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Rooting characteristics of lettuce grown in irrigated sand beds

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Abstract

To avoid the current water pollution from intensive glasshouse horticulture, closed systems have to be developed with recirculating drainage water. For crops with a high planting density, such as lettuce, shallow beds of coarse sand may be used if water and nutrient supply can be regulated adequately. The aim of the present study was to determine the rooting characteristics and root distribution of lettuce in sand beds, as affected by substrate depth, the distance to a drain, drip lines and drip points, and the excess of nutrient solution applied. The hypothesis was tested that a small excess and a large distance between drip points leads to local salt accumulations in the root environment and thus to a less homogeneous root distribution.

The data confirmed both parts of the hypothesis: spatial patterns in salt distribution were found. Detailed measurements in a sand bed with only one drip line per two crop rows and an amount of fertigation solution added of 2 times the estimated evapotranspiration, showed that root length density was negatively correlated with salt content when comparisons were made within the same layer. Crop yield per row was influenced in the extreme treatment, i.e. one drip line per two crop rows and an amount of fertigation solution added of 1.3 times the estimated evapotranspiration, but yield per bed was still unaffected. The increased heterogeneity of the crop will cause problems at harvest and indicates that the most extreme treatment included in the comparison is just beyond the limit of acceptable heterogeneity in the root medium. Lettuce can be grown on sand beds with a recirculating nutrient solution provided that drip lines are well distributed in the bed and the daily nutrient solution excess is more than 30% of demand.

Introduction

Over the last two decades a large part of the Dutch commercial horticultural growers changed from soil-based systems to the use of artificial substrates. The smaller rooted volume and the lower chemical buffering capacity of the root environment offer better opportunities to control plant growth. Nutrient use efficiencies in the presently used open-drain systems are low, however, and result in unacceptable pollution of groundwater and surface water (Van Noordwijk, 1990). In the Netherlands growers are obliged to change to closed growing systems, with drainage water collection and recirculation, before the end of this century. In these closed systems the rooted volume and therefore the depth of the substrates is kept small to maintain the options for rapid change of the root environment to control plant growth. This means that natural soils with a fine texture cannot be used, since conditions that are too wet will occur and oxygen supply to the roots will be a problem for most crops because of their limited ability to make aerenchyma in their roots (Van Noordwijk and Brouwer, 1993). Therefore, coarser substrates have to be used. The choice of substrates, the design

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of the circulation system, and the nutrient and water management regimes should be mutually adjusted.

A wide range of artificial substrates has been or is still used for soilless horticultural systems (Jensen and Collins, 1985). Rockwool is most frequently used and accounts for 80% of the areas with artificial substrates in the Netherlands (Anonymous, 1992). A major problem in the use of rockwool, however, is that each year 112 m^3 or 11 Mg rockwool waste per hectare is to be taken care of (Van Velden, 1988). Rockwool slabs consist of fibers and have typical dimensions of 0.075 m height, 0.15 m width and 1.0 m length. It is only recently that recycling of rockwool slabs has been possible at a practical scale. Examples of other substrates in utilization and in testing are, e.g. organic substrates (peat), wood fibre, perlite, polyurethane foam, glasswool, synthetic polymers, polyester or viscose fleece, sand, coarse sand, gravel, lava and flugsand (Dickob, 1992; Kipp and Wever, 1993; Molitor, 1991). All these substrates bring different conditions for root growth, as well as for water and nutrient transport and storage. Such aspects have been studied in detail only for a few substrates, e.g. NFT (Nutrient Film Technique) and materials like rockwool and polyester fleece (Hurd, 1978; Van Noordwijk and Raats, 1980; Schröder, 1993).

The environmental conditions around plant roots differ strongly between soil-grown and soilless-grown plants. In the soil, there is ample supply of nutrients at the beginning of the growth period. On the other hand, in the classic NFT system only the volume of nutrient solution provides buffering for nutrients. For example, for nitrogen this solution stores only 1% of the demand for the total growing season (Krüger, 1993). In other growing systems with artificial substrates the amount of stored nutrients lies between that in soils and NFT systems.

In all artificial substrates, the average daily supply of nutrients and water has to exceed the demand by an average plant, as both supply and demand show between-plant variability. In fact, to obtain maximum yields, the average supply should be chosen in such a way that the most demanding plant at the least supplied site still obtains sufficient nutrients and water (Van Noordwijk, 1990). An average plant thus requires an excess supply of water and nutrients to guarantee a near-maximum production of the crop. Such a growing system needs a drainage system. The location of the supply system - drip lines, ticklers or other equipment -, the drains, and the physical properties of the substrate determine the flow pattern of the solution in the root environment. A certain further excess supply of nutrient solution and concomitant leaching to the drains is usually needed to ensure a regular distribution of water and nutrients in the root environment and to avoid local salt accumulation in the substrate (Van Noordwijk and Raats, 1980). Large volumes of recirculating nutrient solution, as in a NFT system, increase the size of required storage tanks required and costs, especially where recirculating solution has to be sterilized to control the spreading of diseases.

Most research on artificial substrates has focused on crops with a low planting density, such as tomato, cucumber, sweet pepper or potting plants, where the rooted volume can be kept small, e.g. in substrate slabs or pots. For crops with a high planting density, such as lettuce, spinach, radish, and certain flowers, natural soils are still preferred over artificial substrates, as these are too costly at the volume required. In principle, any crop can be grown in some type of artificial substrate, provided that the water and nutrient supply and the aeration of the root environment can be controlled properly. Against this background the Research Institute for Agrobiology and Soil Fertility (AB-DLO) carries out the research project "Dynamics of water and nutrients in closed, recirculating cropping systems, especially systems based on sand beds". One of the aims is to develop a simulation model for water movement and nutrient transport in the artificial substrate. The sink term in this model represents the roots and requires the determination of their spatial distribution in sand beds. This project together with that of Otten (1994) complements the study on artificial substrate growth systems. In future publications the model and other data will be published separately. In the study presented here we attempted to grow lettuce in shallow beds of coarse sand, with a recirculation system for the drained nutrient solution. To our knowledge, root growth of lettuce in coarse sand has not been investigated before.

Fröhlich (1956) described the root distribution of a wide range of vegetable crops on a deep sandy soil, rich in organic matter; lettuce was among the crops with a relatively fast development of a deep root system. Schuurman and Schäffner (1974) found that lettuce roots can reach a depth of 0.5–0.7 m in five weeks after planting seedlings on a similar soil, with a lateral spread of 0.2–0.4 m. Greenwood et al. (1982) derived equations describing root distribution of lettuce (and six other vegetable crops) on a sandy loam. Such results cannot be directly extrapolated to glasshouse sand bed systems, however.

Sand has been used as substrate in greenhouses. For example, Kirkham and Gabriels (1979) used sand boxes to grow wheat, and to determine parameters such as, root development and water content or *EC* patterns in the root zone. Plants watered from above gave a higher production than those watered from below. Watering from below resulted in higher *EC* values in the top part of the root zone, which is commonly found in growth systems with watering from below (e.g. Otten, 1994).

The aim of the present study was to determine the rooting characteristics and root distribution of lettuce in sand beds as a function of depth, the distance to a drain, drip lines and drip points, and the surplus of nutrient solution applied. The hypothesis was tested that a small surplus of nutrient solution and a restricted amount of drip lines leads to local salt accumulations in the root environment and thus to a less homogeneous root distribution.

Materials and methods

Sand bed and recirculation system

An experimental greenhouse compartment (250 m^2) was used with four separate sand beds, number I and II with an area of 42 m^2 and number III and IV with an area of 47 m^2. A schematic cross-sectional view of a sand bed is presented in Figure 1A. The boundaries of the beds were made of concrete walls 0.25 m high. Extended polystyrene foam insulation plates were placed on the concrete floor of the greenhouse across the length of the beds. These plates were 0.04 m thick, 0.78 m wide and spaced 0.04 m apart. Impermeable plastic sheet was placed over the plates. Drain tubes were located in the open spaces between the plates, i.e. the drains were 0.8 m apart. The drains ended in a collecting PVC tube, which ran to a drain tank. An anti-rooting mat was situated on top of the drains plus plastic sheet to prevent roots from growing into the drain. A 0.15 m coarse sand (median diameter $6 \cdot 10^{-4}$ m) layer was put on top of this anti-rooting mat. Each system had its own supply tank (1.3 m^3) and drain tank (0.14 m^3). The nutrient solution was supplied by means of drip lines located between the crop rows. The drip points were spaced 0.30 m apart (Fig. 1B) and the supply rate was approximately 1 L h^{-1}. An overhead sprinkling system was used during the first week to ensure sufficient availability of water and nutrients in the early stages of growth. Excess drainage water was pumped to the corresponding supply tank. Thus a closed, recirculating nutrient solution system was used.

Table 1. Treatments used for the four sand bed systems

Sand bed number	Daily nutrient solution excess, % of estimated evapotranspiration	Number of drip lines per number of crop rows
I	30	1:2
II	100	1:2
III	30	1:1
IV	100	1:1

Experimental treatments

Before planting, the four sand bed systems were flushed several times with clean water in order to remove most of the nutrients present from earlier experiments, so that the initial condition in the four sand beds was the same. After flushing the supply and drain tanks were emptied. The supply tanks were filled with a fresh nutrient solution for lettuce according to Sonneveld and Straver (1988) at an *EC* of 2.3 mS cm^{-1}

Twenty-day old lettuce seedlings, *Lactuca sativa* cv. Cortina, were planted in the still wet sand beds on July 31 and harvested on September 7, 1992. The distance between plant rows was 0.20 m, and within the rows the plants were 0.30 m apart (Fig. 1B; note that the between-row distance is smaller than the in-row distance in our terminology, contrary to the normal convention; our rows were parallel to the drains and drip lines). This planting pattern differs from that normally used, but was chosen to let the distance between two drains be a multiple of the distance between two crop rows, i.e. 0.8 m and 0.2 m, respectively. So every fourth plant row was located exactly above a drain. All plants within a row were located next to a drip point (Fig. 1B).

Four treatments were imposed on the sand beds, in a two-by-two factorial design with distance between drip lines and solution surplus as treatment factors, without replication (Table 1). Either all drip lines were open, or the drip lines farthest from the drain were open and the ones closest to the drain were closed (Fig. 1B). The second treatment factor was the surplus of nutrient

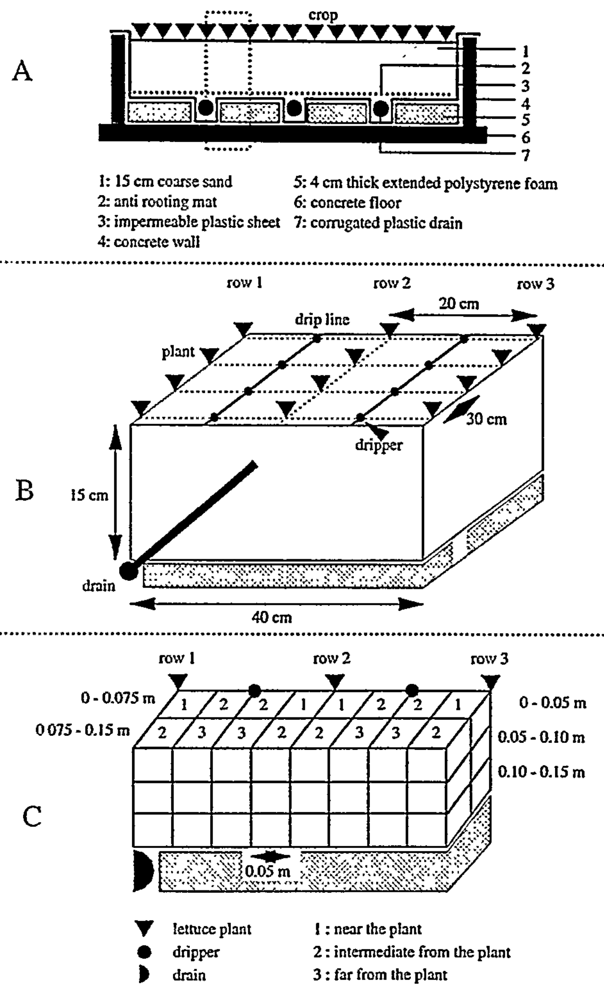

Fig. 1. Schematic cross sectional view of the sand bed. system (A); a three-dimensional view of half the area between two drains (dotted area in A) is given in **B**, while the volume of the root zone that was sampled (shaded area in B) is given in detail in **C**; the total volume sampled in C is $9{\cdot}10^{-3}$ m^3, divided into 48 samples. One quarter of the total rooting volume of plants in rows 1 and 3 and two quarters of the total root volume of the plant in row 3 were thus sampled.

solution supplied, either 1.3 (or 30%) or 2 (or 100%) times the estimated evapotranspiration.

The first treatment factor was chosen to investigate possibilities for reducing the number of drip lines in the system to save costs. By opening only the drip lines farthest from the drains, the worst case 'minimal water supply condition' was imposed. The plants growing in the rows directly above the drains can be expected to have difficulties with this water supply, since the majority of the streamlines are directed from the dripper towards the drain, i.e. away from these plants.

The second treatment was chosen to check whether salt accumulation in the top layer would become a problem with a relatively small surplus of fertigation solution. Salt accumulation in the top layer may be harmful to plant growth. On the other hand, large amounts of recirculating drainage water may increase the risks of diseases spreading in the system, while increasing the costs for sterilization of the solution and of energy. The excess of nutrient solution supplied was either 30% or 100% more than the estimated evapotranspiration as computed according to the method proposed by De Graaf and Spaans (1989). The evapotranspiration ET (mm) is estimated from the net incoming radiation and the heating of the glasshouse according to

$$ET = (aR + bH)\ s \tag{1}$$

where R is the global radiation outside the greenhouse (J cm^{-2}), H is the heating or 'degree-minutes' defined as the difference in temperature between the heating pipes and greenhouse during one minute (K min^{-1}), s is a plant size factor with $0 \leq s \leq 1$ (–), and a (mm cm^2 J^{-1}) and b (mm min K^{-1}) are crop-specific parameters. De Graaf and Spaans (1989) defined s as the actual length of a plant relative to the maximum length. Since it is difficult to speak of the length of lettuce, it was decided to consider lateral expansion of lettuce and to express this in s. The shape factor s was defined to increase linearly in time from zero at the beginning to one at the end of the growth period. In this study a and b were set equal to those of De Graaf and Spaans (1989): $a = 1.78 \cdot 10^{-3}$ mm cm^2 J^{-1}, and $b = 2.2 \cdot 10^{-5}$ mm min K^{-1}. In a later study the parameters a and b were optimized for lettuce grown on sand beds (Heinen and Van Moolenbroek, 1995).

Shoot measurements

The fresh and dry weights of the shoots were determined at harvest time. In each of the four beds six shoots of plants in a row above a drain, six shoots of plants in a row between two drains, and six shoots of plants in a row between these two rows were sampled in two replications. The plants were dried at 70 °C.

Root measurements

At the end of the growth period a substrate block with a volume of $9 \cdot 10^{-3}$ m^3 (0.15 m thick, 0.15 m wide, 0.40 m long; Fig. 1B, C) was taken from all sand beds in two replications. These substrate monoliths were divided into 48 small samples of $1.875 \cdot 10^{-4}$ m^3 each. Roots were washed from these substrate samples and collected by decantation and dried for 48 h at 70 °C. Root dry weight data are expressed as

- root dry weight density per volume of substrate, D_{rv}, (kg m^{-3}), and
- root dry weight per plant, D_{rp}, (g $plant^{-1}$), which is related to D_{rv} according to

$$D_{rp} = D_{rv} \ \ V \ \ 1000 \tag{2}$$

where D_{rv} is averaged over 12 substrate samples taken in three depths of 0.05 m each, $V = 9 \cdot 10^{-3}$ m^3 is the volume of the substrate space of one plant (0.15 m deep, 0.30 m wide and 0.20 m long, see Fig. 1C), and 1000 is a conversion factor from kg to g. The shoot/root weight ratio was calculated as well.

Root length, L_r and root diameter, $2R_0$, where R_0 is the root radius, were measured in one replication of beds II and IV only, with the line intersect method of Tennant (1975). The data are presented as

- specific root length, L_{rw}, or root length per root dry weight (m g^{-1}),
- root length density, L_{rv}, or root length per unit substrate volume (km m^{-3}), and
- root length per plant, L_{rp}, (m $plant^{-1}$).

Root diameters were measured in twenty random samples - every tenth line root intersection until twenty readings were obtained - and are presented as frequency distributions.

All root data obtained in a single bed were analyzed by analysis of variance (Genstat 5 Committee, 1975), with substrate depth, sample position with respect to plant position denoted by 1 (near the plant), 2 and 3 (far from the plant) (Fig. 1C), and distance to the drain as factors in an orthogonal scheme, with two replications. Significant differences in the figures are demonstrated by different letters. The standard error of differences *sed* is used to compare the difference in means between two populations, and it is defined as

$$sed = \sqrt{s^2 \left(\frac{1}{n_1} + \frac{1}{n_2} \right)} \tag{3}$$

where s^2 is the population variance, and n_i is the number of observations of each population i. The standard error of differences is given standard by Genstat 5.

Water content and salinity

The final water content distribution was determined in sand samples taken at depths 0–0.05 m, 0.05–0.10 m and 0.10–0.15 m in beds I and. III. The gravimetric water content, determined after 24 h oven drying at 105 °C, was converted to volumetric water content according to

$$\theta = w \frac{\rho_d}{\rho_l} \tag{4}$$

where θ is the volumetric water content (m^3 m^{-3}), w is the gravimetric water content (g g^{-1}), ρ_d is the dry bulk density of the sand (Mg m^{-3}), and ρ_l is the density of water (1.0 Mg m^{-3}). The average dry bulk density of the three layers was 1.55 Mg m^{-3}. It was assumed that the water contents in beds II and IV were the same as those of beds I and III, respectively. Sampling was carried out in three depths and at four distances perpendicular to the drain.

The *EC* of the substrate solution was meant to be measured in samples obtained with porous hydrophilic

Table 2. Gravimetric, w (g g^{-1}), and volumetric, θ (m^3 m^{-3}), water contents of beds I and III for three different layers: top (0–0.05 m), middle (0.05–0.10 m), bottom (0.10–0.15 m). The *sed* values for the three effects layer, bed and layer × bed were: 0.00490 (8 replications), 0.004 (12 replications), and 0.00694 (4 replications), respectively

Layer	Bed I		Bed III	
	w	θ	w	θ
Top	0.1388	0.215	0.2050	0.318
Middle	0.1993	0.309	0.2085	0.323
Bottom	0.2408	0.373	0.2520	0.391

polymer suction tubes (Meijboom and Van Noordwijk, 1992). Substrate solution is obtained by applying a vacuum (e.g. by using vacuum blood transfusion tubes) at the end of the tubes. The *EC* can be measured directly in the obtained samples with an *EC* electrode. However, it was not possible to obtain enough solution from the tubes installed in the top layer. The few samples that were obtained from the top layer had *EC* values similar to those from the deeper layers, so that solution from below was apparently sucked away. It was, therefore, decided to take substrate samples from bed II only to obtain the *EC* distribution in the root zone. The *EC* of the substrate solution was measured in 1:2 by volume substrate extracts of substrate samples obtained from the three different substrate layers at the end of the experiment, i.e. at depths 0–0.05 m, 0.05–0.10 m and 0.10–0.15 m. The 1:2 extract results yield *EC* values of diluted substrate solution. The dilution factor is given by

$$F = 1 + \frac{2}{\theta} \qquad (5)$$

where F is the dilution factor (dimensionless) and θ is the volumetric water content (m^3 m^{-3}). The *EC* measurements were carried out in bed II. It was assumed that the water content in bed II was the same as that in bed I (see above).

Root distribution was related to *EC* distribution by linear regression analysis.

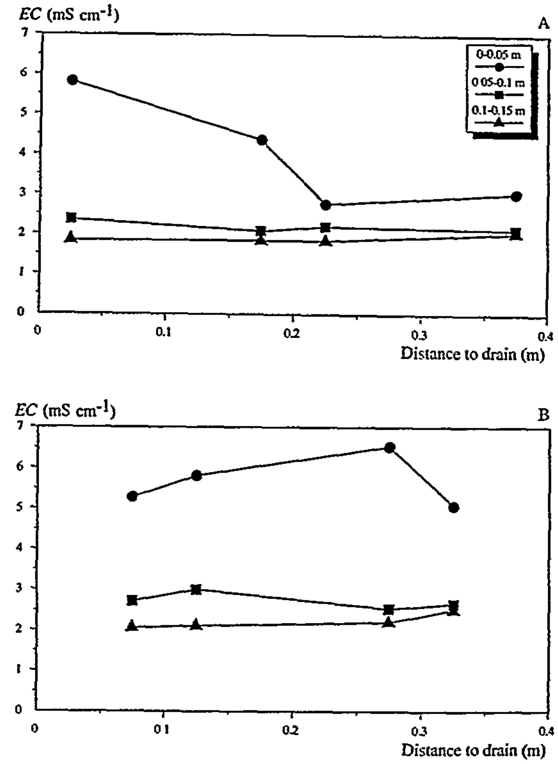

Fig. 2. *EC* distribution near (A; near = columns 1 of Fig. 1C) and far from (B; far = columns 3 of Fig. 1C) a plant as observed in bed II at three substrate depths at harvest time.

Results

Water content and salinity

Analysis of variance on all data of the gravimetric water content w in beds I and III showed that there was no significant effect of distance perpendicular to the drain, but there was a highly significant layer effect (Table 2) and a significant layer × bed interaction. On average, bed III was significantly wetter than bed I, where only one drip line per two crop rows was used: 0.344 m^3 m^{-3} versus 0.299 m^3 m^{-3}, respectively. The plants in bed I above the drain and far from a drip point apparently had ample water available. The porosity of the sand is on average 0.42 m^3 m^{-3} so that near-saturation conditions existed in the bottom layer.

At the end of the experiment the *EC* distribution near the plant position (Fig. 2A; refer to position 1 in Fig. 1C) differed from that far from the plant position (Fig. 2B; refer to position 3 in Fig. 1C). The two bottom layers (0.05–0.15 m) near the plant and the bottom layer (0.10–0.15 m) far from the plant had a constant

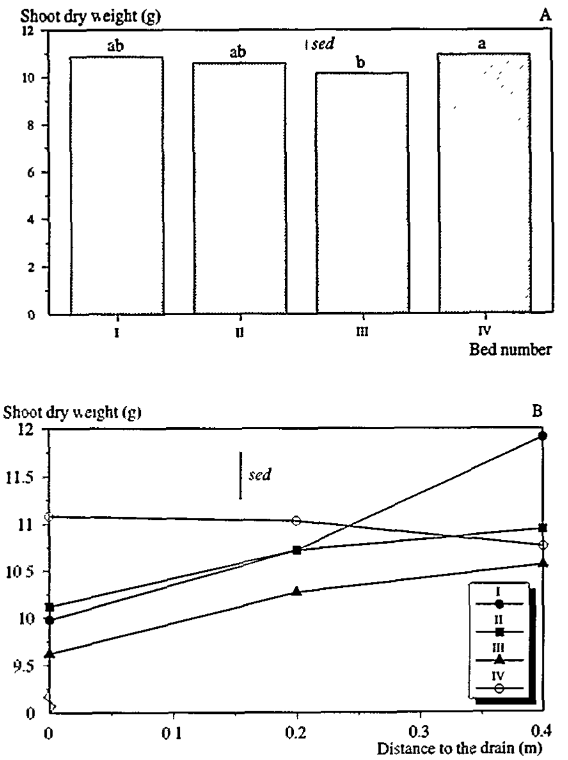

Fig. 3. Average shoot dry weight of the lettuce heads per bed (A) and shoot: dry weights as a function of distance to the nearest drain (B). Differences between columns not identified with the same letter are statistically significant (*sed* = standard error of differences; $p < 0.05$).

EC value independent of the distance to drain or drip point (Fig. 2). For these layers the average *EC* value was a good reflection of the *EC* of the supplied nutrient solution of 2.3 mS cm^{-1}. This means that the *EC* in this part of the root zone was similar to the optimal salinity for lettuce (2.5 mS cm^{-1}) recommended for recirculating systems (Sonneveld and Straver, 1988). The middle layer of the position far from the plant had a slightly higher average *EC*, and the *EC* value of the top layer was 2 to 2.5 times higher than that of the supplied nutrient solution. The *EC* in the top layer of the position near the plant decreased with increasing distance from the drain. Thus, with a restricted number of drip lines, but with a high surplus of nutrient solution, salt accumulated in the top layer at locations far from the drip line.

Shoot fresh and dry weight

The average fresh weight of the heads for the four beds was 230.3 g $plant^{-1}$ and the dry weight was 10.6 g $plant^{-1}$. There was no significant difference in the fresh weight of the shoots between the four beds. A visual judgement of the crops before harvesting also suggested no differences between the beds. The average dry shoot weights obtained for the four beds did not differ, except for a significant difference between beds III and IV (Fig. 3A). The standard error of differences, *sed*, given in this figure is based on the internal replicates in each bed as well the results of statistical significance. The latter cannot be assigned to the difference found between beds, due to the lack of replication between beds. It should be noted that the crop was harvested in the sixth week because of a preset time schedule, not because plants were fully-grown. The average weight is similar to the weight data after four weeks on the NFT system of Heinen et al. (1991); the starting weights, however, may have been different, so that a true comparison fails.

Within the beds, samples were replicated with regard to distance from the drain, and a significant increase in dry weights with increasing distance from the drain was found on beds I and III, the beds with the lowest solution excess (Fig. 3B). This effect was most pronounced on bed I, where the rows farthest from the drains were also closest to the drip points. On beds II and IV, where supply of nutrient solution was twice the estimated evapotranspiration, no relation between shoot dry weight and distance to the drain was found. Differences in fresh weight between the row positions were similar to those for dry weights. It is surprising that, even though the crop weights in bed I differed with distance perpendicular to the drain, the average weight was the same as that of the other beds.

Root dry weight and shoot/root ratio

Average root dry weight per plant, D_{rp}, was 0.78 g (range 0.34 g to 1.41 g), which is considerably lower than the value of 1.49 g per plant given by Fröhlich (1956) for soil grown lettuce and the value of 2.4 g per plant given by Heinen et al. (1991) for a NFT system.

Average root weight density, D_{rv}, of the $1.875 \cdot 10^{-4}$ m^3 substrate samples was 0.087 kg m^{-3} for the four beds. The highest value found was 0.26 kg m^{-3} and the lowest value was 0 kg m^{-3}. The average value of D_{rv}, and thus D_{rp}, was highest in bed III and lowest in bed I; the difference between the highest and lowest value was more than a factor of 2 (Fig. 4A). Differences between beds I, II and IV were not significant. Averaged over the four beds, D_{rv} within each bed was

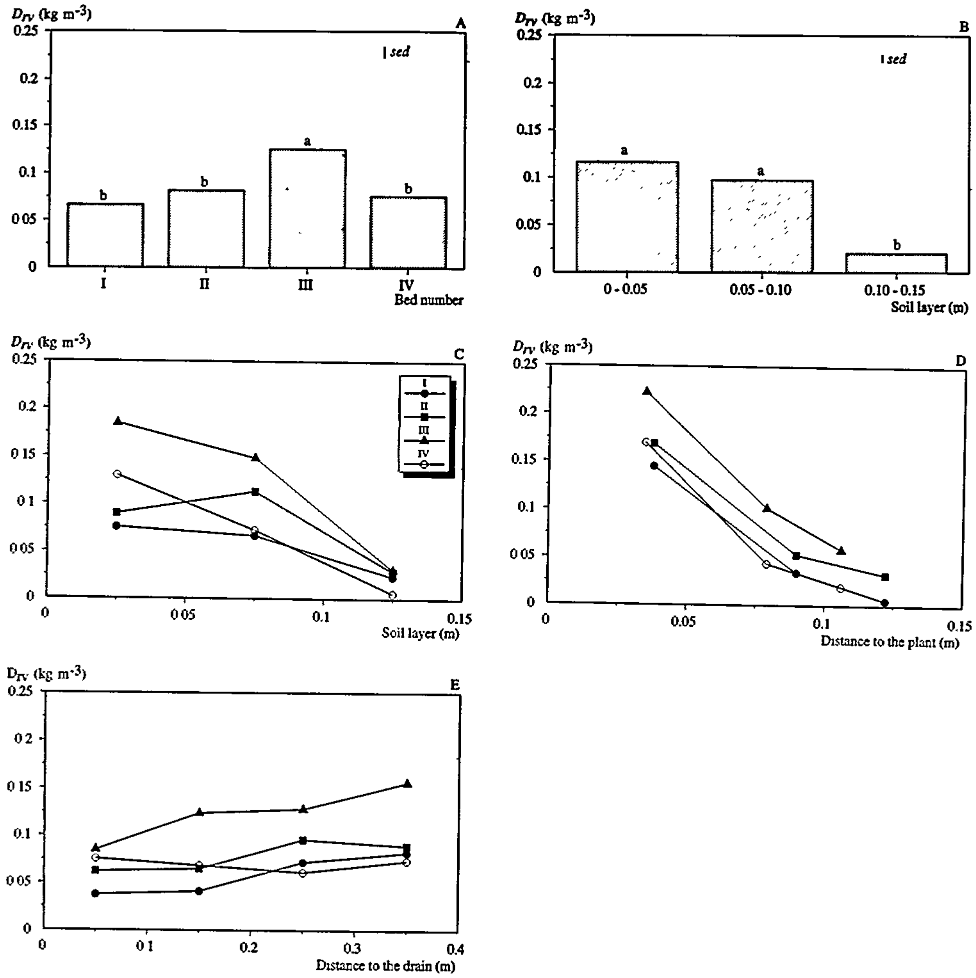

Fig. 4. Root dry weight density per substrate volume, D_{rv}, of lettuce in sand beds I-IV. A: average D_{rv}; B: averaged values in different substrate layers; C: results per substrate layer; D: results for horizontal distance to the plant; E: results for distance to the drain. Differences between columns not identified with the same letter are statistically significant (*sed* = standard error of differences; $p < 0.05$).

found to vary significantly with depth and with distance to the plant, but not with distance to the drain. In all beds D_{rv} decreased significantly with depth. Averaged over the four beds, about 50% of the roots were found in the upper 0.05 m layer and only about 10% in the lower 0.05 m (Fig. 4B). The difference between the lowest and the other two layers was highly significant; the difference between the upper and middle layer was not. No major differences between the beds were found in root distribution with depth (Fig. 4C). For all beds an approximately linear decrease of D_{rv} was found with increasing distance to the plant (Fig. 4D). Averaged over the four beds, 56% of the roots were found in the first 0.05 m from the plant axis (refer to Fig. 1C for sample positions). The top 0.05 m of this zone contained 35% of all root dry weight. An effect of distance to the drain on D_{rv} was only found in bed III (and possibly bed I) (Fig. 4E).

The average shoot/root ratio on a dry weight basis was highest in bed I and lowest in bed III, 22.4 g g^{-1} and 10.5 g g^{-1}, respectively. In bed II and IV intermediate values of 15.4 g g^{-1} and 17.5 g g^{-1} were found, respectively. As no total root dry weight per individual plant or per crop row could be obtained to match the shoot data, no statistical evaluation of these differences could be made.

Table 3. Summary of estimated intercept *a*, slope *b* and correlation coefficient *r* of the different linear relationships in Equations (6)–(10)

Eq.	*a*	*b*	*r*	Substrate depth and comment
6	0.574	424.38	0.79	0–0.05 m, for $D_r \leq 1.12$ g
6	542.45	-58.92	0.79	0–0.05 m, for $D_r > 1.12$ g
6	78.18	181.05	0.87	0.05–0.10 m
6	9.92	185.32	0.98	0.10–0.15 m
7	0.308	-0.045	0.85	0–0.05 m
7	0.528	-0.169	0.89	0.05–0.10 m
8	46.830	-6.999	0.89	0–0.05 m
8	105.442	-34.369	0.81	0.05–0.10 m
9	146.51	45.041	0.75	
10	0.407	-0.023	0.78	

Root length and diameter

Data on root length and diameter were only obtained in samples from beds II and IV, which differ in number of drip lines but with the same solution excess of 100%. The specific root length, L_{rw} averaged over all sample positions, was much higher on bed IV than on bed II: 515 m g^{-1} and 281 m g^{-1}, respectively. In both beds L_{rw}, decreased with increasing depth (Fig. 5A) and increased with distance to the plant (Fig. 5B); directly under the plant a thick tap root caused a low specific root length. This effect was most pronounced on bed IV (Fig. 5A and B). A linear relation between root length, L_{rp}, and root dry weight, D_{rp}, was observed for the three substrate layers (Fig. 5C) according to

$$L_{rp} = a_1 + b_1 \; D_{rp} \qquad (6)$$

The intercept a_1 (m) is ideally equal to zero, and the slope b_1 is equal to the specific root length L_{rw}, (m g^{-1}). For the top layer, the samples with a root dry weight of less than 1 g had a L_{rw}, of about 420 m g^{-1} (Table 3). Some samples of the top layer, however, had a much higher dry weight for the same root length. These samples were taken directly underneath the plant. For these samples a completely different linear relation was obtained (Fig. 5C, Table 3), which has no physical meaning, but is only given for completeness. Most samples from the middle and bottom layers had a L_{rw}, of about 180 to 185 m g^{-1}, with the middle layer having a rather large intercept (Table 3). This decrease in specific root length with depth was more distinct in bed IV than in bed II (Fig. 5A). This might be related to an increase in root diameter. Normally, high

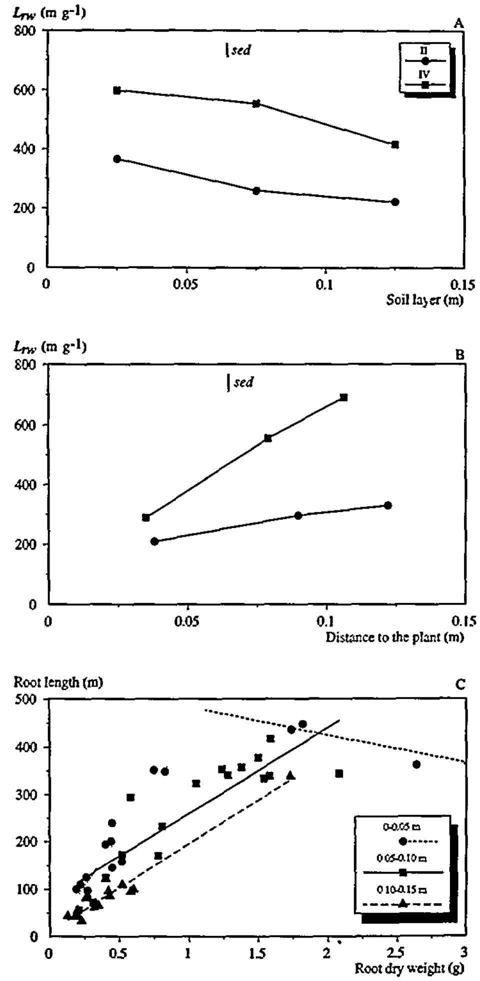

Fig. 5. Specific root length, L_{rw}, of lettuce roots in sand beds II and IV as a function of depth (A) or distance to the plant (B), and the relation between root length and root dry weight of lettuce in three substrate layers in sand bed system II (C) (*sed* = standard error of differences; $p < 0.05$).

values of L_{rw}, are accompanied by small average root diameters.

Figure 6 shows the frequency distribution of root diameters for three depth zones in two beds. All frequency distributions are skewed and most show two peaks, a small one for a diameter of 0.7–0.8 mm and a larger one at 0.2–0.3 mm. The coefficient of variation for the root diameters was 17.0% for bed II and 14.9% for bed IV. The average root diameter for all samples was 0.331 mm (tap root included); diameter increased significantly with depth (Fig. 6); this increase was mostly caused by the absence of roots of less than 0.15 mm diameter and a shift of the left peak to the 0.3–

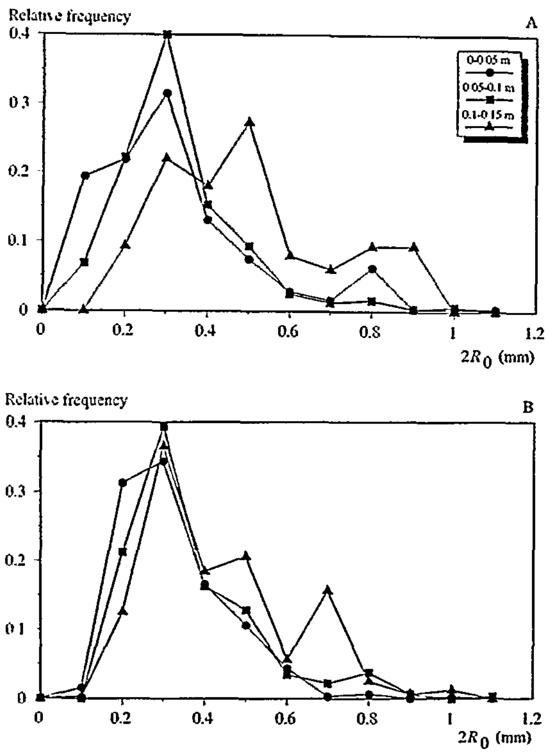

Fig. 6. Frequency distribution of root diameters, $2R_0$, of lettuce for the three substrate layers in sand beds II (A) and IV (B).

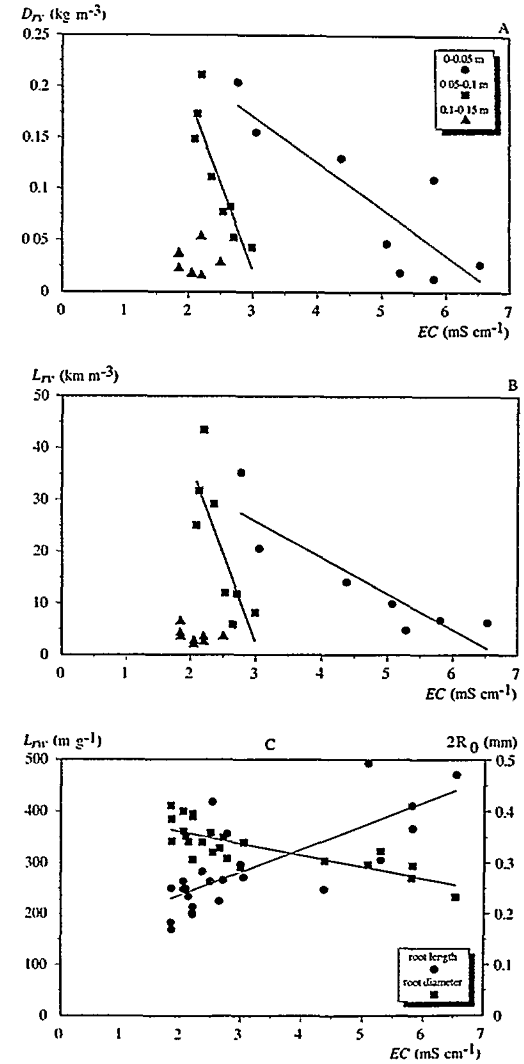

Fig. 7. Fitted linear relationships between root parameters and *EC* for the three substrate layers in sand bed II (supply two times estimated evapotranspiration, one drip line per two crop rows); **A**: root weight density per substrate volume, D_{rv}, distribution at three substrate depths; **B**: root length density per substrate volume, L_{rv}, distribution at three substrate depths; **C**: all data of specific root length, L_{rw} and root diameter, $2R_0$.

0.5 mm range. Root diameter did not differ between the beds or with the distance from the plant (data not shown).

The average root length density, L_{rv}, calculated with the measured L_{rw} was 16 km m^{-3} for the two beds; it ranged from 3 km m^{-3} in the bottom layer to 33 km m^{-3} in the top layer.

Root distribution related to EC *distribution*

In bed II, root distribution and *EC* distribution were determined at comparable locations. Linear correlation could be determined between D_{rv} (kg m^{-3}), L_{rv} (km m^{-3}) and *EC* (mS cm^{-1}) in the top and middle layers (Fig. 7A and 7B) according to

$$D_{rv} = a_2 + b_2 \; EC \qquad (7)$$

and

$$L_{rv} = a_3 + b_3 \; EC \qquad (8)$$

respectively, where a_2 (kg m^{-3}), a_3 (km m^{-3}), b_2 (10 kg m^{-2} S^{-1}) and b_3 (10 km m^{-2} S^{-1}) are empirical parameters (Table 3). Root weight and root length per unit substrate volume decreased as *EC* increased. In the bottom layer there was no significant relation between both parameters of root distribution and *EC* distribution.

The *EC* also influenced specific root length L_{rw} (m g^{-1}) and root diameter $2R_0$ (10^{-3} m) independent of substrate depth (Fig. 7C). Linear relationships existed between L_{rw}, and *EC* and between $2R_0$ and *EC* according to

$$L_{rw} = a_4 + b_4 \; EC \qquad (9)$$

and

$$2R_0 = a_5 + b_5 \ EC \tag{10}$$

respectively, where a_4 (m g^{-1}), a_5 (10^{-3} m), b_4 (10 m^2 g^{-1} S^{-1}), and b_5 (10^{-2} m^2 S^{-1}) are empirical parameters (Table 3). With increasing *EC* the specific root length increased, whereas the root diameter decreased.

Discussion

The main aim of this study was to test the hypothesis that a small surplus of nutrient solution and a restricted amount of drip lines leads to local salt accumulation in the root environment and thus to a less homogeneous root distribution. Since there was no control treatment available, the conclusions are somewhat subjective. The data confirmed both parts of the hypothesis: spatial patterns in salt distribution were found, especially with a restricted number of drip lines (Fig. 2), and root density was negatively correlated with salt content when comparisons were made within the same layer (Fig. 7). Crop yield per row was influenced in the extreme treatment (bed I: one drip line per two crop rows and solution added at 30% surplus over evapotranspiration), yield per bed was still unaffected. The unaffected yield may be due apparently to a compensation effect caused by a higher efficiency of uptake of water and nutrients by roots in favorable positions (De Jager, 1985). The increased heterogeneity in the beds is a negative aspect for the grower, so we may conclude that the heterogeneities introduced by the most extreme treatment start to have effects relevant to the grower. Apparently, the most extreme treatment included in the comparison is just beyond the limit of acceptable heterogeneity in the root medium.

Göhler and Drews (1989) state that a minimal surplus of 30% offers an optimal range for water and nutrient supply to the crops. In bed I, however, differences in crop development were observed with a 30% surplus. Thus, a single value of 30% surplus is insufficient to ensure good conditions for root growth and development; it is only valid in case of homogeneous water distribution, as in bed III.

Root activity is a major cause, apart from evaporation at the surface of the sand bed, of increase in salt concentration, especially because the concentrations in the medium are higher than the average nutrient needs divided by the transpiration needs of the crop. The flow pattern of the solution between drip lines and drains determines to which position the solution from the main root zone is pushed by mass flow during infiltration of new solution via the drip lines (Van Noordwijk and Raats, 1980). Diffusion of heterogeneously distributed salts in between the irrigation intervals will cause only a partial homogenization of the solution. The distribution of salts in the medium is thus influenced by the zone of main root activity; vice-versa, the salt accumulation pattern may affect subsequent root growth.

The presented *EC* values refer to the *EC* of the actual substrate solution. They are normally higher than values obtained from saturated extracts or 1:2 extracts (e.g. Sonneveld et al., 1990). Lettuce belongs to the moderately sensitive crops (e.g. Richards, 1954; Maas and Hoffman, 1977a, b). Bernstein (1964) gives the following yield reduction of lettuce at different *EC* values in saturated extract, EC_e: 10%, 25% and 50% reduction at 2, 3 and 5 mS cm^{-1}, and at $EC_e > 7$ mS cm^{-1} he gave no data, which indicates that lettuce might not survive under these conditions. Sonneveld et al. (1990) obtained an average ratio of 1.6 between *EC* in substrate solution and *EC* in saturation extract. Thus maximum estimated EC_e would become < 4 mS cm^{-1}. Most of the root zone had an average *EC* of 2.3 mS cm^{-1}, which corresponds to an estimated EC_e of 1.4 mS cm^{-1}. Based on these estimates it can be concluded that lettuce growth was hardly affected.

The shoot/root ratios on the sand beds (ratios of 10–22 g g^{-1}) were higher than those reported by Heinen et al. (1991) for an NFT system with a shoot/root ratio of 5.5 g g^{-1} six weeks after planting. Van Noordwijk and De Willigen (1987) and Van Noordwijk (1990) reported high shoot/root ratios, up to 20 g g^{-1} or 30 g g^{-1}, for tomato and cucumber in solution culture, especially where root volume was physically restricted. Under these conditions small root systems may be sufficient for maximum plant growth and physical restrictions of root system size do not restrict shoot growth over a considerable range.

The marked vertical distribution of the root system is probably caused by the high water content and possibly restricted aeration in the bottom layer. The increased root diameter in this zone was related with increased aerenchyma formation in the cortex (qualitatively confirmed only), which is normally an adaptation to reduced aeration (Van Noordwijk and Brouwer, 1993). The present system with coarse sand may be less suitable for crops with less ability to form aerenchyma than lettuce. De Willigen and Van Noordwijk (1987) reported a root diameter of 0.37 mm in a water culture which corresponds with the average root diameter observed in the lower layers of the sand beds; lettuce roots can have a gas-filled root porosity of 5–6% (De Willigen and Van Noordwijk, 1989).

Despite these physical limitations, lettuce can be grown on sand beds with a recirculating nutrient solution, provided that nutrient supply (drip lines) are well distributed in the bed and the daily nutrient excess is at least more than 30% of demand. Well distributed drip lines in this study refers to drip lines between all rows with drippers next to the plants in the two rows, i.e. dripper was located 0.10 m from each plant. Thus the dripper density was equal to the planting density, i.c. 16.67 drippers or plants per square meter.

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