrigation (Scotter, 1978). Thus, benefits of raised-furrow irrigation system can be reapplied when accumulated salts are effectively leached out from the raised beds, or if permanent raised beds can be used in combination with residue retention on the soil surface to markedly reduce evaporation from the surface of the beds. We hypothesized that salts accumulated in dry furrows can be leached out efficiently, if their redistribution (between the irrigated and dry sides of the beds) can be minimized/prevented during leaching events. This can be reached by a ‘managed salt accumulation and leaching’ approach with the objective to direct salt concentrations away from the plant roots by applying irrigation water very rationally and targeted. In addition, this procedure allows higher levels of salt to accumulate without damaging crops, as salts are ‘pushed’ across the bed from the irrigated side of the furrow, where plants are located, to the dry side without plants. During irrigation/leaching events irrigation water therefore first applied to the permanently irrigated furrow and thereafter to the skipped dry furrows to leach down the accumulated soluble salts. This watering sequence will prevent the accumulated salts in the dry furrows from moving laterally towards the irrigated furrows. As a result, salinity on this sites of the beds remain lower. This hypothesis was field tested by comparing the effects of three furrow irrigation methods on salt distribution, salt leaching and crop performance under raised bed cultivation in the irrigated, arid lands of Uzbekistan, Central Asia.

2. Materials and methods

2.1. Study area and site description

The study was conducted in the Khorezm region, Uzbekistan (41°32′12″N, 60°40′44″E, and 100 m a.s.l.) in 2008 and 2009. Cotton is the major summer crop grown in the region covering annually almost 50% of the cropped area (Djanibekov et al., 2012). Intensive soil tillage and low irrigation water use efficiencies are common for crop cultivation (Tischbein et al., 2012) which takes place with generally shallow groundwater tables (0.5–2 m). The climate is arid, with long, hot and dry summers and short, very cold winters (Conrad et al., 2012). Long-term average precipitation is less than 100 mm yr−1 and is greatly exceeded by annual evaporation (Conrad et al., 2012). The soils have a sandy loamy texture, are low in organic matter (0.3–0.6%) and moderate to heavy saline (2–16 dS m−1). According to FAO (2003) classification, soils are Calcaric Gleysoils, i.e., meadow soils in the irrigated areas characterized by a shallow saline groundwater table resulting in excessive secondary salinization of surface soil layers.

2.2. Experimental set up and treatments

The study was conducted within an on-going experiment demanding a cotton mono-cropping in both years at the Cotton Research Station in the Khorezm region. After conventional tilling, fresh raised beds had been established to seed cotton in the center of 90 cm wide beds, (center of one furrow to the center of the next furrow), in April, in both years. At the 2–4 leaf stage (35–40 days after seeding) a high salinity area was identified in the experiment as evidenced by soil salinity mapping using a portable EC meter (Geonics EM-38). In 2008, the affected area had very few cotton plants, as a result of low germination and survival rates because of the high soil salinity. The average initial soil salinity in the top 30 cm soil of the affected area selected for the case study was more than 12 dS m−1. In 2009, the average initial soil salinity in the top 30 cm soil of the selected area was 6–7 dS m−1 with a resulting cotton plant density of 4–5 plants per m².

The irrigation mode experiment was laid out in a complete block design with three irrigation treatments each replicated three times. Each replication consisted of 12 beds with 0.9 m spacing (10.8 m width), and 25 m length in both years. The irrigation included three methods, namely, (i) Every-furrow irrigation (EFI), (ii) Alternating skip furrow irrigation (ASFI) and (iii) Permanent skip furrow irrigation (PSFI). During the EFI which is the conventional furrow irrigation mode, water is applied uniformly to all furrows during each irrigation event (Fig. 1A). With the ASFI method, one of two neighbouring furrows was alternately irrigated during each irrigation event. This implies that in next irrigation event the previously irrigated furrow was kept dry and the other previously dry furrow was irrigated (Fig. 1B). With the PSFI method, one of the two neighbouring furrows was permanently skipped for watering and kept dry until it became desirable to leach the salts out of the root zone for enhancing a healthy growth of crop plants (Fig. 1C).

The treatments in each replication were allocated as shown in Fig. 2. Irrigation treatments were initiated 55 days after seeding (DAS), i.e., at budding stage, in both years. Three irrigation cycles in 2008 and four irrigation cycles in 2009 were applied in each treatment at 10–12 days intervals. The average salinity level in the irrigation water was 1.1 dS m−1.

In 2008, ASFI and PSFI treatments received 31 and 32 percent less water, respectively, compared to EFI (Table 1). The amounts of irrigation water was measured using a standard trapezoidal Cipolletti weir combined with a DL/N 70 diver (installed 40 cm in front of the weir crest), which measured water flow through the weir in one-minute intervals. The irrigation time during each irrigation event for each treatment was recorded. The height of water above crest width was measured 4–5 times manually during each irrigation event. The pressure measured by the diver was transformed to height above crest (m) to estimate the discharge (m³ s⁻¹) as (Kraatz and Mahajan, 1975):
Q = 1.86 L H^{3/2} \text{where } Q = \text{discharge (m}^3 \text{ s}^{-1}), L = \text{crest width (m)}, H = \text{height of water above the crest width (m)},

Although measurements are not available for 2009, similar amounts of water as in 2008 had been applied to each treatment and during each irrigation event.

2.3. Salt leaching

After applying 3–4 irrigation events, i.e., at 80–85 DAS (boll formation stage) the accumulated salts on tops and side slopes of the beds were leached from all treatments. For leaching salt, irrigation water was applied in all furrows at the same time in the EFI and ASFI treatments. Under PSFI, salt leaching started by applying irrigation water to the permanently irrigated furrow first. After filling these furrows, the dry furrows were filled with irrigation water to leach the accumulated soluble salts from the dry furrows. Leaching was performed by keeping 5–6 cm of standing water (on the top of the bed) for about 24 h to leach down the salts with water. A boundary was made at the end of the furrows that prevented runoff.

2.4. Soil sampling

Soils were sampled before each irrigation event and before leaching, i.e., after three irrigation cycles in 2008 and four irrigation cycles in 2009 and three days after leaching. Soils were sampled

<table>
<thead>
<tr>
<th>Application time</th>
<th>Every furrow irrigation</th>
<th>Alternating skip furrow irrigation</th>
<th>Permanent skip furrow irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 DAS</td>
<td>535</td>
<td>363</td>
<td>363</td>
</tr>
<tr>
<td>66 DAS</td>
<td>596</td>
<td>419</td>
<td>395</td>
</tr>
<tr>
<td>78 DAS</td>
<td>605</td>
<td>422</td>
<td>415</td>
</tr>
<tr>
<td>Total</td>
<td>1736</td>
<td>1204</td>
<td>1173</td>
</tr>
</tbody>
</table>

Fig. 1. Methods of irrigation applied under raised bed planting. The arrows denote the direction of anticipated salt movement.

Fig. 2. Irrigation treatments allocated in each replication in raised beds. The arrows denote the bed where soil samples were taken and also the dotted furrow denotes the irrigated furrow.
each time from seven points (centre of the bed, two sides of the bed, slope of both furrows and centre of the furrows) (Fig. 3) with three replications in each treatment. Samples were taken at every 15 cm soil depth down to 90 cm using a tube auger.

The collected soil samples were air dried and analyzed for electrical conductivity (ECp) which is the EC of 1:1 water soil suspension (Richards, 1954). The ECp was converted to an international standard EC value of the saturated soil extract, ECe (Rhoades et al., 1999) especially developed for the soils in the study region (Akramkhanov et al., 2010) (Eq. (1)).

$$EC_e(\text{dS m}^{-1}) = (2.06 \times ECP_{1:1})(\text{dS m}^{-1}) \quad (R^2 = 0.90) \quad (1)$$

2.5. Yield and yield components measurement

Cotton yield and yield components were measured in 2009 only since due to the high salinity level very few cotton plants grew in the experimental area in 2008. Cotton yield and yield components were measured for each treatment plot. Raw cotton was harvested from an area of 0.9 m × 15 m (equal to an entire bed where soil samples had been taken) in three pickings and weighed separately. The average number of bolls per plant was calculated by counting the bolls in each plant of the harvested row and dividing this by the number of plants. Concurrently, ten bolls were picked randomly at each of the three pickings and oven dried at 70°C for 16 h and weighed to calculate the average boll weight.

2.5.1. Statistical analysis

Analysis of variance was conducted using repeated measures in the statistical analysis system GenStat Discovery Edition 3, VSN International Ltd., Hemel Hempstead, UK. The treatment means were separated by Fisher’s protected LSD (least significant difference ($P=0.05$)). For yield and yield components, treatment mean ± standard error is reported.

3. Results

3.1. Pre-experiment soil salinity

The pre-experiment soil salinity level, measured as ECe in the surface 30 cm soil in 2008 was significantly higher than in 2009 (Table 2). The soil salinity levels at the different depths were in the range of 2.8–14.5 dS m$^{-1}$ in 2008 and 5.7–6.8 dS m$^{-1}$ in 2009.

3.2. Salt distribution in raised beds under different irrigation techniques

The amount of total water applied to the selected furrows for the three irrigation methods amounted to 1738, 1204 and 1173 m$^3$ ha$^{-1}$, respectively, for EFI, ASFI and PSFI (Table 1). Data brought out that nearly equal water volumes had been applied in ASFI and PSFI methods during irrigation events. After 3–4 irrigation cycles, salt distribution on raised beds was significantly affected by irrigation methods in both years (Table 3; Figs. 4 and 5). The salinity level on top of the beds (15 cm depth) was significantly higher with EFI. In case of ASFI, soil salinity in the top layer was pushed around by the method of alternate skip irrigation watering, from the wet furrow towards the dry furrow side and vice versa in the next irrigation cycle (Fig. 1B). This led to a salt distribution in a larger soil volume and hence some salt dilution as compared with the pre-experiment salinity level in both years. However, under the PSFI method, the dry soil always wicked away the soluble salts from the irrigated furrow resulting in more salt accumulations at the dry furrow side. This reduced the overall salinity level in raised beds by 38% in 2008 after three irrigation cycles, but it remained unchanged in 2009 compared to the pre-experiment level. With PSFI, the salts had moved towards the top 15 cm of the side and center of the dry furrows in both years, where the salinity level in the irrigated furrows and side of the beds was lower than in the dry furrows. The treatment effects on salinity changes at deeper soil layers were not as large as in the case of the top 15 cm soil (Figs. 4 and 5).

3.3. Salt distribution in raised beds after leaching

After applying leaching water, the accumulated salts were washed out of the raised beds; hence soil salinity levels in all three treatments decreased significantly in both years (Table 4; Figs. 4 and 5). Among the treatments, the salinity level on the top 15 cm soil in all positions and in the top 90 cm soil on the center of the beds was lower, i.e., <3 dS m$^{-1}$ under PSFI. This concentration was lower also than the 5–6 dS m$^{-1}$ that remained on the side to center of the bed in the top 60 cm soil depth in EFI and ASFI in both years (Figs. 4 and 5). This indicates that the salts from the top of the bed in the PSFI treatment, i.e., under managed accumulation, were leached properly compared to the EFI and ASFI treatments. The results (Figs. 4 and 5) clearly illustrated a salt accumulation in the top and side layers of the raised beds under EFI and ASFI as they were leached to lesser extent due to lower leaching fractions compared to those for lower raised bed positions.

3.3.1. Cotton yield and yield attributes with different furrow irrigation techniques

Raw cotton yield was significantly affected by the irrigation methods; the highest cotton yield (2003 kg ha$^{-1}$) was observed with PSFI, where the yield was increased by 984 kg ha$^{-1}$ (96% higher) and by 787 kg ha$^{-1}$ (64% higher) compared to EFI and ASFI, respectively. Similarly, cotton yield in ASFI was 1216 kg ha$^{-1}$ and was higher by 19% than under EFI. Bolls per plant and per boll weight were higher in PSFI than under ASFI, where the number of bolls per plant was higher by 55% and boll weight by 15%.

Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Soil salinity (dS m$^{-1}$) at different soil depths (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–15 cm</td>
</tr>
<tr>
<td>2008</td>
<td>14.5 ± 1.5</td>
</tr>
<tr>
<td>2009</td>
<td>6.8 ± 1.1</td>
</tr>
</tbody>
</table>
Fig. 4. Salt distributions (ECe, dS m⁻¹) before (BL) and after leaching (AL) with different irrigation/leaching methods in 2008.

Fig. 5. Salt distributions (ECe, dS m⁻¹) before leaching (BL) and immediately after leaching (AL) with different irrigation/leaching methods in 2009.
respectively. The difference in bolls per plant between ASFI and EFI was statistically not significant (Table 5).

4. Discussion

In a recent review on the future of conservation agricultural (CA) practices in the irrigated areas of Central Asia, Kienzler et al. (2012) concluded that a major constraint for the spreading of permanent raised beds, the most promising CA practice in irrigated agriculture in this region, is the reluctance of farmers to retain crop residues. This is due partly to the non-availability of appropriate machinery, which can seed into loose and anchored residues and the high demand for residues as livestock feed. Reducing the mulch component in this CA practice would obviously nullify the potential benefits of raised beds, for example increase soil salinity level on top of the beds (Devkota, 2011; Devkota et al., 2015). Results of the PSFI showed however that salt accumulation can be reduced on top of beds even in absence of crop residues. After 3-4 cycles of furrow irrigation, salts in the EFI and ASFI treatments had accumulated mainly on the top and sides of the beds, while in the PSFI treatments salts had accumulated towards the dry furrow (Figs. 4 and 5). The higher salt accumulation towards the side and center of the bed under EFI and ASFI indicated that when applying irrigation water to both furrows of the raised beds concurrently, the salts tended to move towards the side and center of the bed. Consequently, in salt-affected, irrigated croplands the EFI mode, which is common under bed and furrow systems, increases salt accumulation on the center of the beds. Under such conditions, crops grown on the bed are likely to become injured by the salts (Brady and Well, 2008) which results in decreased yield and yield components of crop grown as was observed also in our experiment under EFI.

However, the accumulation of salts predominantly at the site of the dry furrow under PSFI indicated that salts had moved from the irrigated side (wet zone) of the bed across the beds to the dry side (dry zone) once a sufficient amount of irrigation water was applied in the same furrow during all irrigation events. This was similar to the reported salt dynamics under PSFI for a salt-affected region in Colorado, USA (Cardon et al., 2010). This implies that with PSFI in raised bed plantings in salt-affected areas a suitable zone for plant growth can be created by effectively lowering the soil salinity level in the designated plant growth zones. Due to PSFI, plant roots grow towards the irrigated furrow in their search for compensating the reduced water and nutrient uptake by roots exposed to the higher saline areas. This is turn leads to increased yield and yield attributes of cotton under PSFI compared to EFI and ASFI (Table 5).

The experimental area had an average salinity in 2009 of 6.8 dSm^-1, indicating moderate soil salinity (Abrol et al., 1988), but the raw cotton yield under PSFI (2.1 t ha^-1) was almost similar to the average 2009 yield of cotton in the study region (2.7 t ha^-1). Although the determination of root growth and nutrient uptake fell beyond the scope of this study, previous findings showed that the root biomass and nutrient and moisture uptake decrease with increased salinity levels (Maas and Grattan, 1999; Chen et al., 2010). Based on these findings, it can be assumed that in salt-affected irrigated dry lands, PSFI could be an effective irrigation alternative to EFI in combination with permanent raised beds.

### Table 3
Analysis of variance of soil salinity distribution before leaching and as affected by irrigation method and position at the beds during 2008 and 2009 (the numbers indicate P values).

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Significance level at different soil depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15 cm</td>
</tr>
<tr>
<td>Treatment</td>
<td>2</td>
<td>0.001</td>
</tr>
<tr>
<td>Position</td>
<td>6</td>
<td>0.01</td>
</tr>
<tr>
<td>Position × treatment</td>
<td>12</td>
<td>0.001</td>
</tr>
<tr>
<td>Treatment</td>
<td>2</td>
<td>0.001</td>
</tr>
<tr>
<td>Position</td>
<td>6</td>
<td>0.01</td>
</tr>
<tr>
<td>Position × treatment</td>
<td>12</td>
<td>0.001</td>
</tr>
</tbody>
</table>

ns = non significant.

### Table 4
Analysis of variance of soil salinity distribution after leaching and as affected by irrigation method and position of the beds during 2008 and 2009 (The numbers indicate P values).

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Significance level at different soil depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15 cm</td>
</tr>
<tr>
<td>Treatment</td>
<td>2</td>
<td>0.04</td>
</tr>
<tr>
<td>Position</td>
<td>6</td>
<td>0.003</td>
</tr>
<tr>
<td>Position × treatment</td>
<td>12</td>
<td>0.01</td>
</tr>
<tr>
<td>Treatment</td>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>Position</td>
<td>6</td>
<td>ns</td>
</tr>
<tr>
<td>Position × treatment</td>
<td>12</td>
<td>ns</td>
</tr>
</tbody>
</table>

ns = non significant.

### Table 5
Cotton yield and yield attributes in different irrigation treatments in 2009.

<table>
<thead>
<tr>
<th>Irrigation method</th>
<th>Raw cotton yield (kg ha^-1)</th>
<th>Bolls per plant</th>
<th>Boll weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Every-furrows (EFI)</td>
<td>1019 ± 40</td>
<td>5.6 ± 0.5</td>
<td>4.92 ± 0.04</td>
</tr>
<tr>
<td>Alternating skip furrow (ASFI)</td>
<td>1216 ± 120</td>
<td>5.6 ± 0.9</td>
<td>5.25 ± 0.23</td>
</tr>
<tr>
<td>Permanent skip furrow (PSFI)</td>
<td>2003 ± 182</td>
<td>8.7 ± 0.01</td>
<td>6.05 ± 0.15</td>
</tr>
</tbody>
</table>

± = standard error.
Salinity levels after 24 h of salt leaching on the top to side of the beds under EFI and ASFI reached still 5–6 ds m⁻¹ compared to <3 ds m⁻¹ observed under PSFI; in spite of similar amounts of leaching water: hence the leaching efficiency with EFI and ASFI was much lower than with PSFI. The higher salinity in the bed tops with EFI and ASFI indicates also that the passage of the irrigation water was less in those upper bed-positions leading to a reduced leaching of soluble salts. In previous studies it was postulated that for an 80% reduction in profile salinity, about one cm of leaching water/cm soil depth is required to be passed through the soil (Dieleman, 1963; Leffelaar and Sharma, 1977; Khosla et al., 1979). This indicates that to leach the accumulated salt also from the top of the beds under EFI and ASFI, either more water is needed or the beds need to be dismantled.

Under conventional agriculture practices on the salt-affected, irrigated croplands of Uzbekistan, crop production is made possible after leaching the accumulated salt in early spring only (Forkutsa et al., 2009). Salt leaching in early spring by dismantling the beds, made before vegetative period, and by applying about 4500 m³ ha⁻¹ of water, is a common practice in the study region (Forkutsa et al., 2009). Ochs and Smedema (1996) estimated that in the Aral Sea Basin even more water (about 5000 to 10000 m³ ha⁻¹ yr⁻¹) is applied for leaching highly saline cropland. The use of such immense amounts of fresh water can hardly be sustainable and especially since the availability of irrigation water is bound to decline in the region (Forkutsa et al., 2009; Gupta et al., 2009).

After leaching, the low salinity level (<3 ds m⁻¹) on the top of the beds under PSFI in both years suggests that salinity in permanent raised beds in irrigated arid croplands had been leached effectively through PSFI. This could be due to the fact that the accumulated salts in the dry furrow moved downward instead of laterally (Figs. 4 and 5), indeed caused by filling water in the dry furrow only after filling all the furrows designated for irrigation first. Hence, applying water under PSFI can also reduce the amount of irrigation water by 32% compared to the conventional, every-furrow irrigation method (Table 1). Thus, PSFI on permanent raised beds has the potential also to reduce the harmful effect of over-irrigation which is also common in the study region (Tischbein et al., 2012) resulting also in saline and shallow groundwater areas. Similarly, under PSFI there is a possibility to leach the accumulated salts in the dry furrow even during the vegetative growth stages. This option helps to avoid salt injury during crop growth stages, and increasing crop productivity in salt-affected irrigated lands.

The cotton was planted on the center of the bed however, when planted on the side of the irrigated furrow, and when taking care not reducing the plant population, it can be expected that cotton yields could be further increased under PSFI, as the salinity level on the irrigated side of the furrow is always low and some crops such as cotton can stand this low-saline environment (Figs. 4 and 5). Benefits would, therefore, be even greater if a salt-sensitive crop was planted on the side of the irrigated furrow in combination with a salt-tolerant crop on the side of the dry furrow.

5. Summary and conclusions

Soil salinity on top of raised beds increased when irrigation water was applied to both furrows flanking the beds. In permanent skip furrow irrigation, salts accumulated towards the dry furrows and hence, this technology has the potential to reduce salt concentrations on the top and the side of the raised beds by 2–3 times compared to EFI and ASFI. In addition, the soil salinity level on the irrigated side of the furrow under PSFI was always low, and crop roots can grow in the direction of the low saline environment. As a result, cotton yields were significantly affected by the irrigation methods; with PSFI cotton yields were increased by 984 kg ha⁻¹ (96% higher) and 787 kg ha⁻¹ (64% higher) compared to EFI and ASFI, respectively.

The salts from the beds were leached properly under PSFI compared to ASFI and EFI. After leaching, the salinity level on top of the bed under PSFI was reduced to <3 ds m⁻¹ (i.e., by 100%) compared to 5–6 ds m⁻¹ under ASFI and EFI. Thus, permanent skip furrow irrigation facilitated efficient leaching and concurrently reduced the amount of irrigation water.

The PSFI practice could be possibly more beneficial to farmers if cultivating plant salt-sensitive crops on the side of the irrigated furrows and a salt-tolerant less water requiring crop, for example cotton, on the side of the dry furrows. Further research is however needed to identify the combination of the salt-tolerant and susceptible crops to cultivate on raised beds with PSFI and its benefits to the farmers and the environment.

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