1 Running title: Root aeration, hypoxia and salinity in a heavy clay soil

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9 **Root aeration improves yield and water use efficiency of tomato in**

10 **heavy clay and saline soils**

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1   **Abstract**

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3   Water-logging and salinity of the soil alter both the physical and biological

4   environment of plant roots. In two experiments, we investigated the effects of imposed

5   aeration on yield and the physiological response of tomato (*Lycopersicon esculentum* L.)

6   cv: Improved Apollo growing under protected conditions over a range of salinities (the

7   salinity experiment), and under constant field capacity (FC) or drier soil conditions (the

8   moisture experiment). Subsurface irrigation with aerated water (12% air in water)

9   stimulated above-ground growth, and enhanced the reproductive performance through

10   earliness for flowering and fruiting compared with the control. Fruit yield of tomato with

11   aeration in the moisture experiment was increased by 21 percent compared with the

12   control (4.2 vs. 3.7 kg per plant), and the effect of aeration on fruit yield was greater in

13   FC than in the drier treatment. . Fruit yield was increased by 38 percent in saline soil due

14   to aeration compared with the non-aerated control. Increasing salinity from 2 dS m^{-1} to

15   8.8 and 10 dS m^{-1} reduced fruit yield by 18 and 62 percent respectively, but 4 dS m^{-1} did

16   not suppress yield. Aeration in both the experiments increased plant water use and water

17   use efficiency (WUE), expressed as weight per unit of applied water. Biomass WUE was

18   greater by 16 and 32 % in the moisture and saline experiments, respectively. The

19   increased yield with aeration was also accompanied by an increased harvest index (HI)

20   defined as the proportion of dry fruit biomass to total dry biomass, greater mean fruit

21   weight, high fruit DM, and increase in leaf chlorophyll content and shoot: root ratio, and

22   a reduced water stress index (computed from the difference between air and leaf

23   temperature). The benefit gained from aerating irrigation water was not only observed

1 under conditions where air-filled porosity may be low (e.g., in poorly structure sodic

2 soils, or at field capacity in clay soils), but also in drier soils.

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5 *Keywords: Lycopersicon esculentum;* Aeration; Salinity; Subsurface drip irrigation; Vertisol

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7 **1. Introduction**

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9 Tomato (*Lycopersicon esculentum* L.) can be grown in a wide range of soil types (Kinet

10 and Peet, 1997). However, the ideal soil for tomato should be well drained and yet

11 capable of retaining moisture. As drip irrigation develops a wetting front near emitters,

12 the root zone of the crop remains near-saturated for a proportion of the time between

13 irrigation events, especially on heavy cracking clay (Vertisols) making them the least

14 desirable soil types for drip irrigation. Particularly in poorly drained soils, flood irrigation

15 and wet weather cause water to replace air in the soil thus reducing the availability and

16 mobility of oxygen that remains trapped in soil pores (Meek et al., 1983). By decreasing

17 the supply of soil oxygen to plant roots, heavy rainfall or irrigation on such soils can

18 constrain yields to well below their potential (Poysa et al., 1987). The roots of most crop

19 species need a good supply of oxygen in order to satisfy the water and nutrient needs of

20 the shoots (Meek et al., 1983). Paradoxically, one of the first symptoms of excessive soil

21 wetness is drought stress in the leaves. If these conditions are prolonged for more than a

22 few days, then further serious damage can be effected via nutrient deficiency, build-up of

23 metabolic poisons and increased incidence of root diseases (Vartapetian and Jackson,

24 1997).

1

2   The tomato crop is one of the most sensitive of all crop species to excesses of soil

3   moisture and poor soil oxygen supply (Bradford and Yang, 1981). Periods of excessive

4   soil water content tend to result in smaller crop canopies, and greatly reduced yields.

5   Excess of salt in the soil on its own, or in combination with waterlogging, also has severe

6   consequences for crop production, including that of tomato (Zhang and Blumwald, 2001).

7   Salinity in clay soil is often associated with sodicity, which reduces the porosity in the

8   soil, and the supply of soil oxygen to the roots (Munns, 2002).

9

10   Plant roots require adequate oxygen for root respiration as well as for sound metabolic

11   function of the root and the whole plant. Amelioration of an anoxic/hypoxic root zone in

12   order to improve effective soil aeration is, therefore, crucial in order to improve plant

13   performance in Vertisols and in saline conditions. Compacted soils are also known to

14   lack sufficient oxygen to sustain root activities (Rengasamy, 2002). Because of the

15   delicate nature of subsurface drip irrigation (SDI) lines, cultivation does not take place to

16   their depth, therefore predisposing the soil around the lines to compaction. SDI minimises

17   alternate wetting and drying of the soil surface, a phenomenon that might otherwise

18   predispose them to the cracking that could locally alleviate the lack of aeration. By direct

19   injection of air alone, by irrigation of a crop with aerated water, or by injection of

20   hydrogen peroxide in the root zone, aeration of the crop root zone can now become a

21   reality (Bhattarai et al., 2004). Injection of air alone is expensive and the injected air

22   moves away from the root zone due to the chimney effect (Goorahoo et al., 2001). The

23   economics of golf course greens can sustain commercial-scale aeration with air injection

1   (Walker et al., 2000). Recent studies (Bhattarai et al., 2004) show the promise of using

2   SDI to provide aerated water to improve crop performance in Vertisols. We define

3   oxygation as the delivery of aerated water by way of SDI systems. Aerated through a

4   venturi principle, or with solutions of hydrogen peroxide, SDI provided yield benefits to

5   a range of crops including cotton, zucchini and vegetable soybean. In this study, we

6   examined the effect of aerated subsurface irrigation water on the glasshouse performance

7   of tomato at different soil moisture levels and over a range of salinity levels in a Vertisol.

8   Aeration of the rhizosphere increased most measured parameters of irrigated tomato,

9   including fruit yield, on a Vertisol, whether saline or not.

10

11   **2. Materials and Methods**

12

13   *2.1. Location, soil and crop details*

14

15   Two experiments, the moisture experiment and the salinity experiment, were

16   undertaken at Rockhampton, Australia (23^0, $22^{'}$, $0.345^{''}$S latitude, 150°, $31^{'}$, $0.53^{''}$E

17   longitude). The tomato variety Improved Apollo was directly sown on 19 April and 29

18   April 2003 for the salinity and moisture experiments, respectively. A black cracking clay,

19   which is referred to as a *Vertisol* (Australian Soil Classification System as *6AUG-12*) was

20   filled in sealed black pots of 28 cm diameter x 45 cm height for the moisture experiment,

21   and 25 cm x 24 cm for the salinity experiment, with 26.00 and 10.79 kg of soil,

22   respectively, to maintain a bulk density of 1.3 g cm^{-3}. All pots were fitted with Netafim

23   subsurface drippers placed five centimeters above the base of each pot, and the soil

24   surface was covered with a layer of black low-density polyethylene beads to minimize

1 surface evaporation. The emitters delivered 0.8 L h^{-1} water at a line pressure of 83 kPa.

2 Plants were spaced 75 cm x 60 cm between and within rows maintaining one plant per

3 container by thinning excess plants at the three-leaf stage. Plants were individually

4 staked, and pruned to maintain a branch-less single stem.

5

6 *2.2. Air injection and soil moisture monitoring*

7

8 A "Mazzei" venturi air-injector (Model 384-X designed and manufactured by Mazzei

9 Injector Corporation, USA) was installed in-line immediately following the pump (1 HP

10 Davey designed and manufactured by Davey Australia Pvt. Ltd). Pressure gauges either

11 side of the venturi, in association with a valve-regulated bypass line, permitted the

12 control of inlet/outlet pressure and thus the pressure differential within the venturi. This

13 controlled the amount of air ingress into the irrigation line (12% air by volume of water).

14 The air injection using the Mazzei air-injector followed the Bernoulli's principle. Aerated

15 water was delivered to the soil through the pot drippers, and the excess in the line was

16 returned to the tank. Soil water was measured daily in one pot per plot using a calibrated

17 Micro-Gopher system (Soil Moisture Technology, Australia), the probe of which consists

18 of a capacitance sensor. Irrigation was carried out on a 1 to 3 day interval, between 7:00 h

19 to 12:00 h, based on the readings from the Micro-Gopher; refill was when the soil

20 moisture reached 32 mm (in the FC treatment) and 21 mm (in the dry treatment) and 32

21 mm per 100 mm of soil depth in the salinity experiment, respectively.

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23

1 *2.3. Experimental design and treatments*

2

3   The moisture experiment was laid out as a 2x2 factorial Randomized Complete Block

4   (RCB) design in a screen-house with tomato grown at two soil moisture levels - field

5   capacity (FC - 43 mm H_2O per 100 mm of soil depth) and drier (22-32 mm H_2O per 100

6   mm) with and without aeration. Soil moisture was measured in the middle of the pot, 5

7   cm away from emitter and soil water content was periodically verified gravimetrically.

8   Treatments were replicated three times. The salinity experiment was laid out as an RCB

9   split-plot design with two blocks in a temperature-controlled glass-house. Main plots

10   comprised of aeration and control. Sub-plot treatments comprised four-selected NaCl

11   levels equivalent to EC_e 2.0, 4.0, 8.8 and 10.0 dS m^{-1} created by uniformly pouring 20,

12   45, 75, and 95 mM NaCl solutions to the designated pots. Pots were maintained between

13   the refill point (32 mm) and field capacity (43 mm). The appropriate NaCl solutions were

14   introduced in three equal applications of 1161.1 mL. The initial one third was introduced

15   to the pots seven days after the majority of seedlings had germinated (day 7), and the

16   second and the final amounts on day 9 and day 13 respectively bringing the soil in the

17   pots to FC so as to make the distribution of the salt as uniform as possible. Radiation

18   receipts were 67% of full sunlight in both experiments and aeration was begun as soon as

19   the first true leaf was visible. The nutrient requirement of the crop in both experiments

20   was supplied through fertigation using a "Peter's Professional" general-purpose water-

21   soluble fertilizer (20N [28% nitrate, 20% ammonium and 52% urea]:8.7P:16.6K and

22   0.01%B, 0.004%Cu, 0.05%Fe, 0.03%Mn, 0.001%Mo, 0.003%Zn) at the rate of 0.5 g L^{-1}

23   continuously. To account for different uptake rates of water between treatments, at times

1   irrigation was applied without fertigation to ensure that all plots received the same

2   amount of fertilizer. In the salinity experiment foliar liquid fertilizer ("Stop it"-

3   manufactured by Phosyn Plc, UK which contains calcium chloride 16% W/V) as a 1 %

4   solution was applied twice to the foliage (12 ml per plant) whereas in the aeration

5   experiment it was applied 6 times (36 ml per plant) during the season in an attempt to

6   avoid blossom end rot.

7

8   *2.4. Data recording*

9

10   Weather data were recorded from an adjacent weather station. Soil temperature was

11   measured in the moisture experiment, one probe in each plot at 10 cm depth and 5 cm

12   from the pot wall.

13

14   The oxygen concentration in the soil solution was monitored using PSt3 oxygen sensitive

15   fiber optic minisensors (Optodes) with a Fibox-3 oxygen meter (PreSens GmbH,

16   Regensburg Germany). Probes were located at 15 cm depth from the soil surface in all

17   treatment combinations in the moisture experiment, and in the 2 and 8 dS m^{-1} treatments

18   with and without aeration in the salinity experiment. Due to the small number of sensors,

19   un-replicated, data were collected on 39-46 days after sowing in the moisture experiment,

20   and 53-56 days after sowing in the salinity experiment.   Growth and development

21   parameters such as plant height, leaf area, individual leaf size and stem diameter, and

22   reproductive parameters such as days to flowering, fruit set, and the lower most flowering

23   node number were recorded from individual plants at fortnightly intervals and at final

1   harvest. Data on fruit yield, including number and weight per fruit, were recorded from

2   fruits harvested over different dates as fruits ripened on the plants. The dry matter data

3   for leaf, stem, and roots were derived from final plant harvest. Components were dried

4   for 48 hours at 70 ^{o}C.

5

6   Leaf gas exchange parameters (photosynthesis, transpiration and stomatal conductance)

7   were measured using an infrared gas analyzer (IRGA) model LCA-4 (ADC, Hoddesdon

8   UK) between 10 am and 12 noon, leaf water potential at predawn was measured with a

9   Scholander pressure bomb by soil moisture Inc. USA following Joly (1985), canopy

10   temperature and the crop water stress index (CWSI - values range from 0 (no stress) to 1

11   (severe stress where transpiration ceases completely) using an infrared Ag multimeter

12   (Everest Inc., Tucson USA) between 1-2 pm and canopy light interception using a PAR

13   ceptometer (Decagon, Pullman USA) at midday. Leaf chlorophyll concentration was

14   measured with a SPAD-520 chlorophyll meter (Minolta, Osaka Japan) on the youngest

15   fully extended two leaves of each plant. Sample leaves were analysed using the acetone

16   chlorophyll extraction method following EPA (Anonymous, 1994) to calibrate SPAD

17   data. All these parameters were measured on five occasions throughout the season.

18

19   Plant water use was determined using the stem sap flow system as described by Baker

20   and Bavel (1987). Stem sap flow in the moisture experiment was monitored on one plant

21   per treatment at the 50% flowering stage over the period of three days (83-85 days after

22   sowing (das)). Plant water use efficiency was expressed as season-long water use

23   efficiency of biomass (WUE Biomass$_{sl}$ as g of biomass per litre of applied water over the

1   season), season-long water use efficiency of fruit yield (WUE Fruit$_{sl}$ as g of fruit per litre

2   of applied water over the season), instantaneous water use efficiency (WUE$_i$ – µmol of

3   CO_2 fixed per mmol of H_2O transpired derived from IRGA data), and leaf carbon

4   discrimination, (Δ ‰) as described by Farquhar et al. (1991).

5

6   The integrity of leaf membranes, expressed as the electrolyte leakage ratio, was measured

7   on day 79 in the salinity experiment on the 3rd topmost fully expanded leaves of all

8   treatment x replicate combinations following the method described by Renault et al.

9   (1998). The specific leaf area (SLA - defined as leaf area per unit mass of leaf) was

10   determined at the same time following Garnier et al. (2001). Washed leaf samples

11   (sample leaves first washed immediately in RO water, followed by rinsing in double

12   distilled water, and then spread on clean paper towel until dry) three per plant, were also

13   analysed for the determination of Na^+, Cl^-, Ca^{2+}, K^+, and Mg^{2+} and other major nutrients

14   following routine methods by CSBP, an Australian accredited laboratory. For the salinity

15   experiment plants were harvested once-over on 97 days after sowing whereas for the

16   moisture experiment fruits were harvested as ripening progressed and final harvest took

17   place on day 164.

18

19

20   *2.5. Root samples*

21

22   One core sample per pot in the moisture experiment was collected 145 days after

23   sowing by coring with a 3 cm diameter soil corer to the entire depth of the pot. Core

1   samples were soaked in 1% solution of groundbreaker (active constituent 10 g L^{-1}

2   buffered polylignosulfonate) for 2-3 hours and roots were separated from soil using a 45-

3   micrometer sieve following the floatation technique. The living roots were separated

4   manually by discarding the dead based on visual observation of tissue colour as described

5   by Caldwell and Virginia (1991), and the root length and diameter of the former was

6   determined using a Hewlett Packard scanner and Delta-T software. The washed root

7   samples were oven-dried for 48 hours at 70 $^{\circ}$C for the determination of dry weight.

8

9   *2.6. Data analysis*

10

11   The data collected were subjected to an analysis of variance using the general linear

12   model procedure for a factorial randomised complete block design employing SYSTAT

13   version 9. Where interactions were not significant, main effects only are presented. In the

14   salinity experiment the effects due to salinity x aeration in the split plot design were not

15   significant. Therefore, only the main effects due to salinity and aeration are presented

16   herein.

17

18   **3. Results**

19

20   3.1. Soil Moisture Experiment

21

22   *3.1.1. Environmental parameters and water applied to the crop*

23

1   The mean ambient temperature measured outside the screenhouse averaged 19.5 ^{o}C and

2   ranged from 10.4-25.3 ^{o}C whereas soil temperature averaged 24.8^{o}C and ranged from 20

3   to 31 ^{o}C. There was a gradual decrease in temperature from April to July and a slight

4   increase from August to October. Relative humidity averaged 26 % and ranged from 17

5   % to 43 % and solar radiation within the growing environment averaged 10.6 MJ m^{-2} d^{-1},

6   with a minimum of 1.6 to a maximum of 17.7 MJ m^{-2}d^{-1}. Following irrigation dissolved

7   O_2 declined by 45% in non-aerated pots while in aerated pots soil O_2 decreased by only

8   25% (Figure 1). Oxygen measurements in the rhizosphere over a 72 hour period during

9   the flowering stage revealed greater dissolved oxygen concentration with aerated

10 treatments compared with the control at both FC (8.1 ± 0.96 vs 7.1 ± 1.0 mg L^{-1}) and

11 drier (9.2 ± 0.82 vs 8.1 ± 1.39 mg L^{-1}) conditions. In general, dissolved O_2 concentration

12 was higher at night and lower between 2-4 pm (Figure 1).

13

14   The cumulative water applied throughout the season was greater for FC compared

15 with the drier treatment but aeration per se had no effect on the amount of water applied.

16 Crop applied water at FC was greater by 10% compared to the drier treatment (Table 1).

17 As illustrated in Figure 2, soil water content was maintained effectively at 24-28 and 40-

18 43 mm H_2O per 100 mm soil depth throughout the season in drier and FC treatments,

19 respectively.

20

21 *3.1.2. Plant growth characteristics*

22

23   Plant height at harvest did not differ due to aeration, but plants under FC were

24 somewhat taller than in the drier treatment (Table 2). A marked positive effect of aeration

1   was observed on leaf area per plant, primarily because of larger individual leaves (262 vs

2   239 cm^2, SED (6 df) = 4 cm^2), however, these leaf properties were not affected by soil

3   moisture treatment (Table 2). The interaction effect on leaf area was significant, showing

4   a greater positive effect of aeration at FC. Stem diameter did not vary in response to soil

5   moisture or aeration.

6

7   *3.1.3. Plant reproductive performance*

8

9   The first flowering node occurred at a significantly lower node number under aeration

10 compared with the control, but soil moisture had no effect (data not presented). Similarly,

11 first flowering was significantly earlier for aeration, and the dry treatment was also earlier

12 compared with FC (Table 2). The fruit set percentage did not vary significantly in

13 response to treatments (data not presented).

14

15 *3.1.4. Fruit yield and yield components*

16

17   Fresh fruit yield was significantly greater for aeration compared to the control and

18 almost so for FC compared to the dry treatment (Table 2). Although the effect of aeration

19 and soil moisture was not significant for number of fruits per plant, the individual fresh

20 fruit were significantly heavier due to aeration compared to the control (136 vs. 124 g

21 $fruit^{-1}$, SED (6 df) = 1 g). The soil moisture effect on weight per fruit was not significant.

22 Fruit dry yield per plant did not differ significantly in response to soil moisture but

23 aeration increased fruit dry yield compared to the control (Table 2).

24

1   *3.1.5. Dry matter partitioning*

2

3   Dry weight of root and leaf did not vary significantly in response to soil moisture or

4   aeration. However, stem dry weight was significantly greater at FC compared with the

5   dry treatment but did not differ significantly between aerated and control treatments

6   (Table 2). Aboveground dry biomass and harvest index (HI - the proportion of dry fruit

7   biomass to total fresh biomass) were significantly greater and the root:shoot ratio was

8   lower with aeration compared with the control (Table 2). The effect of soil moisture on

9   these traits was not statistically significant. The interaction effect was significant for

10   above ground dry biomass such that aeration showed a greater positive effect in the dry

11   than in the FC treatment (data not presented).

12

13

14   *3.1.6. Water relations and water use efficiencies*

15

16   The stem sap flow measured over three days at the flowering of the 6th inflorescence

17   (83-85 das) indicated that plant transpiration increased by 8 % with aeration compared to

18   the control and by 18% with FC compared to the dry treatment (Table 1). Aeration

19   significantly reduced the crop water stress index (CWSI – derived from the difference

20   between air and canopy temperature) compared to the control (Table 1). Likewise, FC

21   significantly reduced CWSI compared with the dry treatment. The LWP was only

22   affected by the soil moisture treatments such that a significantly more negative LWP was

23   recorded for the dry compared to the FC treatment. The WUE_i (i.e. instantaneous water

24   use efficiency) did not differ significantly between treatments, but biomass WUE_{sl} (i.e.

1 season long water use efficiency) was significantly higher for the dry treatment compared

2 with the FC and for aeration compared with the control (Table 1). Fresh fruit WUE_{sl} was

3 significantly greater in the aeration treatment compared to the control but did not differ

4 significantly between the soil moisture treatments. WUE assessed with carbon

5 discrimination (Δ ‰) technique did not differ significantly due to either soil moisture or

6 aeration treatments (Table 1).

7

8 *3.1.7. Leaf properties and gas exchange*

9

10   The leaf chlorophyll concentration was greater with aeration but was not affected by

11 soil moisture (Table 3). Leaf gas exchange properties did not differ significantly between

12 treatments. Similarly the effect of treatment was also not significant for canopy light

13 interception or specific leaf area although aeration tended to produce thicker leaves

14 (Table 3).

15

16

17 3.2. Salinity Experiment

18

19

20 *3.2.1. Water input, soil water content and soil oxygen concentration*

21

22   Water applied to the crop over the season decreased with salinity and increased,

23 although not significantly so, with aeration (Table 4). Soil water content was maintained

24 between 25-37 mm per 100 mm H_2O per 100 mm soil depth throughout the season and

1 was on average lower with aeration and with lesser salinity, reflecting their greater water

2 use (Table 4). Oxygen concentration in the soil solution was greater for the aeration

3 compared with the control treatment, and was less with increase in salinity (Figure 3).

4

5

6 *3.2.2. Plant growth characteristics*

7

8 Plant height decreased with increasing salinity and plants treated with aeration were

9 significantly taller than those in the control (Table 5). Total leaf area per plant was

10 lowest at the highest salinity due to an effect of salinity on both leaf number and leaf size.

11 Differences in total leaf area per plant and its components were too small to be significant

12 between aeration and its control (Table 5). However, the SLA was significantly smaller

13 with aeration (317 vs. 366 $cm^2 g^{-1}$, SED (49 df) = 20.6).

14

15

16 *3.2.3. Reproductive performance*

17

18 A marked effect of salinity and aeration was observed on reproductive performance of

19 the crop (Table 6). Number of inflorescences counted at 87 das increased significantly

20 with aeration and decreased with increasing salinity levels. Flowering was delayed

21 significantly by higher salinity but the delay by aeration was not significant. No

22 difference in fruit set was observed between treatments (experimental average = 57%)

23 although number of fruits per plant was greater in the aeration compared to its control

24 and lower at higher salinity levels (Table 6).

1

2 *3.2.4. Dry matter accumulation and partitioning*

3

4   With the exception of the root, all other components and total biomass weight

5 decreased significantly ($P<0.05$) at higher levels of salinity (Table 7) and consequently

6 the root: shoot ratio was greater at higher salinity. In contrast, the HI was greatest at the

7 lowest salinity. The difference between aeration treatments was significant only for fruit

8 weight and total biomass, although the components were consistently heavier under

9 aeration compared to the non-aerated control (Table 7).

10

11

12 *3.2.5. Leaf gas exchange properties*

13

14   Neither salinity nor aeration significantly affected photosynthesis, transpiration rate or

15 chlorophyll concentration (data not presented) although there were tendencies for

16 photosynthesis and transpiration to decline, and chlorophyll concentration to rise with

17 increasing salinity.

18

19 *3.2.6. Plant water use and water use efficiency*

20

21   Significant effects of both aeration and salinity were noted for water use efficiency of

22 biomass and fresh fruit. Aerated plants achieved higher water use efficiencies for both

23 fruit and biomass compared with the control, although WUE decreased significantly with

24 increasing soil salinity (Table 8). Unlike the WUE_{sl} of biomass and fruits, WUEi did not

1   differ significantly between salinity or aeration treatments (data not presented). WUE

2   assessed by carbon discrimination revealed a significant improvement in WUE with

3   increasing salinity levels but not due to aeration (Table 8).

4

5   *3.2.7. Leaf salt analysis*

6

7   Leaf tissue concentrations of Na^+, Cl^-, Ca^{2+}, and the K^+:Na^+ ratio were significantly

8   affected by both the aeration and salinity treatments (Table 9). Potassium concentration

9   was not affected. Na^+ concentration in the leaf tissue steadily increased with increase in

10   salinity from 2-10 dS m^{-1} and in non-aerated compared to the aeration treatment. Non-

11   aerated plant Na^+ tissue concentrations were 42 % higher than their aerated equivalent

12   (Table 9). Similarly, leaf Cl^- concentration differed significantly due to salinity with the

13   highest recorded at 10 dS m^{-1}. Higher calcium leaf tissue concentrations were evident

14   with increased salinity. The effect of aeration on Ca^{2+} was also significant; non-aerated

15   plants had leaf tissue concentrations greater than those of aerated plants (Table 9).

16   Although differences in the K^+ concentrations in leaf tissue were not significant, the ratio

17   of K^+: Na^+ differed significantly due to salinity and aeration. The ratio decreased

18   progressively with increased salinity, and aeration resulted in a significantly greater ratio

19   than that of the control (Table 9).

20

21

22   **4. Discussion**

23

1   Both aeration and soil salinity influenced tomato growth, development and yield. Leaf

2   properties i.e. leaf size and area, were significantly enhanced by aeration in the moisture

3   experiment. This positive effect of aeration on leaf area was mainly evident at FC

4   (aeration - 0.817 m^2 vs. control - 0.673 m^2, SED (18 df) = 0.04) and only minimally

5   (+8%) in the dry treatment. A positive effect of aeration on leaf area at the higher

6   moisture level in the Vertisols may be due to an alleviation of O_2 deficiency in the

7   rhizosphere. Root respiration has been shown to be favoured by aeration while irrigating

8   to FC (Bhattarai et al., 2004). Aeration maintained higher dissolved soil O_2

9   concentrations in both the FC and dry treatments (Figure 1).

10

11   Although statistically non-significant in the salinity experiment, leaf area and leaf dry

12   weight were somewhat greater for the aeration treatment compared with the control.

13   They were, however, significantly reduced by the most saline treatment (Tables 5 and 7).

14   Reduction of leaf area and leaf dry weight due to suboptimal soil moisture and increasing

15   salinity were observed by Rudich and Luchinsky (1986) to be due not to a reduction in

16   number of leaves but to a reduction of both leaf area and leaf thickness, i.e. an increase in

17   SLA. Our own data also show that the SLA increased as salinity increased (steadily but

18   non-significantly from 331 to 363 $cm^2\ g^{-1}$), as it did without aeration. Reduction in leaf

19   growth rate has been related to reduction in cell turgidity or cell wall properties (Li and

20   Stanghellini, 2001), which results in reduced leaf water potential as evidenced by a lower

21   leaf water potential for non aerated and higher salinity treatments (data not presented).

22

1   Plants in both experiments were pruned to a single stem and as a consequence the

2   leaf area index for each was low (LAI of 1.43-2.09 for the moisture experiment)

3   compared to values of non-pruned plants. The reductions in leaf area brought about by

4   salinity (Table 5), and shown in previous studies (Li and Stanghellini, 2001), almost

5   certainly contributed to low fruit yield, just as enhanced leaf area (Table 2) and light

6   interception (Table 3) in the moisture experiment contributed to higher yields in the

7   aeration treatment, for leaf capture of solar energy is related to fruit yield in many crops

8   (Olympios et al., 2003).

9

10   Aeration and salinity were found to markedly affect the reproductive performance of

11   the tomato crops. Earlier flowering (Table 2 and Table 7) and a lower position of the

12   lowermost flowering nodes (data not presented) were evident in the aerated treatment in

13   the moisture experiment, and more fruits were harvested in less saline treatments. Sharaf

14   and Hobson, (1986) also reported an enhanced earliness due to the shorter time period

15   required from ovule fertilization to fruit ripening in saline compared with non-salinized

16   conditions.   Greater fruit yield in our aerated or less saline treatments was more

17   dependent on the size of the fruit rather than the number of flowers and fruit set per se.

18   Pollen fertility of salt-treated tomato plants has been found to be similar to that of the

19   control (Adams and Ho, 1992). The implication from the work of Johnson et al. (1992) is

20   that such reductions in fruit size were related to lowered water potential that constrained

21   the rate of fruit expansion. The reduction in fruit size due to salinity is variety specific. In

22   general, the larger the fruit size, the more important is its reduction in size by salinity

1   (Cruz et al., 1990). The variety used in these experiments has a large fruit and, therefore,

2   the reduction in fruit size in response to salinity and lack of oxygen was likewise large.

3

4   Of interest, the effects of aeration and salinity were not evident in terms of leaf gas

5   exchange properties. The rate of photosynthesis is generally reduced under salt stress

6   (Cuartero and Fernadez-Munoz, 1999). However, no such marked effect was noticed in

7   our experiments. In tomato, growth declines more rapidly, and at lower concentrations of

8   Na^+ in the leaf, than does photosynthesis (Yeo and Flowers, 1989; Alarcon et al., 1994).

9   Similarly, growth in response to salinity has been shown to decline more than

10   photosynthesis in long-term studies (Seemann and Critchley, 1985); and tomato is sink–

11   rather than source limited with respect to carbon assimilation (Hooking and Steer, 1994)

12   which means that the tomato can withstand a certain loss in photosynthetic rate with only

13   little effect on fruit growth. Indeed, mild water stress had no effect on the rate of

14   photosynthesis (Hsiao, 1993). If the reduction in the rate of photosynthesis caused by

15   salinity and reduced aeration were the major limiting factor for a low yield, possibly such

16   loss of photosynthetic rate could be counteracted by minimizing the pruning-induced loss

17   of leaf area.

18

19   Salinity and reduced aeration in general showed detrimental effects on the total and

20   component biomass of tomato. This is in contrast to the report by Li and Stanghellini

21   (2001) who showed that dry weight was not responsive to increased salinity over the

22   same salinity range as in our trial. However, superimposed upon a clay soil, the negative

23   effects of salinity on soil structure and aeration in our experiment may have been

1 responsible for such an effect. In spite of the reported negative effects of salt on root

2 growth of other species (Cordoba et al., 2000), root growth in tomato appears to be less

3 affected by salt than shoot growth, hence the root:shoot dry weight ratio increased with

4 respect to salinity (Table 7). The rise in the root:shoot dry weight ratio under salt stress

5 must be accompanied by changes in the allocation of assimilates between root and shoot.

6 Previously, Perez-Alfocea et al. (1996) have shown that in salt-treated tomato plants a

7 greater proportion of assimilate was allocated to the root compared to that in control

8 plants.

9

10   In line with the expected, whole plant transpiration measured with the stem sap flow

11 method over the period was greater in the FC compared with the dry treatment, and in the

12 aerated compared with the control treatment (Table 1), but accumulated water use to

13 harvest indicated that a difference was only evident between the moisture treatments

14 (Table 1)**.** Although no significant differences were recorded in term of instantaneous

15 transpiration rate, stomatal conductance or WUE_i, trends were as expected and tomato

16 plants grown on more saline soil had a lower water use and consistently moister soil

17 compared with less saline treatments (Table 4). Strong inverse relationships between

18 increasing salinity and plant water use in tomato have been reported (Pessarakli and

19 Tucker, 1985) and in other species a positive relationship has been shown between

20 improved soil aeration and plant water use (Bhattarai, et al., 2004). Temporal variation in

21 terms of transpiration (E), stomatal conductance (Sc) and leaf photosynthesis (A) occurs

22 in tomato. Data recording for E, Sc and A were only made between 9:00-12:00 h in these

23 experiments and it is possible that long term monitoring of A, E, Sc and monitoring of

1   night time water consumption (Santamaria et al., 2004) would help to establish a firm

2   relationship between crop water use as influenced by aeration and salinity. Tomato plants

3   with their root system in a medium with heterogeneous salt concentration, such as occurs

4   in the soil (Vaughan et al., 2002), develop more roots and absorb more water in the less

5   saline part of the medium. However, our plants were grown in pots in which the soil was

6   uniformly exposed to salinity, and for which surface evaporation was minimised, so

7   preferential absorption of water from less saline areas would not have been possible.

8   Working with cotton and bean, Pessarakli and Tucker (1985) suggested decreased root

9   permeability and Rodriguez et al. (1997) suggested reduced root hydraulic conductance

10   as responsible for reduction in uptake of water in saline environments. Such alteration in

11   root permeability and root conductance has direct bearing on the crop WUE. Our data

12   suggest that WUE_{sl} decreased with increasing salinity and increased with aeration.

13   Carbon discrimination (an integrated indicator of WUE) did not differ due to aeration but

14   did for salinity such that Δ (‰) was significantly lower in the highest salinity level (Table

15   8) indicating a greater stomatal control of transpiration. Similar results with increasing

16   levels of salinity have been reported for other crops (e.g., for pistachio – Hockmabadi et

17   al, 2005). However, in neither experiment were carbon discrimination and WUEsl closely

18   related across the aeration treatments. Similar poor correlations between Δ (‰) and

19   WUE_{sl} or WUE_i were previously reported by Bhattarai et al. (2004) for aeration

20   treatments in cotton and soybean.

21

22   In general Na^+ has been reported to increase, and Ca^{2+} and K^+ slightly decrease, in the

23   leaf with increasing salinity in most tomato species (Adams, 1986). Tomato leaf tissues

1   in the current experiment accumulated more Na^+ at higher salinity and less Na^+ in

2   response to aeration. Letey (1961) has earlier reported a decrease in Na^+ uptake with

3   aeration of the rhizosphere. The accumulation of Na^+ in the leaf of tomato occurs at the

4   expense of K^+, Ca^{2+}, and Mg^{2+}. Salinity generally reduces leaf K^+, Ca^{2+}, and Mg^{2+}.

5   However, in contrast in the current experiment, high calcium concentration was observed

6   at higher salinity, possibly due to the impact of the foliar application of a foliar liquid

7   fertilizer containing Ca^{2+}. The crop at 10 dS m^{-1} had only 61% of the leaf area of the 2 dS

8   m^{-1} treatment, yet received the same amount of spray. The ratio between the ion content

9   of tomato leaves under saline conditions and the corresponding values in the control plant

10   is referred to as the ion regulation index (Cuartero and Fernandez-Munoz, 1999). The ion

11   regulation indexes in terms of K^+: Na^+, Ca^{2+}: Na^+ and Mg^{++}: Na^+ were higher for the

12   aeration treatment (Table 9). Rengel (1992) also used these ratios as an indicator of the

13   salt stress in tomato and reported that Na^+ concentration of the leaf tissue samples alone

14   is not an adequate indicator of salt stress. Our data on ion regulation as reflected by the

15   higher K^+:Na^+ ratio of the aerated treatment suggest that aeration improved plant

16   tolerance, or perhaps more correctly sodium avoidance (because of the lesser uptake), in

17   the saline medium. Transverse sections taken from roots showed that those without

18   aeration were with a greater incidence of root necrosis (unpublished data); a condition

19   that would favour indiscriminate uptake of ions including Na^+.

20

21   In summary, aeration in both non-saline and saline soil environments influenced

22   growth, development and reproductive performance of tomato in a Vertisol. An increase

23   in the leaf biomass, earliness of flowering, and an increase in fruit size were observed due

1   to aeration, and they all contributed toward an improved tomato yield. Aeration

2   increased fruit yield by 21% in the moisture experiment and by 38% in the salinity

3   experiment, and also increased season long water use efficiency of fruit by 11% and 77%,

4   respectively. Reduced Na^+ content in the leaf samples and increase in the ion regulation

5   index, defined as the proportion of potassium and calcium to sodium, were recorded for

6   the aerated treatments compared with the control. Supplementary aeration was also

7   shown to improve plant tolerance to the hypoxic soil. Irrigation at FC in the heavy clay

8   soil resulted in a lower oxygen concentration in the rhizosphere, which potentially could

9   lead to hypoxia. As aeration improved dissolved oxygen concentration at FC, and

10   improved the performance of tomato plants, it is considered that aeration contributed

11   towards avoidance of hypoxia. This would be particularly so under conditions where air-

12   filled porosity may be low (e.g., in poorly structure sodic soils, or at field capacity in clay

13   soils). Nevertheless, the benefit of aeration was also evident in the dry treatment in the

14   moisture experiment, for most measured parameters, and it can be concluded that the

15   benefit of aeration is not only to offset hypoxic conditions, but also to satisfy an unmet

16   demand, presumably for oxygen, in the root zone.

17

18   The cumulative stem sap flow recorded over a three day period showed greater canopy

19   transpiration by the aeration treatment compared to the control, and by FC compared to

20   the dry treatment. As the instantaneous measurements of stomatal conductance and leaf

21   transpiration rate did not differ significantly, it is possible that the higher stem sap flow

22   rate was related to greater leaf area per plant due to aeration. Further studies are required

23   to determine whether the increase in water flow through the root system is due to changes

1 in the water potential gradient across the root system, to changes in hydraulic

2 conductance produced by modifications of the root structure, or to both.

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5 **Acknowledgements**

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12 **References**

13

14 Adams, P., 1986. Mineral nutrition. In: Atherton, G.J. and Rudich, J. (Eds), The tomato

15   crop - A scientific basis for improvements. Chapman and Hall, London: pp. 281-334.

16 Adams, P., Ho, L.C., 1992. Susceptibility of modern tomato cultivars to blossom end rot

17   in relation to salinity. J. Hort. Sci. 67, 827-839.

18 Alarcon, J.J., Sanchez-Blanco, M.J., Bolarin, M.C., Tollecillas, A., 1994. Growth and

19   osmotic adjustment of two tomato cultivars during and after saline stress. Plant and

20   Soil 166, 75-82.

21 Anonymous., 1994. Chlorophyll determination, Environmental Protection Agency, USA,

22   pp.1-4.

1   Baker, J.M., Bavel, C.H.M. v., 1987. Measurement of mass flow of water in stems of

2   herbaceous plants. Plant, Cell Env. 10, 777-782.

3   Barrett-Lennard, E.G., 2003. The interaction between waterlogging and salinity in higher

4   plants: Causes, consequences and implications. Plant and Soil 253, 35-54.

5   Bhattarai, S.P., Huber, S., Midmore, D.J., 2004. Aerated subsurface irrigation water gives

6   growth and yield benefits to zucchini, vegetable soybean and cotton in heavy clay

7   soils. Ann. Appl. Biol. 144, 285-298.

8   Bradford, K.J., Yang, S. F., 1981. Physiological responses of plants to waterlogging.

9   Hort. Sc. 16, 25-30.

10   Caldwell, M.M., Virginia, R.A., 1991. Root systems. In: Rundel, P.W. (Ed.), Plant

11   physiological ecology: Field methods and instrumentation, Chapman and Hall,

12   London, pp. 367-392.

13   Cordoba, A., Garcia Seffino L., Moreno H., Arias, C., Grunberg, K. and Zenoff, A.,

14   2000. Characterization of the effect of high salinity on roots of *Chloris gayana*

15   Kunth: carbohydrate and lipid accumulation and growth. Grass Forage Sci. 56,162-

16   168.

17   Cruz, V., Cuartero, J., Bolarin, M.C., Romero, M., 1990. Evaluation of characters for

18   ascertaining salt stress responses in *Lycopersicon* species. J. Am. Soc. Hort. Sci. 115,

19   1000-1003.

20   Cuartero, J., Fernadez-Munoz, R., 1999. Tomato and salinity. Sci. Hortic. 78, 83-125.

21   Farquhar, G.D., Hubick, K.T., Condon, A.G.; Richards, R.A., 1991. Carbon isotope

22   fractionation and plant water use efficiency. In: Rundel, P.W., Ehleringer, J. R. and

1   Nagy, K.A. (Eds.), Stable isotopes in ecological research. Springer-Verlag, New York

2   pp. 21-46.

3   Garnier, E., Shipley, B., Roumet, C., Lamrent, G., 2001. A standardized protocol for the

4   determination of specific leaf area and leaf dry matter content. Funct. Ecol. 15, 688-

5   695.

6   Goorahoo, D., Carstensen, G., Zoldoske, D.F., Norum, E., Mazzei, A., 2001. Using air in

7   subsurface drip irrigation (SDI) to increase yields in bell pepper. In: Proceedings of

8   the irrigation association technical conference, San Antonio, Texas. pp 95-102.

9   Hocking, P. J., Steer, B. T., 1994. The distribution and identity of assimilates in tomato

10   with special reference to stem reserves. Ann. Bot. 73, 315-324.

11   Hokmabadi, H. Arzani, K. Grierson, P. F. Growth, chemical composition, and carbon

12   isotope discrimination of pistachio (*Pistacia vera* L.) rootstock seedlings in response

13   to salinity. Aust. J. Agric. Res. 56, 135-144.

14   Hsiao, T. C., 1993. Growth and productivity of crops in relation to water stress. Acta

15   Hortic. 335, 137-148.

16   Johnson, R.W., Dixon, M.A., Lee, D.R., 1992. Water relations of the tomato fruit during

17   growth. Plant Cell Env. 15, 947-953.

18   Joly, R.J., 1985. Technologies for determining seedlings water status and their

19   effectiveness in assessing stress. In: Duryea, L. (Ed.), Proceedings of the workshop

20   on evaluating seedlings quality: Principles, procedures, and predictabilities of major

21   tests. October 16-18, 1984. Forest Research Laboratory, Oregon State University,

22   Corvallis, USA, pp. 67-78.

1 Kafkafi, U., Bernstein, N., 1996. Root growth under salinity stress. In: Waisel, Y., Eshel,
2   A. and Kafkafi, U. (Eds.), Plant roots: The hidden half, Marcel Decker inc. New
3   York, pp. 435-451.
4 Kinet, J. M. and Peet, M. M. (1997). Tomato. In: Wien, H. C. (Ed). The physiology of
5   vegetable crops. CAB International, Wallingford, pp. 259-294.
6 Olympios, C. M., Karapanos, I. C., Lionoudakis, K., Apidianakis, I., 2003. The growth,
7   yield and quality of greenhouse tomatoes in relation to salinity applied at different
8   stages of plant growth. Acta Hortic. 609, 313-320.
9 Letey, J., 1961. Aeration, compaction and drainage. Calif. Turf. Cult.. 11, 17-21.
10 Li Y. L., Stanghellini, C., 2001. Analysis of the effect of EC and potential transpiration
11   on vegetative growth of tomato. Sci. Hortic. 89, 9-21.
12 Meek, B.D., Ehlig, C.F., Stolzy, L.H.; Graham, L.E., 1983. Furrow and trickle irrigation:
13   Effects on soil oxygen and ethylene and tomato yield. Soil Sci. Soc. Am. J. 47, 631-
14   635.
15 Munns, R., 2002. Comparative physiology of salt and water stress. Plant Cell Env. 25,
16   239-250.
17 Perez-Alfocea, F., Balibrea, M.E., Cruz, A.S., Estan, M.T., 1996. Agronomical and
18   physiological characterisation of salinity tolerance in a commercial tomato hybrid.
19   Plant and Soil 180, 251-287.
20 Pessarakli, M., Tucker, T.C., 1985. Dry matter yield and nitrogen-15 uptake by tomato
21   under sodium chloride stress. Soil Sci. Soc. Am. J. 52, 698-700.
22 Poysa, V.W., Tan, C.S.; Stone J.A., 1987. Flooding stress and the root development of
23   several tomato genotypes. HortSci. 22, 24-26.

1 Rengasamy, P. 2002. Transient salinity and subsoil constraints to dry land farming in

2   Australian sonic soils: an overview. Aust. J. Exp. Agric. 42: 351-361.

3 Renault, S., Lait, C., Zwiazek, J.J., Mackinnon, M., 1998. Effect of high salinity tailings

4   in water produced from gypsum treatment of oil sands tailings on plants of the boreal

5   forest. Environ. Pollut. 102, 1-8.

6 Rengel, Z., 1992. The role of calcium in salt toxicity. Plant Cell Env. 15, 625-632.

7 Rhoades, J.D., Loveday, J., 1990. Salinity in irrigated agriculture. In: Nielsen, D.R. (Ed.),

8   Irrigation of agricultural crops. Agronomy. No 30 in the series. American Society of

9   Agronomy, Inc., Madison, Wisconsin, USA, 1089-1142.

10 Rodriguez, P., Amico, J.D., Morales, D., Sanchez-Blanco, M.J.; Alarcon, J.J., 1997.

11   Effect of salinity on growth, shoot water relations and root hydraulic conductivity in

12   tomato plants. J. Agric. Sci. 128, 439-444.

13 Rudich, J., Luchinsky, U., 1986. Water economy. In: Atherton, G.J. and Rudich, J. (Eds.),

14   The tomato crop - A scientific basis for improvements. Chapman and Hall, London.

15   pp. 335-361.

16 Santamaria, P., Cantore, V., Conversa, G., Serio F., 2004. Effect of night salinity level on

17   water use, physiological responses, yield and quality of tomato. J. Hort. Sci. Biotech.

18   79, 59-66.

19 Seemann, J.R., Critchley, C., 1985. Effect of salt stress on the growth, ion content,

20   stomatal behavior and photosynthetic capacity of salt-sensitive species, *Phaselous*

21   *vulgaris* L. Planta 164, 151-162.

22 Sharaf, A.R., Hobson, G.E., 1986. Effect of salinity on the yield and quality of normal

23   and non-ripening mutant tomatoes. Acta Hortic. 190, 175-181.

1   Vartapetian, B. B., and Jackson, M. B. (1997). Plant adaptations to anaerobic stress. Ann.

2   Bot. 79 (suppl A), 3–20.

3   Vaughan, L.V., MacAdam W., Smith, S.E., Dudley, M., 2002. Root growth and yield of

4   differing alfalfa rooting populations under increasing salinity and zero leaching. Crop

5   Sci. 42, 2064-2071.

6   Walker, R.H., Li, Z., and Wehtje, G. (2000). Roots improve with summertime air

7   movement beneath greens. Golf Course Manag. 68, 72-76.

8   Yeo, A.R., Flowers, TJ., 1989. Selection for physiological characters - examples from

9   breeding for salt tolerance. In: Jones, M.B. (Ed.), Plant under stress. Cambridge

10   University Press, Cambridge, pp. 217-234.

11 Zhang, H-X., Blumwald, E., 2001. Transgenic salt tolerant tomato plants accumulate salt

12   in foliage but not in fruit. Nature Biotech. 19, 765-768.

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Table 1
Effects of soil moisture and aeration on cumulative applied irrigation, sap flow, leaf water potential, crop water stress index and water use efficiency for tomato in a Vertisol. Means for main effects, with LSD for comparison.

Variables	Levels	Water relations				Water use efficiency (WUE) parameters			
		Cumulative applied water (L plant^{-1})	Average daily sap flow (g plant^{-1} 83-85 das)	[1]LWP (-kPa)	[2]CWSI	Biomass$_{sl}$ (g L^{-1})	Fruit$_{sl}$ (g L^{-1})	Instantaneous [3](A/E)	Δ (‰)
Moisture	Field capacity	110.94	652	1100	0.18	4.23	36.40	5.43	20.42
	Dry	99.42	554	1360	0.26	4.59	38.42	5.50	20.28
Aeration	Aeration	104.68	625	1220	0.20	4.73	39.15	5.41	20.33
	Control	105.57	580	1240	0.24	4.09	35.16	5.52	20.37
	LSD (6 df)	1.79	54.2	54.0	0.04	019	2.17	ns	ns

[1]LWP= Leaf water potential (measurements of negative leaf water potentials)
[2]CSWI= Crop water stress index (1 = completely stressed, 0 = no stressed)
[3]A/E= Instantaneous water use efficiency calculated as, A = net leaf photosynthesis rate ($\mu mol\ CO_2\ m^{-2}s^{-1}$); E = leaf transpiration rate ($mmol\ H_2O\ m^{-2}s^{-1}$)

Table 2
Effects of soil moisture and aeration on plant height, leaf area, flowering, fruit and biomass yield, dry matter partitioning and harvest index (HI) for tomato in a Vertisol. Means for main effects, with LSD for comparison.

Variables	Levels	Plant height (cm)	Leaf area plant^{-1} (m^{-2})	Days to first flowering	Fruit number, weight and yield			Dry weight (g plant^{-1})				Above ground biomass (g plant^{-1})	HI
					No. per plant	g per fruit	kg per plant	Root	Stem	Leaf	Fruit		
Moisture	Field capacity	192.2	0.745	47.2	31	130	4.03	12.19	55.38	97.83	315.88	467.37	0.66
	Dry	181.7	0.760	45.7	29	130	3.81	11.11	49.53	93.37	312.76	455.67	0.62
Aeration	Aeration	190.0	0.803	45.3	31	136	4.15	10.88	53.26	96.36	343.93	493.56	0.68
	Control	183.8	0.701	47.5	30	124	3.70	12.42	51.64	94.84	284.71	431.19	0.64
	LSD (6 df)	9.01	0.023	1.73	1.3	0.85	0.25	2.71	4. 6	ns	10.54	23.1	0.04

Table 3
Effects of soil moisture and aeration on % fruit dry matter (DM), root:shoot ratio, specific leaf area (SLA), chlorophyll concentration, leaf gas exchange properties and light interception for tomato in a Vertisol. Means for main effects, with LSD for comparison.

Variables	Levels	Fruit DM (%)	Root: Shoot ratio	SLA ($cm^{-2}\ g^{-1}$)	Chlorophyll concentration ($\mu g\ cm^{-2}$)	Leaf gas exchange properties and light interception			
						Photosynthesis ($\mu mol\ CO_2\ m^{-2}s^{-1}$)	Stomatal conductance ($mol\ m^{-2}s^{-1}$)	Transpiration ($mmol\ m^{-2}s^{-1}$)	Light interception (%)
Moisture	Field capacity	7.8	0.026	222	58	13.35	0.10	2.57	54.8
	Dry	8.2	0.025	219	58	13.46	0.11	2.62	53.4
Aeration	Aeration	8.3	0.022	209	59	13.38	0.10	2.59	55.3
	Control	7.7	0.029	233	57	13.32	0.11	2.60	52.9
	LSD (6 df)	0.14	0.003	44.6	1.78	ns	ns	ns	ns

Table 4
Comparison of the soil moisture (mm H_2O per 100 mm soil) seasonal means for salinity and aeration treatments and cumulative applied water over the crop period.

Salinity treatment $EC_{(e)}$ (dS m^{-1})	Soil moisture (mm per 100 mm soil depth)		Cumulative applied water per plant (L)	
	Aeration	No aeration	Aeration	No aeration
2.0	22.90	24.17	22.34	21.48
4.0	24.71	26.31	19.83	19.40
8.8	24.01	27.50	19.69	18.23
10.0	27.43	31.18	15.43	16.12
LSD Aeration	2.20 (7 df)		0.96 (37 df)	
LSD Salinity	3.11 (7 df)		1.35 (37 df)	

Table 5
Crop growth and leaf characteristics (per plant) for tomato as affected by aeration and soil salinity treatments.

Factor	Levels	Plant height (cm)	Number of trusses	Number of leaves	Area per leaf (cm^2)	Total leaf area (m^2)	Leaf chlorophyll concentration $(\mu g\ cm^{-2})$
Salinity treatment $EC_{(e)}$ $(dS\ m^{-1})$	2	148	6	21	154.1	0.33	51
	4	132	5	21	145.4	0.30	53
	8.8	131	5	20	163.3	0.34	50
	10	94	4	17	114.6	0.20	49
	LSD 5% (38 df)	20	0.76	2.43	52	0.07	ns
Aeration treatment	Aeration	130	5	20	141.2	0.29	51
	No aeration	123	5	19	148.9	0.30	50
	LSD 5% (38 df)	14	ns	ns	ns	ns	ns

Table 6
Flowering, fruit yield and yield attributes for tomato as affected by aeration and soil salinity treatments

Factor	Level	Inflorescences plant $^{-1}$ (87 days)	Days to 50% flowering in the first inflorescence	[1]Fruits per plant at harvest (87 days)
Salinity treatment $EC_{(e)}$ (dS m^{-1})	2	5.0	47	7.7
	4	4.6	56	7.7
	8.8	4.5	60	7.3
	10	3.2	67	3.7
	LSD 5% (38 df)	0.85	6.1	2.7
Aeration treatment	Aeration	4.5	60	7.8
	No aeration	4.1	55	5.5
	LSD 5% (38 df)	0.60	ns	1.9

[1] The crop was harvested once over at 87 days after seeding without leaving the plant for the full season

Table 7
Dry matter and partitioning, root:shoot ratio and harvest index (HI) for tomato at harvest as affected by aeration and soil salinity treatments.

Factor	Levels	Dry weight plant^{-1} (g)					Root: shoot ratio	HI
		Root	Stem	Leaf	Fruits	Total biomass		
Salinity treatment EC$_{(e)}$ (dS m^{-1})	2	11.16	18.47	30.31	37.61	97.56	0.13	0.38
	4	14.27	18.86	30.82	25.96	89.91	0.19	0.29
	8.8	13.02	17.37	26.55	20.79	75.46	0.21	0.28
	10	12.02	9.41	13.24	10.31	44.97	0.36	0.23
	LSD 5% (38 df)	ns	4.61	7.36	9.71	19.99	0.20	0.07
Aeration treatment	Aeration	12.77	17.80	28.39	31.25	89.87	0.14	0.35
	No aeration	12.49	14.71	22.95	17.58	67.51	0.18	0.26
	LSD 5% (38 df)	ns	ns	ns	6.86	14.14	ns	0.05

Table 8
Water use efficiency for tomato as affected by aeration and soil salinity treatments.

Factor	Levels	WUE for biomass (g L^{-1})	[1]WUE of fruit (g L^{-1})	Carbon discrimination (Δ ‰)
Salinity treatment EC$_{(e)}$ (dS m^{-1})	2	4.26	1.64	21.39
	4	4.54	1.32	21.09
	8.8	4.00	1.07	21.12
	10	2.85	0.65	20.13
	LSD 5% (38 df)	0.87	0.45	0.72
Aeration treatment	Aeration	4.65	1.62	21.01
	No aeration	3.56	0.93	20.79
	LSD 5% (38 df)	0.61	0.32	ns

[1] Determination of WUE of fruit based on dry fruit weight.

Table 9
Salt accumulation, leaf membrane integrity (according to Renault et al. 1998), and root properties as affected by soil salinity and aeration on tomato in a Vertisol.

Factor	Level	Na^+ (g $100g^{-1}$)	Cl^- (mg kg^{-1})	K^+ (g $100g^{-1}$)	Ca^{2+} (g $100g^{-1}$)	K^+:Na^+	Leaf membrane leakage (%)	Root length in sample core (mm)	Root weight (g $plant^{-1}$)
Salinity treatment $EC_{(e)}$ (dS m^{-1})	2	0.22	0.99	2.83	1.51	15.4	15	7820	11.38
	4	0.25	1.39	3.04	1.82	13.14	18	5852	14.27
	8.8	0.31	1.83	2.73	1.85	9.28	20	7486	12.97
	10	0.49	2.56	2.56	2.35	4.12	33	5440	10.72
	LSD (7df)	0.14	0.33	ns	0.34	6.4	LSD=17.9 (38 df)	LSD = 64.6 (38 df)	LSD=5.19 (38 df)
Aeration treatment	Aeration	0.26	1.91	2.75	1.62	13.78	20	7169	12.63
	No aeration	0.37	1.47	2.82	2.15	7.19	26	6160	12.03
	LSD (7df)	0.10	0.13	ns	0.24	4.5	ns	LSD = 15.8 (38 df)	LSD=3.67 (38 df)

Figure Captions for Bhattarai et al.

Fig. 1. Concentration of soil oxygen as affected by aeration (open symbols) or no aeration (closed symbols) at two soil water contents on a Vertisol with tomato.

Fig. 2. Soil water content (mm H_2O per 100 mm of soil depth) in field capacity or drier pots containing tomato plants with (open symbols) or without aeration (closed symbols). Irrigation was withheld close to final harvest.

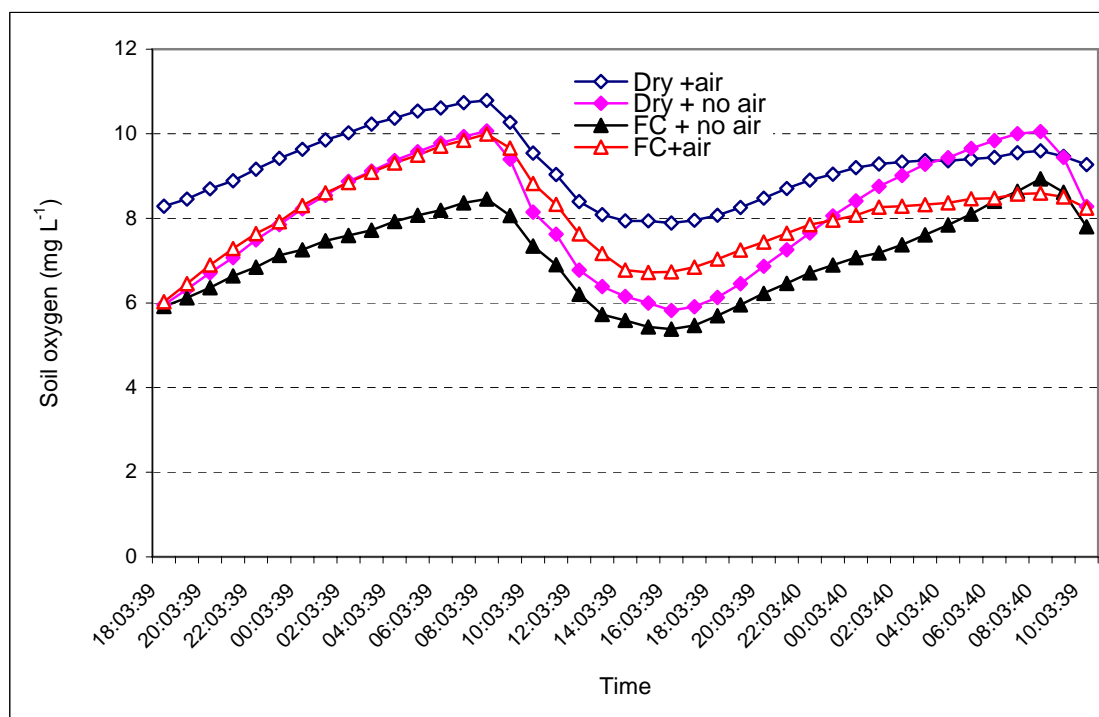Fig. 3. Concentration of soil oxygen as affected by aeration (open symbols) or no aeration (closed symbols) at two soil salinities in a Vertisol with tomato.
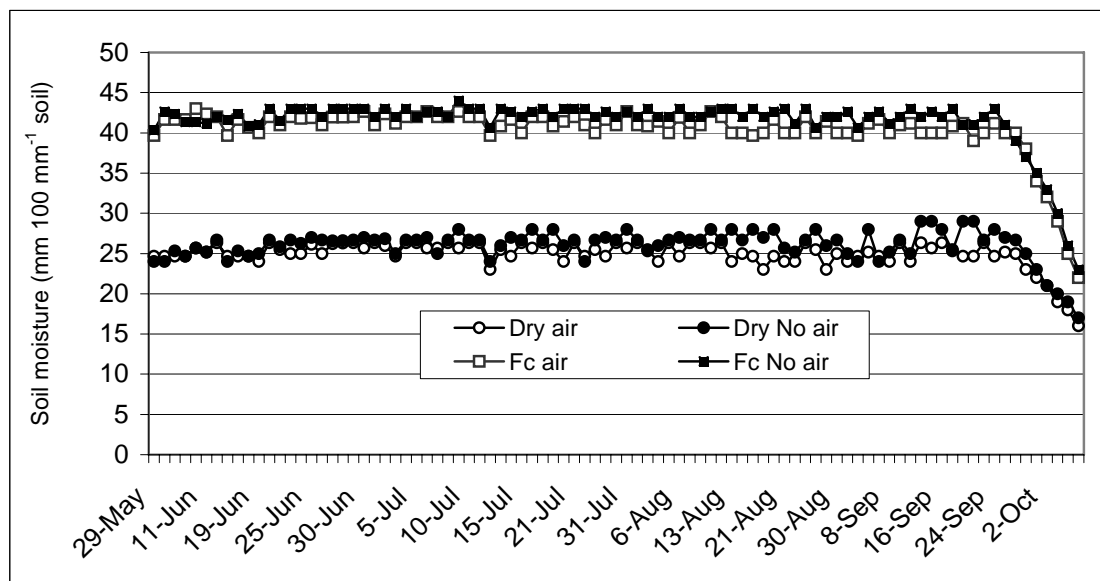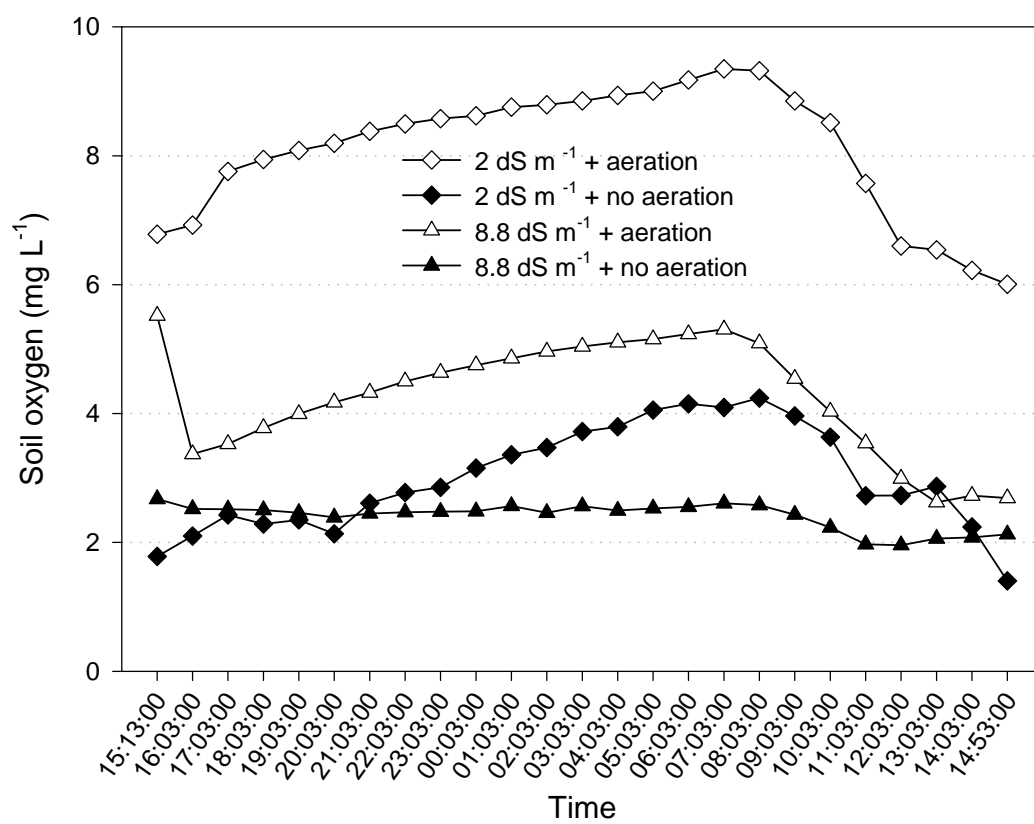
Figure 1

Figure 2

Figure 3