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Impact of spatially variable soil salinity on crop physiological properties, soil water content and yield of wheat in a semi arid environment

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Abstract

In the Birchip region of the Victorian southern Mallee, Australia, subsoil salinity is an important factor determining crop growth and yield. Crop simulation models have performed poorly in this region, presumably due to their inability to account for subsoil constraints, mainly salinity. The objective of this work was to study the impact of subsoil salinity on crop physiological properties, growth, water use and yield of a wheat crop. From a calibrated electromagnetic survey (EM 38) over an area 7 m wide by 100 m long, three sites of low, medium and high salinity levels were identified. For each site, soil electrical conductivity was measured and the values averaged for the depth 0-70 cm were 0.25, 1.14 and 1.63 dS/m at the sites with low, medium and high salinity, respectively. Further, at different stages of crop growth, radiation interception by the canopy as well as soil water content were measured while plant samples were collected to estimate crop physiological properties. Grain yield at each salinity site was also measured. All the physiological properties and yield were negatively affected by increasing salinity levels due to less water use and radiation interception. Compared to the low salinity level, medium and high salinity levels reduced the above-ground dry weight of the crop at harvest by 40% and 41%, accumulated intercepted radiation by 23% and 37%, radiation use efficiency by 25% and 52%, water use by 18% and 35% and grain yield by 41% and 48%, respectively.

Key words: Spatial variability, salinity, water use, wheat yield, radiation use efficiency.

Introduction

Soil salinity in arid and semiarid regions leads to reduced crop growth and yield. The most dominant influences on yield variability (other than climate) are the soil physical and chemical factors such as soil texture and salinity (Whelan and McBratney, 2003). Salinity limits the water uptake of plants by reducing the osmotic potential and thus the total soil water potential (Corwin and Lesch, 2003; Sheldon *et al*., 2004). As soil dries, the concentration of salt in the soil solution increases, further decreasing the osmotic potential (Sheldon *et al*., 2004). In dryland regions with annual rainfall between 250 and 600 mm, saline subsoils having ECe values (electrical conductivity of the soil saturation extract) between 2 and 16 dS/m can dramatically affect crop production through osmotic effects during dry periods. The combination of poor water storage and osmotic stress increase water stress of crops in such areas (Rengasamy, 2002). Salinity affects both vegetative growth and reproductive development. While the more obvious effects are on the rate of leaf appearance and the number of shoots capable of producing fertile ears, the reproductive process itself can be affected (Munns and Rawson 1999). Physiologically, many processes are affected, but the most notable are reduced cell growth and decreased leaf area, biomass and yield (Acevedo *et al*., 2005). A recent investigation of cropping systems on Calcarosols in the Victorian southern Mallee (Nuttall *et al*., 2003c) showed that these soils contain variable but usually high levels of salt, exchangeable sodium and boron. Salinity, alkalinity, and boron toxicity in many soils in this region is also reported by Incerti and O'Leary (1990) and Holloway and Alston (1992). Nuttall *et al.* (2003a) showed that in Calcarosols, the available water in the shallow subsoil (0.10 - 0.40 m) and the level of salinity and sodicity in the deeper subsoil (0.60 - 1.00 m) were the most important factors explaining variation in grain yield of wheat. The difference in root growth of wheat and water extraction also correlated well with the level of salinity in this area (Nuttall *et al*., 2003b). The objective of this work was to study the impact of subsoil salinity on crop physiological properties, *e.g.*, leaf and stem growth, biomass production, radiation use efficiency and water use and yield of a wheat crop in an unreplicated experiment, which could help in improving the performance of crop models in these areas.

Materials and methods

Experimental site

The experimental site for the study was a plot of 7m x 100 m at the Birchip Farming System trial site, about 20

Table 1. Soil properties of samples at low, medium and high salinity levels

Soil Layer (cm)	0-10	10-25	25-40	40-55	55-70	70-85	85-100
	Low salinity level						
EC (1:5) (dS/m)	0.25	0.26	0.24	0.29	0.22	0.27	0.35
Bulk Density (g/cm^3)	1.33	1.36	1.39	1.42	1.44	1.43	1.41
Clay (%)	30	42	45	51	53	55	56
Sand (%)	56	53	45	37	35	37	39
Silt (%)	14	5	10	12	12	8	5
	Medium salinity level						
EC (1:5) (dS/m)	0.42	0.71	1.38	1.52	1.69	1.72	1.21
Bulk Density (g/cm^3)	1.33	1.36	1.39	1.42	1.44	1.43	1.41
Clay (%)	27	41	51	51	48	46	45
Sand (%)	60	46	35	34	39	40	44
Silt (%)	13	13	14	15	13	14	11
	High salinity level						
EC (1:5) (dS/m)	0.85	1.74	1.85	1.88	1.85	1.54	2.21
Bulk Density (g/cm^3)	1.33	1.36	1.39	1.42	1.44	1.43	1.41
Clay (%)	24	54	55	57	51	59	49
Sand (%)	61	32	32	34	32	29	37
Silt (%)	15	14	13	9	17	12	14

km north of Birchip in the Victorian southern Mallee (35.82°S and 148.98°E) Australia. The environment is semi-arid with an average annual rainfall of 376 mm, most of which falls between April and October (Anon., 1999; Nuttall *et al*., 2003b).

Experimental plan, data collection and data analysis

A 7m x 100m experimental plot was selected in the experimental site and an electromagnetic (EM) survey map of the apparent soil electrical conductivity of the plot was obtained by using an EM 38 system (Geonics Corporation Ltd., Ontario, Canada) to represent soil properties, mainly salinity. Three sites corresponding to low, medium and high salinity levels were identified in the plot. Within the plot salinity varied highly, so the experiment was carried out without replication because the sites for replication could not be practically fixed. Also the aim of the study was not to perform any kind of statistical analysis but to observe the impact of salinity on wheat growth, water use and yield at these three selected salinity levels for indicative purpose. This may establish the need to select soil salinity as the main soil constrains to modify the crop models in order to explain yield variation in the study area. At each of the three salinity levels, soil samples up to the depth of 100 cm were collected and analysed by the State Soil Lab at Werribee. At these sites, the laboratory-measured electrical conductivity (EC, in 1:5 soil: water suspension) averaged for the depth 0-70 cm were 0.25, 1.14 and 1.63 dS/m respectively. Other soil properties at low, medium and high salinity levels are shown in Tables 1. Sowing was completed on 13th May 2003 with a row spacing of 23 cm (9 inch) and no fertiliser was applied. During the cropping season, plant samples were collected from one-metre linear distance around each salinity point at different crop growth stages (e.g, tillering, anthesis and harvest) for observation and the following variables were measured: time course of crop intercepted radiation, leaf area, number of leaves, dry weight of different plant parts, above-ground biomass and yield in order to observe the effect of subsoil salinity on crop physiological properties, biomass and yield. From above measurements leaf area index and radiation use efficiency were calculated. The incoming solar radiation was measured five times during the crop growth. At each salinity site, incoming radiation was measured above and below the canopy by SunScan Canopy Analyser (Delta-T Devices Ltd., Cambridge, UK). Three replications were made at each point and average of those three readings was taken to calculate the fraction of radiation intercepted by the plant canopy. Ten plants were chosen as sub samples and leaf area was measured by a leaf area meter then the leaves and stems were oven dried at 70 °C for three days to obtain dry weight of leaves and stems. Shoot dry weight, which is the total dry weight of leaves and stems of the plants, was also measured. The remaining plant samples were also dried in an oven at 70 ºC for three days to obtain above-ground biomass. Plants samples were manually harvested from a linear distance of one metre around each salinity level on 30th November 2003. Total above-ground biomass was calculated by drying plant samples in an oven for 3 days at 70 ºC and then taking their weight. Total numbers of spikes were counted at each harvest sample and they were manually threshed with 100% grain recovery. Grain numbers were counted by a grain counting machine

Table 2. Harvest parameters, water use and rooting depth at different salinity levels

	Low Salinity	Medium Salinity	High Salinity
Harvest area (m^2)	0.23	0.23	0.23
Above-ground biomass (g/m^2)	1268	763	748
# of spikes/m^2	443	343	360
# of grains /m^2	11839	7078	6400
Weight of 1000 grains (g)	38.3	38.1	36.8
Grain yield (t/ha)	4.5	2.7	2.4
Harvest Index	0.36	0.35	0.32
Total water use (mm)	304	249	197
Rooting depth (cm)	90	90	50

and total weight of 1000 grains was measured. Finally, grain yield was measured in tonnes per hectare and harvest index was calculated by dividing grain yield by total above-ground biomass at each harvest sample. Soil water at each salinity level was monitored by means of neutron probes which were already calibrated against the soil water content measured by gravimetric method before installation. One neutron probe was installed at each salinity point in order to measure soil water content at each salinity level. The installation was carried out at the time of sowing and their readings were recorded four times during the crop growth period. They were translated into volumetric soil water content at each layer *i.e*., 15-30, 30-50, 50-70 and 70-90 cm by multiplying the bulk density of the corresponding soil layer. Readings from the top layer of 0-15 cm were discarded because it was believed to be imprecise due to the scattering of neutrons into the atmosphere. At harvest, the gravimetric soil water content was measured up to the depth of 90 cm and it was then translated to volumetric soil water content. Total amount of soil water available at each soil layer was calculated by making adjustment for the depth of that layer. After these calculations were made, total water use by the crop at each salinity level, up to the depth of 90 cm, was calculated by summing up the amount of initial water available during sowing of the crop and the total rainfall during that period less the amount of water available at the next neutron probe readings. The rooting depth was measured by digging a soil pit by back-hoe at harvest and is given in Table 2.

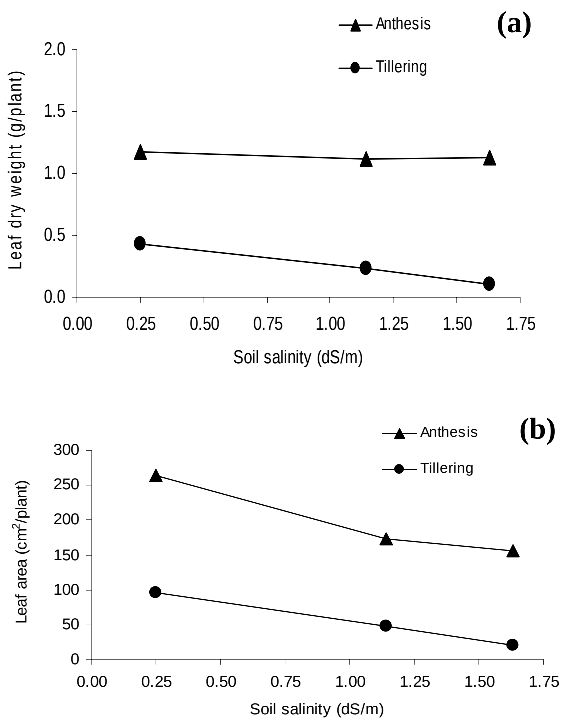

Fig 1. Leaf dry weight (g/plant) (a) and leaf area (cm^2/plant) (b) of wheat at low, medium and high salinity levels

Results and discussion

Leaf and stem development

Leaf dry weight was 47% and 77% lower at tillering and about 38% lower at anthesis for the medium and high salinity levels respectively, in comparison with the low salinity level (Figure 1a). The rate of growth of leaf dry weight from tillering to anthesis was 0.017, 0.011 and 0.013 g/day at low, medium and high salinity level, respectively. It shows that the rate of growth of leaf dry weight was about 35% and 24% lower for medium and high salinity level, respectively in comparison to the low salinity level. The difference in the rate of growth of leaf dry weight for medium and high salinity levels was not observed to be high, indicating that the crop was more sensitive to salinity when salinity increased from 0.25 to 1.14 dS/m but it was less affected when salinity increased, by a lesser factor, from 1.14 to 1.63 dS/m. This is in agreement with the findings of Rengasamy (2002) as ECe is five times higher than EC (1:5). There was about 50% and 77% decrease in leaf area for medium and high salinity compared to low salinity at tillering and 35% and 42% at anthesis (Figure 1b). This shows that leaf growth was more affected by salinity at early stages. Early effect of salinity on plant growth has been reported by many researchers. Munns *et al*. (1995) reported that the initial growth reduction is induced by the decreased water potential of the rooting solution rather than the presence of a specific salt in it. Van Hoorn (1991) reported that in low rainfall areas, due to the evaporation of soil water during germination and emergence, salinity increases strongly in the top layer of the soil and plants are exposed to a higher salinity than during later growth stages. This adversely affects the crop growth at the early

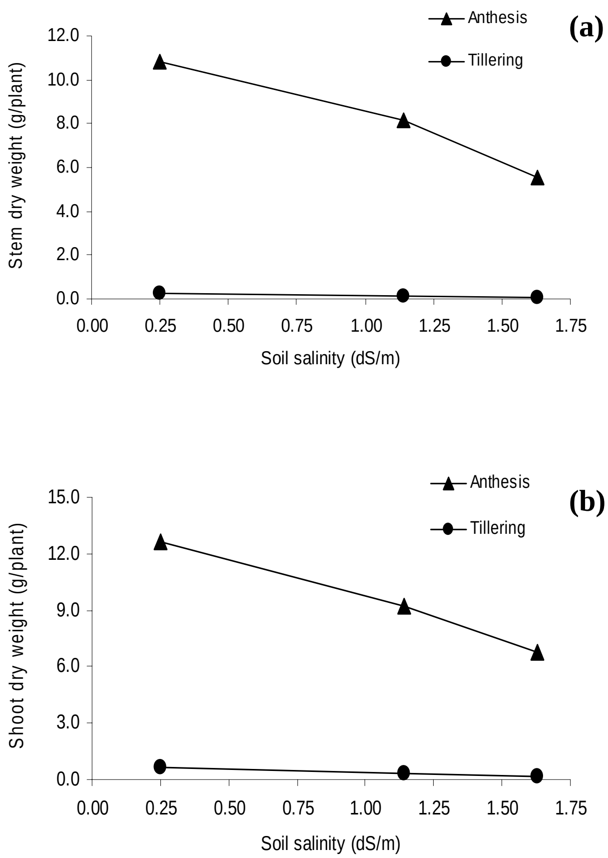

Fig 2. Shoot (a) and stem (b) dry weight (g/plant) at low, medium and high salinity levels

stage. The growth rate of leaf area from tillering to anthesis was found to be 2.08, 1.55 and 1.67 cm^2/day at low, medium and high salinity levels, respectively. This shows that the rate of growth of leaf area was about 25% lower for medium and 20% lower for high salinity level in comparison with the low salinity level indicating decline in leaf area growth with increase in salinity from 0.25 to 1.14 dS/m but only a slight decrease in leaf area when salinity increased from 1.14 to 1.63 dS/m. The decrease in the growth of leaf and leaf area maybe due to the less water available to the plants at high salinity levels as reported by Munns and Termaat (1986) that the rate of leaf area expansion is governed by the response of the root to low water potential in the soil exposed to salinity. Sheldon *et al.,* (2004) reported that in the experiment conducted by them, the most significant impact of increased salinity on growth of wheat was the osmotic effect in reducing plant water uptake. A 45% and 76% reduction in shoot dry weight at tillering and about 27% and 46% at anthesis was observed at medium and high salinity levels, respectively in comparison with the low salinity level (Figure 2a). Shoot dry weight was found to be the lowest in the case of high salinity level. These results show that leaf, stem and total shoot growth were more affected at the initial phase of crop growth and comparatively less at the later stage. Growth rate of shoot dry weight was 0.15, 0.11 and 0.08 g/plant, showing that a 26% and 45% reduction in shoot growth rate was observed in medium and high salinity level in

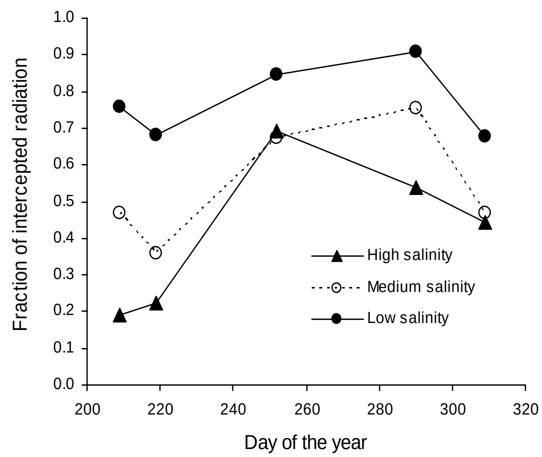

Fig 3. Fraction of intercepted radiation with respect to time. Tillering occurred on day 209 and anthesis on day 290

comparison with low salinity level. These results corroborate with the findings of others *e.g.,* Francois *et al.* (1986) found that the vegetative growth of wheat was decreased by soil salinity more than was grain yield, with a threshold soil salinity of 4.5 dS/m electrical conductivity of the saturation extract *i.e,* 0.9 dS/m of 1:5 in soil suspension. Rivelli *et al.* (2002) reported that the shoot relative growth rate throughout the experimental period showed that salinity reduced growth only during early development (14-20 days after emergence) in wheat. Soil salinity affects the normal development and viability of tillers; it also decreases the number of primary and secondary tillers. A salinity level of 7.5 dS/m electrical conductivity of the saturation extract eliminates the secondary tillers and reduces the number of primary tillers (Acevedo *et al.,* 2005). Different levels of salinity also affected stem growth. There was about 44% and 74% decrease in stem dry weight for medium and high salinity, respectively in comparison with the low salinity at tillering and 25% and 47% decrease at anthesis (Figure 2b). This also shows that the stem growth was more affected by salinity at the early stage of crop growth in the same manner as leaf and shoot growth. The growth rates of stem from tillering to anthesis were 0.13, 0.10 and 0.07 g/day at low, medium and high salinity levels, respectively showing that salinity negatively affected stem growth and a 24% and 47% decrease was observed in stem growth rate at medium and high salinity levels in comparison with the low salinity level.

Accumulated intercepted radiation and radiation use efficiency

Effect of salinity on fraction of intercepted radiation is evident from the early growth of crop (Figure 3). Plants at low salinity level intercepted higher amount of incoming radiation which in turn contributed to the higher leaf area and plant biomass production. Crops at low and medium salinity levels show more or less similar trends for radiation interception during progression of crop growth with the crop at the low salinity level always intercepting more radiation than the crop at the medium salinity level. However, at the high salinity level the crop intercepted the lowest amount of incoming radiation

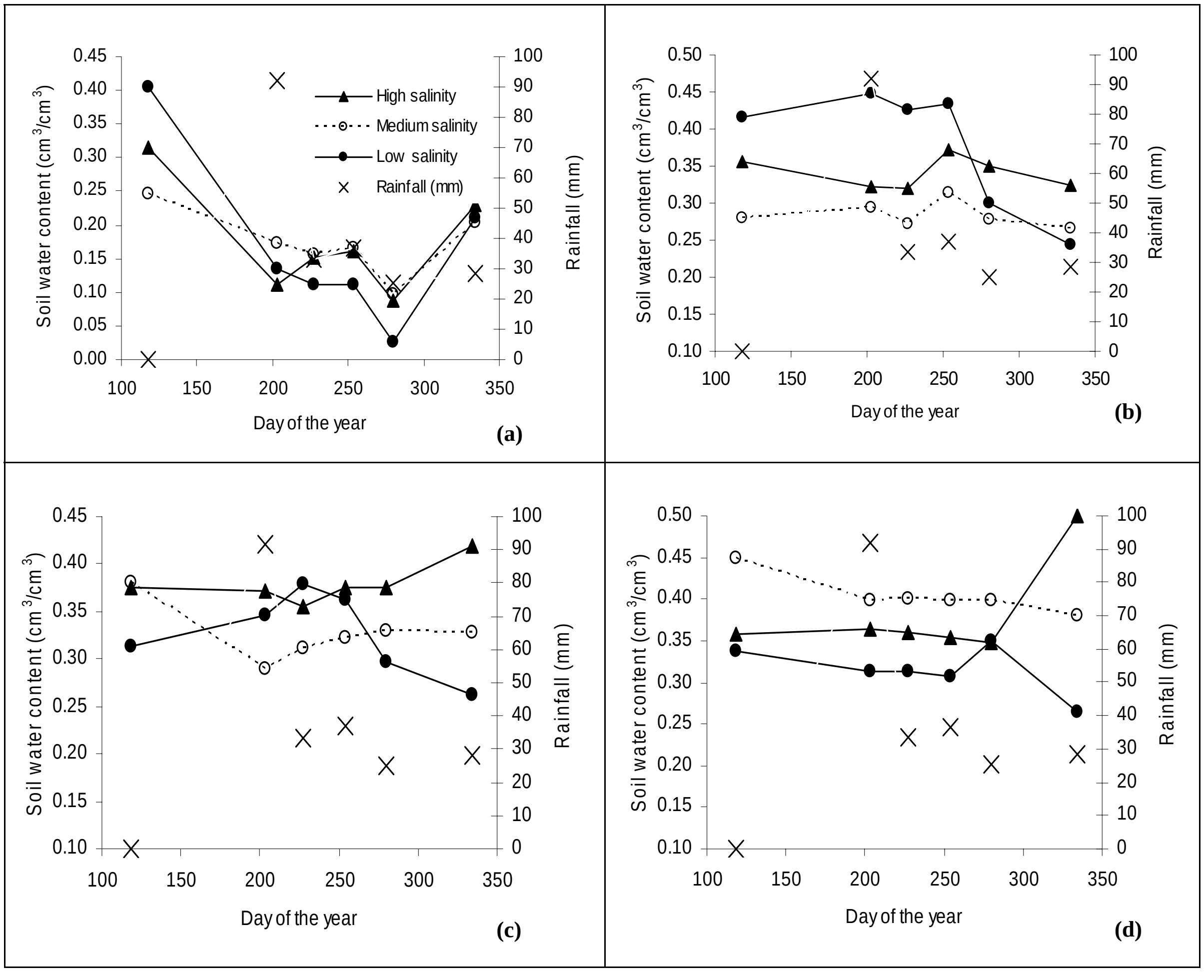

Fig 4. Soil water content at 15-30 (a), 30-50 (b), 50-70 (c) and 70-90 cm (d) soil layers at low, medium and high salinity levels in wheat and corresponding rainfall.

during the early stages of crop development. The Radiation use efficiency (RUE) was found to be 2.06, 1.54 and 0.99 g/MJ at low, medium and high salinity levels, respectively. The RUE is the biomass production per unit of photosynthetically active radiation intercepted by the plants. The effect of different salinity levels on accumulated intercepted radiation and radiation use efficiency of wheat was observed and the results show that both were reduced by higher level of salinity. The accumulated intercepted radiation was reduced by 23% and 37% and RUE was reduced by 25% and 52% at medium and high salinity level, respectively in comparison with the low salinity level. The reduction in accumulated intercepted radiation and radiation use efficiency further contributed to the reduction in biomass production.

Water use

The calibration of neutron moisture meters for 15-30, 30-50, 50-70 and 70-90 cm layers was done on 6 June 2002. The results showed that about 53% of the variability was explained for layer 15-30 cm ($p<0.001$), 47% for layer 30-50 cm ($p<0.01$), 85% for layer 50-70 cm ($p<0.001$) and 82% for the 70-90 cm layer ($p<0.001$). Number of observations were 18 ($n=18$) for all the cases. It can be observed that for deeper layer the calibration results were stronger. The total amount of water use was 304, 249 and 197 mm by wheat growing at low, medium and high salinity levels, respectively. The water use was reduced at high salinity level. An 18% of reduction in water use was observed at the medium salinity level in comparison with the low salinity level whereas the reduction in water use was found to be 35% at the high salinity level in comparison with the low salinity level. At the three measurement sites, the top soil layer was sandy and the subsoil had high clay content (Tables 1). The reduction in water use was caused mainly by two ways, firstly by restricting the rooting depth of wheat at high salinity level to only 50 cm which prevented the crop from absorbing water in deeper layers. Secondly, as suggested by other researchers (Rengasamy, 2002; Katerji *et al.*, 2003; Shatar, 2003) it was reduced by increased soil water stress due to osmotic effect. This finding can be utilised by accounting for the effect of salinity on crop water uptake in a crop simulation model to improve the model and thereby, spatially simulate the grain yield. Figure 4 shows the volumetric soil water content (SWC) at four different soil layers *i.e.*, 15-30 (a), 30-50 (b), 50-70 (c) and 70-90 cm (d) and the rainfall for that period. Crop was sown on 133 Julian days. At the 15-30 cm layer, the SWC was higher at low salinity level before crop sowing which could be because the low salinity level provided higher infiltration rate and better movement of water within soil profile (Thompson *et al*., 1997). This can also be seen at the 30-50 cm layer as higher SWC was observed during first two points even though sharp water depletion was observed at the 15-30 cm layer. From this observation it can be concluded that at the early stage of crop growth, water was mainly depleted from the topsoil layer at all salinity levels because of the shallow roots. The decrease in rooting depth under saline conditions means that a smaller soil volume is available for crop water uptake. So, the moisture availability is not only reduced by less available water per unit of volume due to the osmotic potential, but also by the available soil volume (Katerji *et al*., 2003). At the low salinity level the decline in soil moisture content was more pronounced indicating low salinity provided a good environment for roots and more water was absorbed by the plant. However, not much difference was observed in the case of medium and high salinity levels. After about day 200, there was an increase in soil moisture at medium and high levels of salinity, following rain, which can be observed in Figure 4. Soil water continued to decrease at the low salinity site because of uptake by plants. Before anthesis, around day 250 to 280, there was a sharp decline in water content in all the cases in the top layer indicating good plant growth and need of water to the plants. However, during this time period, a large decline was also observed in the 30-50 and 50-70 cm layers at low salinity level. This shows that low salinity also facilitated root penetration in deeper layers and good root growth as well. In the case of the medium and high salinity levels, there were not much noticeable difference. Only at the low salinity level, moisture was depleted below 70 cm soil depth and it was almost the same at medium and higher at high salinity level, indicating that high salinity inhibited proper root growth and penetration. Overall, the low salinity level provided a conducive environment for good root growth penetration and for plants to absorb more water, which resulted in higher leaf area, biomass and yield.

Above-ground biomass, yield and other harvest parameters

There was a 23% and 19% reduction in number of spikes and a 40% and 46% reduction in number of grains at medium and high salinity levels in comparison with the low salinity level (Table 2). These results comply with the findings of Maas *et al*. (1994) who reported that the yield component most affected under salinity stress is the number of culms that bear ears. At the high salinity level, although the reduction in number of spikes was less than that of medium salinity level, there was more reduction in number of grains, which suggests that high salinity produced spikes each of which contained fewer grains similar to the results of Maas and Poss (1989) who reported that salinity can reduce the number of florets per ear, increase sterility and alter the time of flowering and maturity in wheat. The toxicity to the plant caused by salinity stress is particularly evident after anthesis (Acevedo *et al*., 2005) and is characterized by low kernel weight (Wyn Jones and Gorham, 1991), as well as the abortion of distal spikelets (Grieve *et al*., 1992). Similar results were found in this study. The Table 2 shows the reduction in kernel weight in medium and high

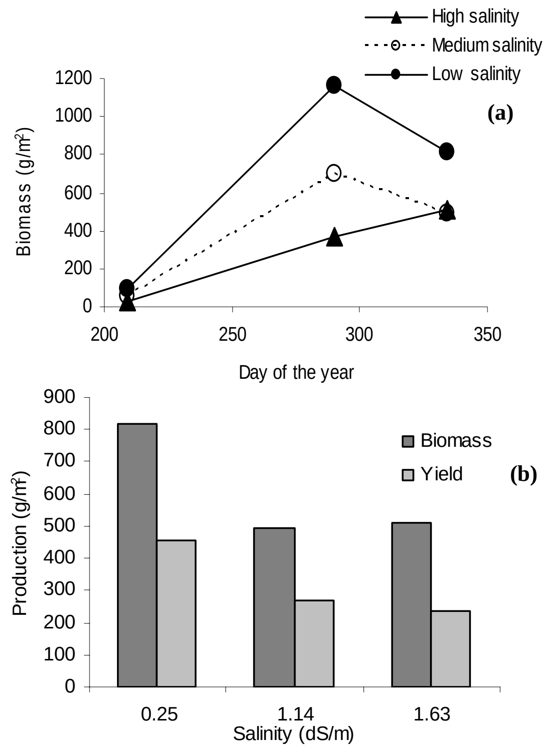

Fig 5. Biomass production and yield of wheat at different growth stages (a) and salinity levels (b)

salinity sites. Weight of 1000 grains was reduced by 0.5% and 3.7% at medium and high salinity levels in comparison with low salinity level (Table 2). The results indicate that apart from low number of grains (although more number of spikes) at high salinity level, weight of grains was also reduced because of high salinity. This indicates that salinity caused abortion of distal spikelets. Although, only smaller amount of reductions in grain weight were observed, yet it can be established from the findings of this study and similar results reported in the above mentioned references that salinity causes reduction in grain weight in wheat. Higher salinity levels, than in this study, may provide more profound results. The physiological properties most affected by salinity were leaf and stem development, biomass, number of spikes, number and weight of grains and so were grain yield, rooting depth and water use. Holloway and Alston (1992) reported that in a greenhouse experiment, salt decreased tillering, dry matter production, grain yield, root length and water use efficiency with respect to total dry weight. Above-ground biomass production was adversely affected by increasing level of salinity. Decreases of 35% and 70% in biomass at tillering and 40% and 68% at anthesis were observed at medium and high salinity level, respectively, in comparison with the low salinity (Figure 5 a). Figure 5a shows that at harvest, higher biomass was achieved at the low salinity level. However, biomass was found to be almost the same at medium and high salinity levels. About 40% reduction at medium salinity level and 41% reduction at high salinity level were observed in final above-ground biomass at harvest in comparison with the low salinity level (Figure 5 b). Katerji *et al*. (2003) showed that the dry matter production of wheat about one month after sowing was affected by salinity for leaf, stem and root. They observed growth reductions of 20–30% at an ECe of 4 dS/m. They also reported 5% and 14% yield reduction in wheat when ECe increased to 2.3 and 4.6 dS/m respectively, from 0.8 dS/m. Poustini and Siosemardeh (2004) reported that a significant negative correlation exists between grain dry matter along with grain size and leaf sodium concentration under saline conditions. The effect of salinity on harvest index and grain yield was clearly seen and about 1.2 % and 11.7% decrease in harvest index (Table 2) and 41% and 48% reduction in grain yield (Figure 5 b) was observed at medium and high salinity levels in comparison with the low salinity level. Salinity causes a yield reduction by affecting the number and weight of grains (Katerji *et al*., 2003). Mass and Hoffman (1977) reported yield reductions of around 84% per dS/m (ECw, electrical conductivity of irrigation water) (7.1% per dS/m ECe) above a threshold of 0.5 dS/m (ECw) in wheat. Ayers and Wescot (1976) reported that wheat yield was decreased by 50 percent at soil saturation extracts of 13 dS/m. In this study 7% yield reduction is observed when EC (1:5) increases from 1.14 to 1.63 dS/m which shows the results are similar to Mass and Hoffman (1977).

Conclusions

All the measured crop physiological properties *i.e.,* leaf and stem growth rate, leaf area, accumulated intercepted radiation and radiation use efficiency along with plant water uptake, above-ground dry weight and grain yield were adversely affected by increasing level of salinity. The adverse effect was more prominent during early stage of crop growth. As found from this experiment and from several references, subsoil salinity reduces the ability of plant to take up water from deeper layers, which results in reduced grain yield. By modelling this phenomenon *i.e.,* the effect of salinity on crop water uptake and the amount of reduction in water absorption by the crop, the spatial variability in grain yield caused by salinity may be explained. Although, no statistical analysis has been performed in this study however, the indicative results confirm the previously published effect of salinity on physiological properties, grain yield and water use of the wheat crop. The relationships between salinity and these properties provide a basis on which to add the effects of salinity to a simulation model. It is concluded that to account for the impact of salinity on crop yield in a crop simulation model, the impacts of salinity on the amount of intercepted radiation, the conversion efficiency of intercepted radiation into biomass, water use and harvest index need to be taken into account. Ideally a crop simulation model should be modified to take these factors into account. But in the study area, potential growth and yield of wheat are limited by water, the availability of which is reduced by salinity. Hence the model should be modified by adjusting crop water uptake in the presence of salinity.

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