Effects of salinity on substrate grown vegetables and ornamentals in greenhouse horticulture

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Effects of salinity on substrate grown vegetables and ornamentals in greenhouse horticulture

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus van Wageningen Universiteit
dr C. M. Karssen
in het openbaar te verdedigen
op woensdag 22 maart 2000
des namiddags te vier uur in de Aula

Voor Co.

Nederlandse vertaling titel:

De invloed van verzouting op in substraat geteelde groenten en siergewassen in de glastuinbouw.

Digital version January 2004.

ISBN 90 – 5808 – 190 – 7

Abstract

Salinity in substrate systems was studied in relation to fertilization, climatic conditions and spatial distribution of ions in the root environment. Negative as well as positive effects of low (strongly negative) osmotic potentials were examined for a number of vegetables and ornamentals. The yield reduction of crops was analysed according to the model of Maas/Hoffman. Quality of the produce could be positively as well negatively effected by low osmotic potentials in the root environment. Guidelines for nutrient and total ion concentrations in the substrate solution for optimum production are given. The study is concluded with some calculations of environmental consequences following different strategies of irrigation and drain-off.

Voorwoord

Hoe kom je er toe, na het beëindigen van je loopbaan een dissertatie te schrijven. Precies kan ik u dat ook niet vertellen. Bij een dergelijke beslissing speelt veelal meer dan één factor een rol. Het heeft in ieder geval te maken met het gevoel nog geen afscheid te willen nemen van een loopbaan als wetenschappelijk onderzoeker. Onderzoek is voor sommige mensen een vorm van verslaving en blijkbaar behoor ik bij die mensen. De VUT bood mij de gelegenheid nog een aantal onderzoekresultaten te publiceren van experimenten uitgevoerd tijdens mijn loopbaan op het Proefstation voor Bloemisterij en Glasgroenten. Toen ik daarover sprak met mijn toenmalige directeur Dr Rob Bogers, suggereerde hij er een dissertatie van te maken. Dat was eigenlijk de eerste aanleiding daar serieus over na te denken.

De eerste contacten over die plannen bij de Landbouwuniversiteit in Wageningen werden gelegd via mijn co-promotor Dr Rien van Beusichem. Sinds het midden van de jaren zeventig hadden al wij regelmatig contact over onderzoekwerk wat ons beiden boeide en organiseerden en bezochten we samen internationale colloquia op ons werkgebied. Snel waren de contacten gelegd met Prof. Dr Hugo Challa en de resultaten van een gezamenlijke bespreking waren van dien aard, dat het besluit viel een dissertatie te schrijven. Jullie stimulerende invloed, Hugo en Rien, heeft er voor gezorgd dat ik met groot genoegen aan deze dissertatie heb gewerkt en dat het resultaat daarvan nu voor u ligt. Het consciëntieus redigeren, van de manuscripten, de waardevolle discussies en adviezen waren voor mij steeds weer een reden er met veel inzet aan te werken. Ik ben jullie beiden veel dank verschuldigd. Het was een genoegen aan de manuscripten te kunnen werken in het tempo waartoe de VUT-regeling mij de gelegenheid bood. Dat wil zeggen zonder de druk van het tijdschrijven, inmiddels misschien wel de grootste plaag voor veel wetenschappers.

Als ik terugkijk, dan zou het onderzoek beschreven in deze dissertatie nooit tot stand zijn gekomen zonder de inspirerende invloed van de boeiende werkomgeving die de glastuinbouw met al haar facetten biedt. Het Proefstation voor Bloemisterij en Glasgroenten Aalsmeer/Naaldwijk neemt daarin een speciale plaats in voor wat betreft het toegepast wetenschappelijk onderzoek. De directie van deze instelling gaf mij steeds alle ruimte en de medewerkers in het onderzoek hebben de proeven welke ten grondslag liggen aan deze studie nauwgezet uitgevoerd. Hartelijk dank daarvoor. Een weerslag van de samenwerking vindt u terug in de namen van de co-auteurs van de publicaties in de hoofdstukken 2-6. De namen van medewerkers van beide locaties van de gefuseerde Proefstations komen daarin terug. Het is mij niet mogelijk de namen van alle collega's die aan het onderzoek hebben meegewerkt afzonderlijk te noemen. Toch wil ik graag één uitzondering maken en wel voor Ir Joost van den Ende. Joost, de vele jaren dat wij hebben samengewerkt wil ik niet onvermeld laten. De talloze concepten van publicaties die je kritisch hebt doorgelezen en van commentaar hebt voorzien en de discussies die daaruit volgden, zijn voor mij altijd zeer waardevol geweest. Het was een belangrijk stuk van mijn wetenschappelijke vorming. Naast de collega's die direct bij het onderzoek waren betrokken wil ik graag ook de medewerkers van de ondersteunende diensten noemen. Het verzorgen van de proeven, het uitvoeren van de analyses op de laboratoria, de statistische verwerking van de resultaten en het nalezen van manuscripten op Engels taalgebruik zijn voor iedere onderzoeker onmisbare zaken. Het is voor mij een erezaak deze diensten, die zo weinig voor het voetlicht treden, nu eens met nadruk te noemen.

Naast een werkomgeving is er altijd ook een thuisfront. Nu de verplichtingen mij niet meer noodzaakten iedere dag naar het werk te gaan, is er toch weer veel "werk"-tijd besteed aan deze dissertatie. Die tijd is dan niet beschikbaar om samen er op uit te trekken. Ik waardeer het erg dat je mij daar de ruimte voor gaf Co, en mij stimuleerde bij het schrijven van deze dissertatie. Op deze wijze hebt ook jij een belangrijke bijdrage geleverd. Graag draag ik dit werk daarom aan jou op.

Nijkerk, december 1999.
Cees Sonneveld.

Contents

1. Introduction

1.1 Greenhouse industry

The Dutch greenhouse industry covers an area of approximately 10.000 ha and the value of the production is about 10 billion guilders per year (LEI-DLO, 1999). The area can be divided into about 4300 ha of vegetables, 3800 ha of cut flowers and 1800 ha of pot- and bedding plants.
At present, 65% of the area of the Dutch greenhouse vegetables and 25% of the cut flowers under glass are grown in substrates, while pot- and bedding plants are grown exclusively in substrates. Together, the crops grown in substrates cover about 55% of the greenhouse area (Proefstation voor Bloemisterij en Glasgroente, 1997). The change from soil growing to substrate growing started in the second half of the seventies, mainly with vegetables and later on in the second part of the eighties with cut flowers. Among the growers who did not make the switch from soil growing to substrate growing are a relatively large number with lower than average yields. This means that substrate growing production can be estimated to be at least 60 to 70% of the total production, thus at least 6 to 7 billion guilders.
Over the last decades the greenhouse industry was often criticized by the general public as using unnatural production methods and heavily polluting the environment by residuals of fertilizers, pesticides and other agrochemicals used. Furthermore, there is strong competition on the market from the Mediterranean countries, especially for crops grown in winter and early spring, when light conditions in The Netherlands are very poor.
One thing and another requires the Dutch growers to be critical of their production methods and to offer the market products of optimum quality for competitive prices. Therefore in the last decade the greenhouse industry focussed its research programme strongly on improvement of the produce quality, on reduction of the use of pesticides and agrochemicals and on restriction of the environmental pollution of ground and surface water by nutrients.

The Dutch greenhouse industry is the largest glasshouse area in the world. The huge potential of such a large area and the high degree of organisation of the growers have provided this greenhouse industry with opportunities for a strong technological and scientific development over the last decades. A special aspect in the technical development over the last two decades is the successful introduction of the means for growing many more crops in substrates than before.
Substrate growing has already a long history in the greenhouse industry with the production of pot plants and special cut flowers like anthurium and orchid. Since the mid-seventies, however, a wide diversity of other greenhouse crops have made the transition from growing in the greenhouse soil to substrate growing. In early stages, the main reasons for this switch were expected higher yields and prevention of infections by soil-borne pathogens. Later on, growers experienced that substrate growing allowed excellent opportunities for a better control of the osmotic potential and for the addition of plant nutrients to the root environment, resulting in a better control of plant development. The early scientific support consisted of the development of nutrient solutions for various crops and growing conditions, but soon this support was also focussed on the possibilities for better control of plant development by management of levels and mutual ratios of plant nutrients and of salinity levels.
Substrate growing has sometimes been the subject of public criticism by people. In particular, growing in artificial materials like mineral fibres and foams has been judged as being "unnatural" and associated with high environmental pollution by leaching of nutrients. The negative image-building by the press in the mid eighties and the failure of the growers' organisations to

form a favourable public opinion about substrate growing, have contributed strongly to this negative image-building.

Irrigation practices, salinity and application of nutrients are strongly mutually related and mainly determine the osmotic potential in the root environment and the leaching of nutrients to the environment. The osmotic potential appears to be an important factor in controlling the produce quality. Thus, a fine mutual tuning of irrigation practices, salinity management and fertilizer application can strongly affect produce quality and environmental pollution and thus the image-building around the produce.

1.2 Characteristics of the root environment

In greenhouse production the natural precipitation is excluded. This offers opportunities for a full control of water supply by irrigation. In principle it seems possible to supply the plant at the right time with the right quantity of water, and losses of water and nutrients to the environment can therefore be severely restricted. However, this is hindered by a heterogeneous water distribution by irrigation systems and a heterogeneous water absorption of crops. Moreover, the water quality may prevent precise matching of the demand and supply of water. Most irrigation waters have too high a salt concentration, causing an easy build-up of salinity in the root environment. This is especially the case when plants are grown in small root volumes, as with substrate systems. Accumulation of salts in the root environment can only be prevented by leaching with extra water, which also leads to substantial nutrient losses.

Another difference between production in greenhouses and in the field are the generally higher production levels and the concomitant higher absorption of nutrients. The high nutrient absorption necessitates high fertilizer applications, which may result in a further build-up of the salinity, especially with fertilizers that contain high salt residues. When fertilizers of the right composition and quality are used, thus preferably types with a sufficiently low residual salt content, this problem can be prevented. The higher price of these fertilizers can hardly be of major concern, because fertilizer costs represent a fraction of the total costs of greenhouse production (Proefstation voor Bloemisterij en Glasgroente, 1997).

Besides the detrimental effects of salinity, the greenhouse industry in The Netherlands also has an eye for the favourable side effects. On the one hand, high osmotic pressure in the root environment reduces plant growth and generally yields as well, but on the other hand it can improve the quality of the produce. This is especially the case for vegetable fruit crops (Adams, 1991; Mizrahi et al., 1988; Ohta et al., 1991; Verkerke et al., 1993). Favourable effects on quality have also been found with other vegetable crops. Maaswinkel and Welles (1986) observed a reduced incidence of glassiness in lettuce by increasing salinity; Sonneveld and Van den Bos (1995) found an improved tuber development in winter-grown radish and a decreased sponginess in spring/summer grown radish with increasing EC. In flower crops, salinity mostly does not affect the quality of the produce (De Kreij and Van Os, 1989). Sometimes, disorders can be controlled by increasing EC, like glassiness in anthurium (Sonneveld and Straver, 1993). Negative salinity effects with respect to quality of flower crops are reductions of stem diameter, length, firmness and vase life (De Kreij and Van der Berg, 1990). Also with vegetable crops negative effects on quality are noticed. Often these effects are related to a reduced Ca uptake or transport in the plant, like blossom-end rot in fruits and tipburn in leafy vegetables (Bernstein, 1975; Ehret and Ho, 1986; Geraldson, 1957; Marschner, 1998; Van den Ende et al., 1975).

1.3 Substrate and soil

A striking difference between crop production in the greenhouse soil and in substrates is the volume of the root environment. In Table 1.1 a comparison is made between the amount of water and nitrogen available in both systems in relation to the total uptake of nitrogen by a high yielding tomato crop (after: Sonneveld, 1995). It is clear from this comparison that for the soil-grown crop one quarter of the total required nitrogen is actually available in the soil, while in a substrate system like rock wool this is only a few percent. This implies, on the one hand, that growing in substrates requires a more accurate fertilization than growing in soil. With insufficient supply of fertilizers, crops grown in substrate quickly develop deficiency symptoms; supra-optimum supply of nutrient may, however, lead to undesirable accumulation of nutrients in the rooting medium with related osmotic/salinity effects. On the other hand the figures of Table 1.1 reflect the easier control of the "soil(substrate) solution" in the root environment of a substrate system in comparison with the greenhouse border soil. Apart from adsorption and precipitation effects, which will be larger in soil than in substrate systems, there will be about 8 times more fertilizers required for changing the concentration in the soil solution in the upper layer of a greenhouse soil than in a rock wool substrate system.

Table 1.1. Quantities of available nitrogen in a greenhouse soil over a depth of 0.30 m and in a rock wool system in relation to the total nitrogen uptake (7 mol m^{-2}) of a high yielding tomato crop.

	Greenhouse soil	Rock wool system
Volume of substrate l m^{-2}	300	14
% water by volume	25	70
Quantity of water l m^{-2}	75	10
Nitrogen concentration mmol l^{-1}	25	23
Nitrogen available in mmol m^{-2}	1875	230
% of total N uptake	27	3.3

Another difference between the root environment of a greenhouse soil and that of a substrate system is the composition of the "soil solution". In soil higher salt accumulation is mostly accepted or consciously recommended. This can be demonstrated in a comparison of the values of the nutrient concentrations recommended to growers for soil- and rock wool-grown crops. In Table 1.2 such values are listed for tomato and rose (IKC, 1994; De Kreij et al, 1997). The recommended nutrient concentrations for soil-grown crops, as determined in the 1:2 volume extract, are converted into values for the soil solution according to Sonneveld et al. (1990).

The data in Table 1.2 show that in a rock wool system much higher concentrations are recommended for tomato than for rose. The reason for this difference is not a higher demand of the crop with respect to nutrient uptake, but the need of a higher EC in the root environment for production of good quality tomato fruits. The fact that the values for the tomato crop in the soil are higher than in substrate should be explained by the bigger root volume of soil-grown crops. The bigger root volume offers an easier escape for the roots to places with an accidentally lower EC. Formerly, the difference in the recommended EC for tomato in soil and rock wool was much greater, because of much lower concentrations for rock wool systems recommended to growers (Sonneveld and Welles, 1984). The concentrations for rock wool and soil, however, became closer over the years by the need for higher values for crops grown in rock wool suggested by the market demand for a higher fruit quality. The relatively high values recommended for the soil solution for the rose crop are more connected with the problem of leaching of residual salts from the soil during the cultivation period and traditional fertilization practices than with the need of this crop. Therefore, it is likely that optimum values for soil-grown rose crops are close to the values in rock wool.

Table 1.2. Recommended values for nutrient concentrations for tomato and rose crops grown in rock wool and in greenhouse soil. The values of the greenhouse soil are expressed on the basis of 1:2 volume extract and converted into soil solution composition (Sonneveld and Van den Ende, 1990). The EC is expressed as dS m^{-1} and the ions as mmol l^{-1}.

Determination	Tomato			Rose		
	Rock wool	1:2 volume extract	Soil solution	Rock wool	1:2 volume extract	Soil solution
EC	4.0	1.4	5.2	2.2	1.0	4.0
K	8.0	2.2	6.6	5.0	1.5	4.3
Na	<12.0	<5.0	<19.1	<4.0	<4.0	<15.0
Ca	10.0	2.5	14.2	5.0	2.0	12.9
Mg	4.5	1.7	7.8	3.0	1.2	6.0
NO_3	23.0	5.0	25.6	12.5	4.0	20.5
Cl	<15.0	<5.0	<28.7	<4.0	<4.0	<22.6
SO_4	6.8	2.5	12.3	3.0	1.5	10.9
P	1.0	0.15	0.18	0.9	0.15	0.18

There is also a difference between substrate- and soil growing with respect to the solution of the environmental problems arising from leaching of salts and nutrients. Research of Verhaegh et al. (1990) with fruit vegetable crops grown in rock wool with free drainage, showed that the water efficiency in such systems was about 0.70, and the nutrient recovery about 0.50 - 0.60. With soil-grown radish (Korsten and Voogt, 1994) and chrysanthemum (Korsten et al., 1994) a water efficiency of 0.60 and 0.52, respectively, was found. The recovery for N and K in this study varied between 0.33 and 0.64. So, the contribution to the environmental pollution of both growing methods is comparable. The total N and K emission from the Dutch greenhouse industry to the environment is substantial and for each of the two elements estimated as 6 10^6 kg per year (Sonneveld, 1996). This implies that the greenhouse industry is responsible for 5 - 10% of the total fertilizer emission of Dutch agriculture (Sonneveld and Heinen, 1997).

The reduction of fertilizer emission for greenhouse cropping in substrates may be found in collection and reuse of drainage water. For soil-grown crops this option is mostly not possible, because the collection of drainage water is often impossible. That means that as long as crops will be grown in greenhouse soils, the management of the irrigation and fertilizer application should be improved to achieve an optimum water and fertilizer recovery.

The environmental pollution of a horticultural system is equivalent to the product of the drainage water quantity and its concentration of nutrients. So in case no reuse of drainage water is possible, growers have to focus on restrictions of both factors: water quantity and concentration of nutrients in the drainage water. Reduction of the quantity of drainage water requires matching of water supply and consumption. This, however, is limited by the salt content of the water used and the excess irrigation necessary to cope with heterogeneity in irrigation and in water uptake. Reduction of the concentration of nutrients in the drainage water requires a fertilization programme in which the fertilizer use is carefully tuned as close as possible to a minimum quantity necessary for a maximum production of the quality desired. However, such measures are often not sufficient to meet the limits dictated by the Dutch Government (Ministerie van Verkeer en Waterstaat, 1994; Stuurgroep Glastuinbouw en Milieu, 1997). When the legal criteria with respect to surface water and ground water quality cannot be met through manipulation of nutrient concentration and irrigation volume, growing in closed substrate systems will be the best alternative. In such systems drainage water can be collected completely and, in case of an optimum quality of the primary water after adjustment of the nutrient status, totally reused.

1.4 Closed growing systems

A total reuse of the drainage water in closed growing systems is possible (Voogt and Sonneveld, 1997), provided that the primary water is of sufficient quality. Too high a salt concentration in this water, i.e. higher than the uptake concentration (the ratio between the absorption of ions and water) of the crops grown in the system, easily leads to salt accumulation in the system followed by growth reduction. So far, insufficient information is available about the salt absorption of greenhouse crops, about limits for salt concentrations in the root environment and about the interaction of these factors with the growing conditions. The present study will attempt to fill this gap in knowledge and to develop good management tools for a system producing greenhouse crops of a quality tuned to the demand of the market, with minimum environmental pollution.
With respect to salinity Na and Cl are the most abundant ions in irrigation waters, thus being the most common ions that may accumulate in root environments and, therefore, the NaCl concentration will often determine the need for leaching. In other cases Ca, Mg or SO_4 concentrations are higher in relation to their uptake by crops than those of Na and Cl. In such cases, one of the latter ions determines the need for leaching.

1.5 Management of the system

Through adequate management of the nutrient solution of a substrate growing system the concentration of individual ions can be independently controlled. For this purpose a number of tools should be available, to achieve an optimum control of the ion concentrations in the root environment of substrate systems for greenhouse crops.
In the first place it is necessary to get quantitative information about the absorption of water and ions by the crop during growth. In addition to ions that are essential for adequate plant growth, absorption of other ions from the root environment, of which Na and Cl are the most important, has to be considered, especially with respect to undesirable accumulations in the root environment. In many cases Na and Cl are required in much lower quantities than available, while their absorption by most crops is quite small. Na and Cl are mainly introduced into the growing system via irrigation water and, to a much lesser extent, via fertilizers. Therefore, the quality of the irrigation water is the most important factor with respect to undesirable ion accumulation in the root environment.
The quality of irrigation water is mainly determined by its ion concentrations. Preferably, these concentrations should be equal to or lower than the apparent uptake concentration of the crop grown. In that case crop production is possible without any loss of drainage water. This choice, however, is often not the most economic solution, because water of this quality is scarce and often expensive. Preparation of such water by desalination is seldom a realistic option. When water is used with ion concentrations higher than the apparent uptake concentration of the crop grown, it is necessary to drain water from the system to the surface water or groundwater, which results in environmental pollution. The choice of the irrigation water should be made taking the following factors into account:

- quality, in particular the ion composition of the water.
- price of the different types of water available.
- characteristics of the substrate with respect to adsorption or desorption of ions.
- maximum acceptable ion concentrations in the root environment and the
- apparent uptake concentration of the crop involved.
- environmental levying of the Government for the drain water emitted.
- costs of a possible desinfestation of the drainage water.

With respect to the latter factor it should be mentioned that reuse of drainage water without desinfestation is too risky for many crops. The type of desinfestation depends on the crop and expected pathogens (Runia 1995).

Fertilizers are required which provide all necessary cations without affecting the mutual ratios of the anions and vice versa. Furthermore, fertilizers should be easily soluble in water and should not contain insoluble residues, contaminants of heavy metals or other components leading to concentrations in nutrient solutions toxic to plants or, after absorption by plants, to humans. In Table 1.3 a list of more or less traditional fertilizers is given that enabled preparation of nutrient solutions for all greenhouse crops grown in substrate until now. Besides this group of fertilizers the Dutch fertilizer industry has manufactured special groups of chemical compounds and mixtures of such compounds, tuned to substrate growing (Sonneveld and Voogt, 1994). Full automatic computer-controlled dosing systems have been developed for the preparation of nutrient solutions. Such systems are helpful tools for an accurate and quick adjustment of the nutrient solution to the needs of the crop during cultivation.

Table 1.3. Fertilizers used in the greenhouse industry to compose nutrient solutions.

Fertilizer	Chemical composition
Calcium nitrate	$5[Ca(NO_3)_2 2H_2O].NH_4NO_3$
Ammonium nitrate	NH_4NO_3
Potassium nitrate	KNO_3
Magnesium nitrate	$Mg(NO_3)_2.6H_2O$
Nitric acid	HNO_3
Mono potassium phosphate	KH_2PO_4
Phosphoric acid	H_3PO_4
Potassium sulphate	K_2SO_4
Magnesium sulphate	$MgSO_4.7\ H_2O$

The mutual ratios and the quantities of nutrients absorbed by crops vary with growing stage and growing conditions (Adams, 1979; Savvas und Lenz, 1995; Schacht and Schenk 1990; Sonneveld 1995; Voogt, 1988; Voogt, 1993). Such effects on nutrient absorption vary among crops and are often not exactly known. Unexpected changes in the composition of the nutrient solution in the root environment frequently occur in commercial sytems. Therefore, it is currently not advisable to grow crops in soilless culture systems without frequent analyses of nutrients in the root environment. Such analyses are useful to maintain the composition of the nutrient solution in the root environment during crop cultivation at an optimum level.

The water balance of the root environment is controlled mainly by water supply, water absorption by the crop, size and shape of the rooting volume and characteristics of the substrate.

The water necessary for crop production in greenhouses is exclusively given through irrigation. In substrate systems ebb and flow and trickle systems are widely used, while sprinkler irrigation is seldom used in such systems. The choice for a particular irrigation system depends primarily on the growing system. The irrigation frequency varies from crop to crop and with climatical conditions, ranging from less than 1 to 50 times a day. High irrigation frequencies are in no way hindered by labour costs, for the systems used are fully automatic. High irrigation frequencies are not primarily necessary to compensate for the water use of the crop, but to prevent irreversibly drying out of the substrate. This phenomenon, well known for peaty materials, also occurs in other materials like mineral wool (Van der Burg, 1988; Van der Burg, 1990). The amount of available water in many substrate systems is at least 10 l m^{-2}, which is generally sufficient for at least one to two days. It is, therefore, not surprising that in experiments with different water supply frequencies in substrate systems no differences in crop growth are found, provided that no exceptionally low frequencies are incorporated (Grimstad and Bævre, 1989; Karlovich and Fonteno, 1986; Snijder and Bauerle, 1985; Van der Burg, 1990; Van Gurp en De Bruijn, 1990).The water in most of the substrates is available at low tension (Kipp and Wever, 1993) and substantial drying out of the medium in the root environment hardly increases the matric potential.
The transpiration of crops in greenhouses is controlled by many factors like global radiation, ambient temperature and humidity, leaf area, CO_2 concentration and wind speed (Howell, et al., 1986; Nederhoff, 1994, Stanghellini, 1987; Stanghellini, 1995). For practical purposes transpiration of crops can roughly be estimated, taking global radiation, energy used for heating of the greenhouse, and the crop size into account (De Graaf, 1988). The results of this estimation together with a feedback on the results of measurements of the drainage water quantity offer good possibilities for an automatic control of the water supply (De Graaf, 1990; De Graaf and Esmeijer, 1996).

The distribution of water and ions in the root environment depends on the method of water supply, the method of fertilizer application, the leaching fraction, the ratio between addition and absorption of ions by the crop, the characteristics of the substrate, the shape of the root environment and the cover of the top layer. Furthermore, the heterogeneity of the water supply by the irrigation system and of the water absorption by the crop strongly affects the distribution of water and ions in the root environment.
In substrate sytems water and nutrients are applied by fertigation, i.e. a combined application via the irrigation system. The spatial concentration patterns in the root environment with sprinkler irrigation and ebb and flow are mainly vertically directed and with trickle irrigation horizontally. A high leaching fraction will generally diminish these differences. High or low ratios between supply and apparent uptake concentrations of the ions accentuate these differences. Substrates with a high capillary power promote salt accumulation in the top layer, especially when the substrate is placed in horizontally-shaped models, because of promotion of evaporation from the surface. Covering the top surface of substrates with a material restricting or excluding evaporation will reduce surface evaporation and hence concentration differences in the root environment.
The strong increase in ion concentration from top to bottom often found in peaty substrates with pot plants grown on flooded benches can easily be explained by evaporation from the pot surface. The frequent irrigations and strong capillary forces of the substrate are responsible for a high evaporation and hence a strong ion accumulation at the surface. After a growth period of some weeks the ratios between top and bottom concentrations can easily reach values between 5 and 10 and over longer growth periods much higher ratios can occur (De Kreij and Straver, 1987; Otten,

1994; Schwemmer,1990). Also with fruit vegetables grown in rock wool big differences occur in slabs, although the top surface is covered with plastic film (Van der Burg and Sonneveld, 1988; Van Noordwijk and Raats, 1980). Ratios of about 2 and 3 found between highest and lowest EC values, can easily be explained by the difference between the concentration of the irrigated solution and that of the drainage water (Voogt and Sonneveld, 1997).
Strong differences between ion concentrations in root environments are often associated with heterogeneity in the water supply. When such a heterogeneity is caused by mistakes in the design of the system it can be prevented. However, a heterogeneous water supply is often the result of clogging of the irrigation system; especially trickle irrigation systems are sensitive in this respect (Gilbert and Ford, 1986; Van der Burg and Hamaker, 1987). Sprinkler systems may also show a great heterogeneity in water supply (Sonneveld 1995; Strasser, 1994), but are less sensitive to clogging than trickle irrigation systems. Heterogeneity in water absorption by plants also contributes to an uneven distribution of ions in the root environment. This phenomenon seems to be partly systematic and partly random (De Graaf, 1995; Van der Burg and Hamaker, 1987). Systematic heterogeneity offers possibility for adjustment by selective water supply. Random heterogeneity has to be corrected by extra overall water supply.

1.6 Effects of salinity on crops

In studies on salinity effects on crops, osmotic effects and specific salinity effects should be distinguished (Bernstein, 1976; Hayward and Long, 1940-1941). In this classification osmotic effects are determined by the osmotic potential of the solution. Such effects are independent of the composition of the osmotics, and generally restricted to effects without any essential disturbance of ion uptake by plants or distribution in plants. With specific salinity effects mainly two groups are distinguished, namely effects through nutrition and effects through toxicity. Specific salinity effects through nutrition imply that crop growth is affected by disturbance of uptake or distribution of ions essential for plant growth. Toxic salinity effects occur via excess absorption of an osmotic significant ion. This means that toxicity of micro elements like B, Mn, F, Li, Se etc., not being of osmotic significance, is beyond the scope of these considerations. In the classification presented here there is no place for the so-called sodicity problem. Bernstein (1976) considered this problem as “salinity related” only, but there is no reason to classify this problem as not belonging to the field of salinity. Sodicity is related to an unbalanced ratio between (bi)carbonate and bivalent cations, mainly Ca and Mg (Bernstein, 1975; Richards, 1954). In principle, when in water the (bi)carbonate concentration exceeds twice the (Ca+Mg) concentration this will cause sodicity. (Bi)carbonate precipitates with Ca and Mg. When the water contains insufficient Ca and/or Mg the remaining part of the (bi)carbonate precipitates with Ca or Mg from the soil/substrate solution and the adsorption complex. The remaining cation from the irrigation water, practically always Na, survives in the substrate. Soils or substrates affected by this phenomenon are chemically characterized by high Na, low Ca and Mg and high pH, and physically characterized by dispersion of structure of soils and certain substrates (Hilgard, 1919). In substrate growing, this problem can partly be solved by acid application. This optimizes pH and prevents precipitation of Ca and Mg in the root environment, but does not decrease the often too high Na concentrations.
It is not always possible to distinguish clearly between osmotic and specific salinity effects. Often combinations of osmotic and specific salinity effects occur. In particular combined effects can be expected from nutritional and toxic effects. In such cases a decrease of absorption of a nutrient is often accompanied by an increase in absorption of ions involved in salinity (Bernstein, 1964). For most crops and growing conditions the osmotic effects of salinity predominate (Bernstein, 1976).

The best-known phenomenon of osmotic effects is the wilting of crops with suddenly increased salinity, related to a lost or reduced osmotic gradient for water absorption of plants. This, however, is not the most common symptom. In practice, with salinity the osmotic potential of the solution in the root environment decreases slowly and plants can adjust to it (Bernstein, 1961; Bernstein, 1963; Nukaya, 1983; Van den Ende et al., 1975). These adjustments are very diverse and there is no single mechanism underlying the growth reduction of crops caused by osmotic effects and the phenomenon is not yet completely understood (Greenway and Munns, 1980). It is likely that the adaptations by plants are responsible for the growth reduction, as has been suggested by Bernstein (1976).
The impact of salinity in greenhouses, especially in substrate systems, differs from salinity under field conditions. In Table 1.4 chemical compositions of soil solutions from field soils are given in comparison with those from greenhouse industry. The most striking difference is the overall much higher concentrations of nutrients in greenhouses in comparison with those in field soils. This especially holds for greenhouse soils, where the EC maintained in solution is highest. Furthermore it is clear that in greenhouse cultivation nutrients contribute substantially to the osmotic potential of the soil solution. This is especially the case in substrate systems where low salinity water is used, and the osmotic potential is thus more or less solely brought about by nutrients. In substrate systems a relatively small addition of fertilizer increases nutrient concentrations in the substrate solution to undesirable, growth reducing, levels. On the other hand, sometimes high levels of nutrients are consciously used in greenhouse cropping systems in order to control plant growth under poor light conditions or to achieve/improve quality.
The effect of salinity strongly depends on crop and even on cultivar and root stock. Climatic conditions can affect salinity, e.g. high temperature and high transpiration increase salinity effects and CO_2 enrichment decreases salinity effects. Irrigation methods are also an important determinant. Crops suffer more from salinity with sprinkler irrigation than with trickle or furrow irrigation. Other important factors are the fertilization level, the salt distribution in the root environment, the method of sampling and analysis, and the interpretation of analytical data. So, it is clear that many factors affect the salt tolerance of crops, and these factors will together be responsible for the major part of the huge variability in crop response to salinity in the vast amount of literature on this subject (Maas, 1986).
In Figure 1.1 a relational diagram is given for different aspects of salinity. In this diagram the EC of the soil solution is affected by fertilization and salinity. The latter mainly by the irrigation water. The ions in the soil solution are partly nutrients or osmotics. Nutrients are essential for plant growth and osmotics affect physiological processes in plants by osmotic adjustments made, nutrient disturbance or toxicity. Sodicity follows a different pathway. Growth and quality of crops can be affected negatively as well as positively.

Table 1.4. Ion composition of soil solutions. Ions expressed as mmol l^{-1} and EC in dS m^{-1}. Nos 1 - 5 are derived from field soils and nos 6 - 9 from greenhouse industry.

No*	K	Na	NH_4	Ca	Mg	NO_3	Cl	SO_4	HCO_3	P	EC
1	1.7	5.4	-.-	8.9	3.7	9.1	8.4	1.6	0.8	0.02	-.-

2	0.3	0.2	-.-	2.2	0.6	3.7	2.1	0.2	-.-	-.-	0.6
3	0.5	0.3	0.05	1.6	0.5	3.2	2.4	0.6	-.-	0.02	-.-
4	0.1	-.-	0.03	1.1	0.0	0.6	-.-	-.-	-.-	0.01	-.-
5	0.2	-.-	1.10	5.3	0.1	12.3	-.-	-.-	-.-	0.01	-.-
6	6.6	13.2	0.39	22.3	8.7	24.1	15.0	19.1	-.-	0.31	6.5
7	4.6	1.8	1.2	4.2	3.2	11.4	1.3	3.2	-.-	1.7	2.3
8	8.0	-.-	<0.5	10.0	4.5	23.0	-.-	6.8	-.-	1.0	4.0
9	5.0	-.-	<0.5	5.0	3.0	12.5	-.-	3.0	-.-	0.9	2.2

*Compositions derived from: 1- means of a historical series of Adams, 1974; 2 - means of data of Qian and Wolt, 1990; 3 - means of data of Peters, 1990; 4 and 5 - data of Barraclough, 1989 before and during top dressings with N, respectively; 6 - means of greenhouse soils by Van den Ende, 1989 and Sonneveld et al., 1990; 7 - means of peaty substrates of Sonneveld and Van Elderen, 1994; 8 and 9 - recommended values for rock wool grown tomato and rose, respectively (Sonneveld 1995).

1.7 Salinity models

In an extensive review Maas and Hoffman (1977) have presented an analysis of salt tolerance phenomena on the basis of a simple model. The model is characterized by two parameters, the salinity threshold (c_t) and the salinity yield decrease value (SYD). The model can be given in equation form (Figure 1.2A):

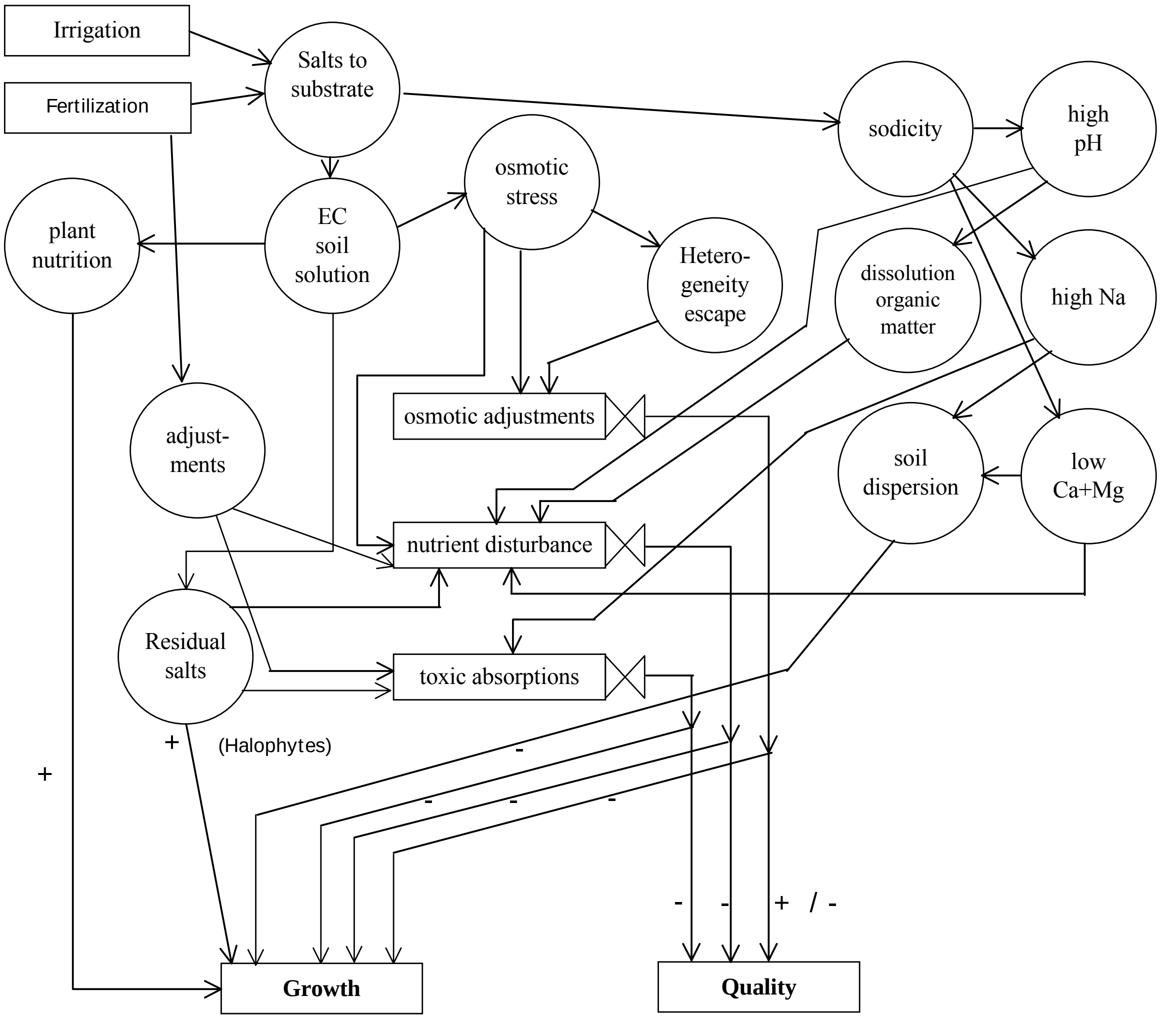
$$
\begin{aligned}
Y_r &= 1 && 0 \le c_{ss} \le c_t \\
Y_r &= 1 - SYD\,(c_{ss} - c_t) && c_t < c_{ss} \le c_z \\
Y_r &= 0 && c_{ss} \ge c_z
\end{aligned}
\qquad (1.1)
$$

in which:

- Y_r = relative yield in relation to the yield under non saline conditions
- c_{ss} = ion concentration in the substrate solution in dS m^{-1}
- c_t = salinity threshold value, being the maximum root zone concentration without yield reduction in dS m^{-1}
- c_z = root zone concentration beyond which the yield is zero in dS m^{-1}
- SYD = salinity yield decrease value, being the slope of the salinity response function between c_t and c_z in % per dS m^{-1}

Soil salinity is generally expressed as the EC of the saturation extract (EC_e) and for substrate and soilless culture often the EC of the substrate solution or nutrient solution is used. For soils a close relationship exists between EC_e and the EC of the soil solution. For greenhouse soils the ratio calculated between the average EC of soil solutions and those of saturation extracts of a huge series of soil samples was about 1.6 (Van den Ende, 1989; Sonneveld et al., 1990). Thus, the EC of saturation extracts can be reliably compared with actual values for the soil solutions.

Figure 1.1 Relation diagram for salinity effects



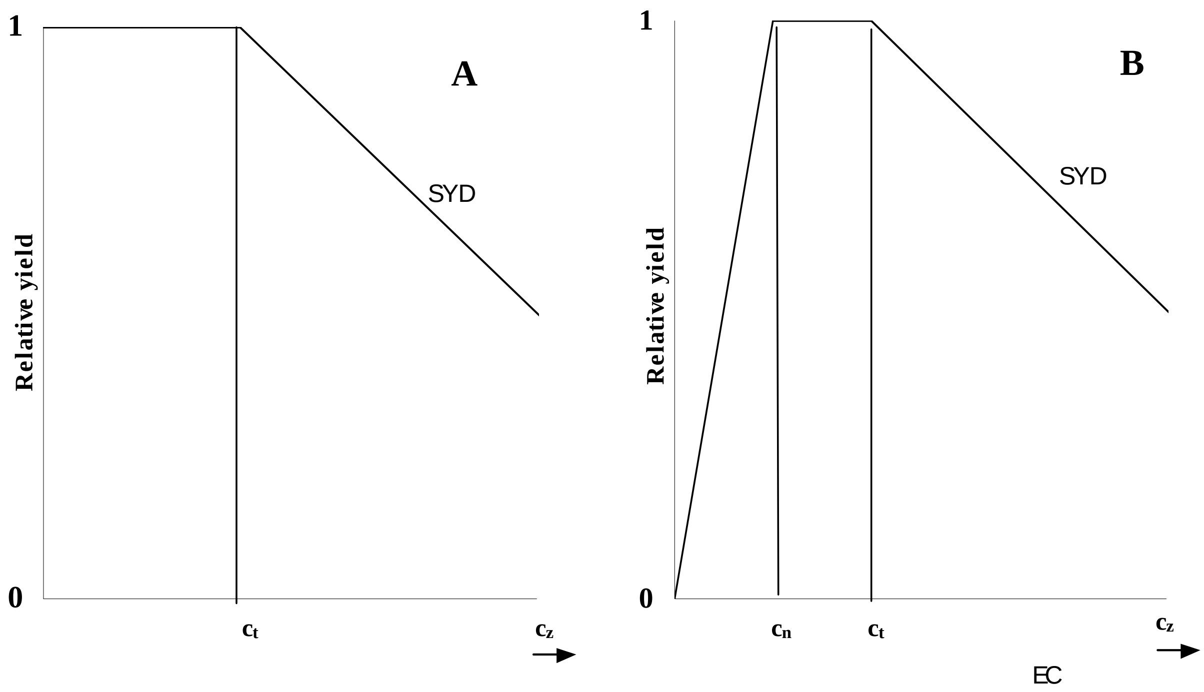
In the Maas/Hoffman model there is no place for the EC caused by the plant nutrients, because the model starts with maximum yield at EC = 0. This is understandable because the model has been developed for field crops. In open fields fertilization with N, K and P has generally only a marginal effect on the EC of the soil solution and when there is a significant effect of these nutrients on the EC, they never have a long duration effect on it. The effect of plant nutrients, however, is different in greenhouse soils. Sonneveld et al. (1990) found that one third of the total ion concentration of soil solutions of Dutch greenhouse soils consisted of N and K. Thus, plant nutrients available in greenhouse soils form a substantial part of the EC. In substrate systems and water cultures plant nutrients play an even more important role. For this type of growing systems the EC of the solution in the root environment is sometimes exclusively determined by plant nutrients. Thus, for greenhouse crops the Maas/Hoffman model needs refinement with respect to the EC related to plant nutrients. In equation (1.2) the adjusted model is given and shown in Figure 1.2B.

$$
\begin{array}{lll}
Y_r = < 1 & 0 \le c_{ss} \le c_n & \\
Y_r = 1 & c_n < c_{ss} \le c_t & (1.2) \\
Y_r = 1 - SYD\,(c_{ss} - c_t) & c_t < c_{ss} \le c_z & \\
Y_r = 0 & c_{ss} \ge c_z &
\end{array}
$$

in which:

c_n = minimum total ion concentration of plant nutrients necessary for optimum growth in dS m^{-1}
other parameters are as in equation (1.1)

Figure 1.2 The relationship between the EC value in the root environment and the yield of crops



according to the model of Maas and Hoffman (1977) (A) and our model (Sonneveld 1991) (B)

Yield response curves in salinity experiments do not always show the linear relationship as predicted by the models. In particular with dramatic yield reductions the response is often non linear. Van Genuchten and Hoffman (1984) presented functions for non-linear response. The use of such functions should be recommended with data from experiments with a wide range of salinities and strong yield depressions, e.g. over 50%. In our study such situations do not occur, and therefore the Maas/Hoffman model will be used unless stated otherwise.
A main problem in predicting salinity effects by means of models is the lack of experimental data. Accurate and reliable salt tolerance data require elaborate and time consuming field trials (Van Genuchten and Hoffman, 1984). Such experiments are costly, especially under greenhouse conditions, and often the number of observations in an experiment provide limited possibilities for the estimation of the parameters concerned.

In a study of plant nutrition under saline conditions Kafkafi (1984) proposed a model on the basis of data of Hayward and Long (1940-1941) which give the impression that addition of NO_3 is less harmful to a tomato crop than SO_4 and Cl. This proposal, however, is misleading, for the treatment with the lowest concentration of 10 mmol l^{-1} NO_3 did not result in the maximum yield. In this way, part of the nutrition effect was confounded with the salinity effect. Salinity effects should always be calculated starting from the concentration resulting in maximum crop development, as pointed in the model of equation (1.2). Moreover, the Cl and SO_4 series got the same NO_3 application as the lowest NO_3 treatment and thus their production capabilities were lower than those of the NO_3 series. The nutrients in the Cl and SO_4 series were supplied on a level of 0.5 bar and this level seemed to be a sub-optimum in the NO_3 series. Thus, comparison is only possible on a relative basis. In Figure 1.3A the data of Hayward and Long (1940-1941) as redrawn by Kafkafi (1984) are shown. The nutrition concentration c_n calculated was for the NO_3 series 1.1 bar and for both other series 0.5 bar. It is clear from Figure 1.3B that, on a relative basis, there is no real difference between the different salts as was suggested by Kafkafi (1984). This conclusion is in good agreement with our findings with tomato (Sonneveld and Van den Ende, 1975). In this study addition of $NaNO_3$, NaCl and Na_2SO_4 on the basis of equal ion concentrations under optimum nutrition did not show significant yield differences.

Salinity effects in the root environment under growing conditions often show temporal variation. Such variation is related to differences in the salt concentration of the irrigation water, to the accumulation of salts in the root environment, and to changes in the water content. It is likely that there will be a distinct difference in effect between an abrupt and a slow change in salinity. In the first situation crops have no time to adjust to the sudden change of the osmotic potential, while in the second situation crops do have the possibility to adjust. Approaching adaptation of plants to salinity by a linear response in time, the crop will respond to average EC over a given time interval.

$$EC_t = \sum_{i=1}^{n} t_i \, EC_i / n \qquad (1.3)$$

in which:

EC_t	= apparent EC, being the average EC over a period of n days in dS m^{-1}
t_i	= time in d
EC_i	= EC in the root environment over the period t_i in dS m^{-1}
n	= number of observations

Meiri (1984) summarized changes of the EC over longer periods and mainly argued for a linear response model as given in equation (1.3). However, such a response of crops to changing EC is not always realized, because under field conditions changes in time mostly coincide with changes in growth stage and climatic conditions, being factors interacting with salinity effects. Furthermore, it is possible that the range of salinity change includes levels lower than the threshold value and such levels are outside the linear range of equation (1.3). When the EC changes over short periods of time estimation by a simple average EC like in equation (1.3) is questionable. With short-term changes plants do not have sufficient time to adjust to the changed conditions. Diurnal variations in salinity have been studied by Van Ieperen (1996) and he found, for example, a positive effect on the production and quality of tomato at a low EC during the day and a high value during the night.

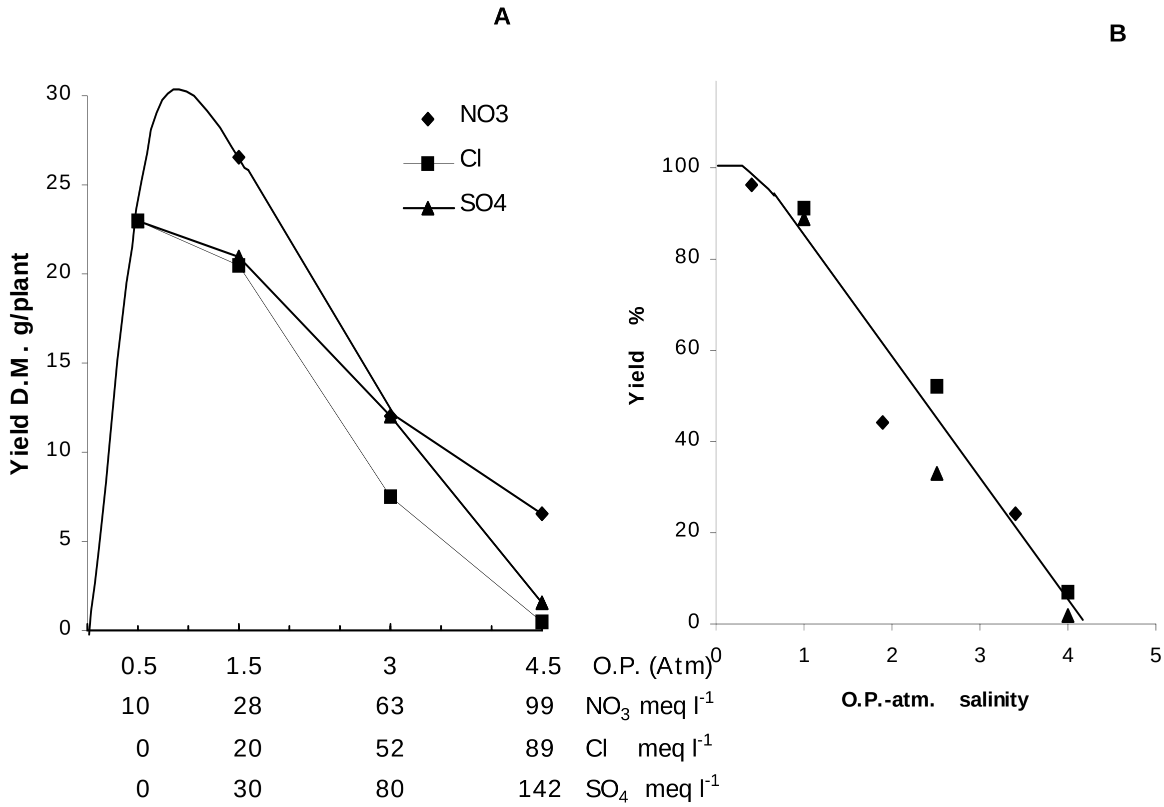


Figure 1.3 The response of tomato to nutrient and saline solutions of equal osmotic pressure based on the data of Hayward and long (1940-1941). Redrawn by Kafkafi (1984) (A) and redrawn on basis of our model as shown in figure 1.2B (B)

An abrupt increase in the EC of the root environment decreases the water absorption (Van Ieperen, 1996), but over long periods big differences in water use of plants grown at different EC have not necessarily been found, as long as the transpiration capacity (e.g. leaf area) is not strongly affected. This has been shown for tomato (Table 1.5) and for radish (Sonneveld and Van den Bos, 1995). Despite the significant yield reduction by increased EC no difference in water use has been found between treatments. Thus, in the case of salinity plants soon adjust with respect to their water absorption. That does not alter the fact that in many cases a reduced water absorption has been observed with increasing salinity (Baas et al., 1995; De Kreij and Van den Berg, 1990; Yaron et al., 1969).This however is caused by adaptation of plants to salinity stress and not directly by a hindrance of the water absorption (Lagerwerf and Eagle, 1962).

Table 1.5. Water absorption of tomato plants grown at

different EC in a recirculation system. Growing period from June until September. Data from Sonneveld (1981).

EC $dS\ m^{-1}$	Relative yield	Water used $l\ m^{-2}$
1.5	99	258
2.5	100	264
3.5	96	276
4.5	89	252

Given the high salinity gradients in the root environment as mentioned before, identification of an effective response parameter for salinity is of primary importance. Studies of salinity variations in space are summarized by Meiri (1984); he proposed three models for estimating a salinity parameter under a spatially variable salt profile:

$$EC_{ss} = \sum_{i=1}^{n} EC_i / n \qquad (1.4)$$

$$EC_{ss(W)} = \sum_{i=1}^{n} EC_i \ W_i \ / \sum W_i \qquad (1.5)$$

$$EC_{ss(Ro)} = \sum_{i=1}^{n} EC_i \ Ro_i \ / \sum Ro_i \qquad (1.6)$$

in which:

EC_{ss}, $EC_{ss(W)}$ and $EC_{ss(Ro)}$	= apparent EC for salinity under spatial variation
EC_i	= EC value of the soil water in compartment i
W_i	= water uptake from compartment i
Ro_i	= root length or weight in compartment i
n	= number of compartments

The average salinity in the root environment is calculated with equation (1.4). Equation (1.5) is based on the water uptake from a compartment and its salinity, while equation (1.6) is related to the presence of roots and the salinity in a compartment.
Meiri (1984) used yield data of maize (Bingham and Garber, 1970) and of alfalfa (Shalhevet and Bernstein, 1968) for a comparison of the three response parameters given. The EC calculated on the basis of equations (1.4) and (1.6) in a linear regression model gave more or less equal correlation coefficients. The correlation coefficients with the EC calculated on the basis of equation (1.5) were lowest for both crops. A disadvantage of equations (1.5) and (1.6) is the difficulty in determining water uptake and root intensity in compartments under field conditions. So, these equations are of minor practical value as estimators for salinity response. Moreover, differences in water uptake from a compartment and measured root intensity are results rather than causes of salinity. Thus, the causality between the variables of equations (1.5) and (1.6) can be criticized.

1.8 Estimations of salt tolerance

The salt tolerance of crops has been extensively studied in many experiments. In these experiments great differences have been found in crop response to salinity. Besides the differences between crops and cultivars, effects of environmental factors and experimental procedures generally contributed to the wide ranges found in crop reaction to salinity as mentioned before. Despite these conflicting results some reviewers have tried to summarize data of crop reaction to salinity and have classified crops according to their salt tolerance. These reviews are mainly based on outdoor experiments and cannot be translated directly to greenhouse conditions. The most important factors that should be kept in mind when comparing data of outdoor and greenhouse experiments are the humidity and the growing conditions in the winter season. Many salinity experiments are carried out in arid regions of the world, because there salinity problems frequently occur and are most evident. Such regions are characterized by high temperatures and low humidity.

The North-West European greenhouse industry is situated in areas with much lower average outdoor temperatures, but during summer time the temperature in the greenhouse often approximates the outdoor levels in arid regions. A higher humidity in the greenhouses, however, will persist as a climatic difference in summer. The differences between the winter climatic conditions in the North-West European greenhouses and the average climatic conditions in the fields in arid regions are striking, certainly for crops grown at more or less ambient temperatures in winter. In that case not only the higher humidity, but also the lower temperature and the lower light intensity in the North-West European greenhouses will be responsible for a different crop reaction to salinity. As a consequence of the lower radiation the transpiration of crops is decreased dramatically. The role of high humidity, low temperature and low transpiration rate are well recognized in salt tolerance literature (Maas and Hoffman, 1977; Maas, 1986; Magistad et al., 1943) as factors restricting salt injury of crops. Nevertheless, available data sets can be used as a basis to assess salt tolerance of greenhouse crops. In these comparisons, however, it should be expected that crops under greenhouse conditions are more tolerant to salinity, especially under North-West European winter conditions.

The most extensive reviews of crop salt tolerance are made by Maas and Hoffman (1977) and Maas (1986). For this purpose they gathered all usable data and standardized those following the model given in formula (1.1). The salinity of the root environment (EC_{ss}) was expressed as the EC of the saturation extract (EC_e). For the calculations from the soil solution to saturation extract they assumed that the salt concentration in the soil solution was twice that in the saturation extract. For greenhouse soils, as outlined before, we found an average ratio of 1.6. In the most recent comparison (Sonneveld et al., 1990) the following relationship was found:

$$EC_{ss} = 1.60\ EC_e - 0.18 \qquad (1.8)$$

Maas and Hoffman (1977) and Maas (1986) have presented salt tolerance data about 8 vegetable crops commercially grown in the Dutch greenhouse industry, namely bean, celery, cucumber, lettuce, pepper, radish, spinach and tomato. The salinity threshold value based on EC_e within this group of crops ranged from 1.0 dS m^{-1} for bean to 2.5 dS m^{-1} for cucumber and tomato. The SYD values were found between 6.2% per dS m^{-1} for celery and 19% per dS m^{-1} for bean.

Sonneveld (1988) compared the SYD values as found by the above authors with data from greenhouse experiments under Dutch growing conditions. A summary of this comparison is given in Table 1.6. As expected, the SYD values from literature are generally higher than those found under Dutch greenhouse conditions. This is especially the case for lettuce, radish and spinach. In the Dutch experiments these crops were grown in winter and early spring. Thus, for these crops the climatic conditions are most different from those in arid zones and favouring a higher salt tolerance. Celery is the only crop with a somewhat higher SYD value under greenhouse conditions. This may be explained by the occurrence of blackheart that was going with the salinity effects in this crop in the greenhouse experiments, and which probably aggravated the growth reduction.

Table 1.6. Comparison of SYD values of greenhouse vegetables on basis of EC_e with SYD values given by Maas and Hoffman (1977) and Maas (1986) after Sonneveld (1988).

Crop	Sonneveld		Maas and Hoffman,
	Exp.A*	Exp.D*	and Maas
Bean	13.9	14.7	19
Celery	-	7.7	6.2
Cucumber	11.7	8.8	13
Lettuce	3.1	4.6	13
Pepper	13.1	12.6	14
Radish	4.1	-	13
Spinach	+0.9	1.2	7.6
Tomato	5.7	6.5	9.9

* Different experiments as given by Sonneveld 1988.

For ornamentals no such review of experiments is available. Bernstein et al. (1972) and Maas (1986) did some classification for ornamental shrubs, trees and ground covers. These crops, however, are different from the ornamentals grown in the Dutch greenhouse industry. So, no current assessments of crop salt tolerance data for Dutch greenhouse ornamentals are available. In the present study attention will be given to this lack of information by presenting data of salinity experiments with greenhouse ornamentals and comparing these with scattered data from elsewhere.

1.9 Problem and research questions

Substrate growing in the greenhouse industry provides excellent possibilities for getting high production of optimum quality with minimum environmental pollution. For nutrient management, closed growing systems offer the best possibilities. This system has potential for crop production without any nutrient drain off. However, not all growers are able to achieve this objective. One of the main problems of growing crops in closed substrate systems is the accumulation of residual ions in the root environment, caused by a discrepancy between ion supply with the primary irrigation water and absorption by crops when no water with sufficiently low residual ion concentrations is available. The absorption of such ions by the crop depends on the growing conditions, in particular the concentration of the ion concerned in the root environment.

To improve the quality of the produce in the greenhouse industry, nutrient concentrations are sometimes higher than necessary for optimum growth and production. It is likely that these concentrations would be realised by accumulation of residual salts from the primary water. With high ion concentrations in the root environment of substrate systems, different concentrations in space and often also in time will certainly occur. The effects of such differences on plant development are, however, not well understood.

To achieve a maximum performance with substrate systems with respect to production, quality and environmental pollution, a fine tuning between irrigation, salinity and fertilization is necessary. The objective of such a system is optimum production - both with respect to quantity and quality - with a minimum emission of nutrients to the environment. In the present study the consequences of irrigation, salinity and fertilization in relation to this objective will be fitted in a model. In the optimization of such a model the following subjects need further study.

- Required and acceptable total ion concentrations with respect to yield and quality of the produce.
- Minimum concentrations of nutrients in the root environment to ensure an optimum growth and development of the crops.
- Interactions between salinity and required nutrient concentrations.
- Effects of different ion concentration gradients in the root environment in space and time on crop growth and development.
- Interaction of salinity and nutrient concentrations in the root environment on the one hand and climatic conditions in the greenhouse on the other hand.

Assuming fixed required or acceptable total ion concentration it is important to know the minimum concentration of nutrients with which maximum production can be maintained. It is to be expected that the ion composition of the space between the EC required for nutrients and the total EC required or accepted is mostly of secondary importance and thus offers possibilities for accumulation of residual salts. This is of great importance in reducing environmental effects. The higher the residual salts can be accumulated and the nutrient concentrations can be reduced, the lower the nutrient drain off to the environment will be. In chapters 2 and 3 the effects of salinity on respectively vegetables and flowers are studied, by determining salinity threshold concentrations (c_t) and salinity yield decrease (SYD) values in substrate systems. Furthermore, in the experiments described in these chapters attention has been paid to partial replacement of nutrients by NaCl as osmoticum.

In chapters 4 and 5 the crop reaction on an unequal distribution of nutrients and NaCl under saline conditions in the root environment has been studied. In these experiments special attention has been paid to the uptake of water and nutrients from root parts differing in nutrient or NaCl concentrations. The experiments in these chapters were suggested by the great EC gradients in space occurring in substrates and the poor reaction of crops to very high EC often noticed in part of the root volume. Slight crop response on high EC-values in drainage water for example offers possibilities for higher salt accumulations and henceforth a lower leaching fraction.

Besides variation in space, salinity variation in time is an important factor in practice. Effects of such variations were studied in chapter 6. In experiments described in this chapter long term variations were taken into account. In view of the strongly changing climatic conditions in greenhouses, in chapter 6 some experiments are also described in which interactions between salinity and climatic conditions in greenhouses were studied. In this way a global exploration of interactions between salinity and climatic conditions was carried out.

As will be clear, the experiments in chapters 2-6 are first of all focussed on salinity. The aspects connected with nutrition are considered in the discussion mainly with data from elsewhere. The model developed is focussed on an improved planning of the supply of water and nutrients to combine optimum production with minimum environmental pollution. The discussion is concluded with the environmental consequences of different parameters in the crop response model considered.

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2. Sodium chloride salinity in fruit vegetable crops in soilless culture

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Published in: Netherlands Journal of Agricultural Science 39 (1991) 115-122

Key words: Capsicum annuum, *Cucumis sativus*, EC, fruit quality, *Lycopersicon esculentum,* NaCl, salinity threshold value, salinity yield decrease value

Abstract

Tomato, cucumber and sweet pepper were grown in hydroponic systems in which the nutrient solutions were recirculated. The electrical conductivity (EC) of the nutrient solution was maintained at values of 2.5, 3.7 or 5.2 dS m^{-1} (25 ^{0}C) in the different treatments. In some of the treatments, the EC values mentioned were achieved by addition of nutrients, and in others by addition of a combination of nutrients and NaCl. Yields of all crops were adversely affected by increased EC values. Most fruit quality characteristics, on the contrary, were favourably affected. However, blossom-end rot increased at higher EC values. For sweet pepper, this was especially the case with NaCl addition. Apart from that, only slight specific NaC1 effects were noticed. Salinity threshold values for the different crops lay between 2.3 and 3.5 dS m^{-1} and salinity yield decrease values ranged from 2.3 to 7.6 % per dS m^{-1}. The absorption of Na and Cl differed with crop and with the Na and Cl concentration.

2.1 Introduction

In the Dutch greenhouse industry, soil salinity is a serious problem. Therefore, in former times when crops were grown in the greenhouse border soil, effects of soil salinity were studied in long standing research (Sonneveld, 1988a). At present, however, greenhouse fruit vegetable crops are mainly grown in soilless cultures, especially in rockwool slabs (Sonneveld, 1988b). This growing system differs widely from the traditional soil system. Therefore a study of salinity effects under these growing conditions was necessary.

The principal salinity problem in soilless cultures is the accumulation of Na and Cl, as these elements are abundantly present in many irrigation waters, while these ions are only sparingly absorbed by most crops. Hence, accumulation of Na and Cl in the root environment occurs, and high concentrations can readily be effected in small root volumes as used in most soilless culture systems.

The object of the present study was to assess the maximum Na and Cl concentrations acceptable in soilless cultures. To this end equal electrical conductivity (EC) values were achieved in the root environment by addition of either nutrients only or a combination of sodium chloride and nutrients. In this way, information was gained about the possibility of a partial replacement of nutrients by Na and Cl. The rather high EC value of 3 dS m^{-1} (25 ^{0}C) maintained for fruit-vegetable crops (Sonneveld, 1988b) suggested the possibility of such a replacement, since the concentrations of nutrients added to achieve an EC value of 3 dS m^{-1} exceed those necessary for plant nutrition.

2.2 Materials and methods

Experimental design

EC values of 2.5, 3.7 and 5.2 dS m^{-1} in the root environment were compared. In three treatments, these values were realised by addition of different quantities of nutrient elements, keeping the ratios between the elements constant. The concentrations of Na and Cl were below 5 mmol l^{-1}. In two other treatments, EC values of 3.7 and 5.2 dS m^{-1} were realised by addition of nutrients up to a level of 2.2, while NaCl was added to achieve the EC value intended. To this end 12.5 and 25 mmol NaCl per litre, respectively, were required.
The treatments were laid out in an experimental design of four blocks. Within each block the treatments were randomized independently. One experimental plot covered 5.5 m^2 greenhouse area. One sweet pepper *Capsicum annuum* crop and two tomato *Lycopersicon esculentum* and cucumber *Cucumis sativus* crops were grown. Growing periods and cultivars used are listed in Table 2.1.

Table 2.1. Growing periods of the crops after planting out and cultivars used.

Crop	Growing period	Cultivar
Tomato (1)	Jul. 85 - Nov. 85	Estafette
Tomato (2)	Jan. 86 - Sep. 86	Turbo
Sweet pepper	Dec. 86 - Oct. 87	Plutona
Cucumber (1)	Jan. 88 - May 88	Ventura
Cucumber (2)	Aug. 88 - Oct. 88	Corona

Growing system

The crops were grown in gutters placed on a slope of 1.5 %. The nutrient solutions used were continuously recirculated in these gutters. The young plants were raised in rockwool cubes of 0.4 1. The tomato plants were placed in the gutter without substrate, like in a nutrient film system (Graves, 1983). Sweet pepper and cucumber were grown on rockwool strips placed in the gutters. The strips were 0.10-0.15 m wide and the height was between 0.075 and 0.10 m.
The experiments were carried out in a heated greenhouse in which blueprint setpoints for heating and ventilation were maintained for the different crops. The recirculating nutrient solution was not heated.

Nutrient solution

To achieve optimal nutrient concentrations in the root environment, the addition of nutrients was adjusted to crops and growing conditions. In the recirculating nutrient solutions at an EC value of 2.5 dS m^{-1} ion contents were maintained as standardized for the crops (Sonneveld and Straver, 1989). To achieve these values during crop growth, on average the following ions were supplied: in mmol l^{-1} water added: NO_3 10 -13, H_2PO_4 1.0 -1.25, SO_4 1.0 - 1.5, NH_4 1.0 -1.25, K 6.0 - 6.5, Ca 2.5 - 3.0, Mg 1 - 1.25; in µmol l^{-1} : Fe 15, Mn 10, Zn 4-5, B 20 - 25, Cu 0.75, Mo 0.5. Simultaneous measurements in recirculating solutions and rockwool slabs made clear that EC values in solutions and slabs were equal.

Crop observations

At harvest, the numbers and the weights of marketable, deformed and blossom-end rot fruits were determined separately. The weights of the deformed and blossom-end rot fruits were expressed as percentages of total fruit weight. Other fruit quality judgments carried out were dependent on the crop. Tomato shelf life was expressed as the number of days between colour stage 100 % orange and fruit softening; russetting as an index between 0 and 5 for none and severely affected fruits, respectively; acids as mmol kg^{-1} puree and refraction as % Brix. For sweet pepper, fruits affected by russetting and green spot were expressed as percentages of total fruit number and the vitamin C content was expressed as mg g^{-1} fresh material. With cucumbers, fruit colour was judged using an index from 1 to 9 for the colour range from completely yellow to dark green, respectively, and shelf life was expressed as the number of days between harvest and colour stage 5.
The storage temperature for the tomato and the cucumber fruits was 20 ^{0}C and the relative humidity was between 80 and 90 %.

Na and Cl absorption

The solutions were analysed weekly for Na and Cl, and the uptakes of these elements were calculated as mmol per litre of water absorbed, from the amounts of NaCl and water removed from the system.

2.3 Results

The marketable fruit yields were reduced by increasing EC value in all crops (Table 2.2). With tomato (crop 2) and sweet pepper, the yield reduction was brought about by a lower fruit number as well as a lower fruit weight. With tomato crop 1 the fruit weight was affected only. With cucumber the lower fruit number was a dominant factor in crop 1 only. High sodium chloride did not specifically affect the fruit yield of tomato. With sweet pepper and cucumber a tendency towards a specific effect was found, but this was significant only for the high EC value in the second cucumber crop.
With the data presented, salinity threshold values (c_t) and salinity yield decrease (SYD) values were calculated by the following equations:

$$c_t = 3.7\ (dS\ m^{-1}) - [(Y_{(2.5)} - Y_{(3.7)})* (5.2-3.7)]\ (dS\ m^{-1}) / [Y_{(3.7)} - Y_{(5.2)}]$$

$$SYD = 100\% * [(Y_{(2..5)} - Y_{(3.7)})] / [Y_{(2.5)} (5.2-3.7)]\ (dS\ m^{-1})$$

in which $Y_{(x)}$ is the fruit yield at the EC value indicated by x.

In the equations given, it is assumed that yield reductions above the salinity threshold value are linear (Maas and Hoffman, 1977) and that the salinity threshold value is below a value of 3.7 dS m^{-1}; this was confirmed by the data. Results of the calculation are listed in Table 2.3.

Table 2.2. Yields of marketable fruits given as number and kg m^{-2}. Average fruit weights (FrW) expressed in g.

Treatment EC/NaCl	Number	kg m^{-1}	FrW	Number	kg m^{-1}	FrW
	Tomato crop 1			*Tomato crop 2*		
2.5/5	79	7.2	91	303	24.7	82
3.7/5	82	7.0	85	296	23.1	78
3.7/12.5	81	7.0	87	298	23.4	79
5.2/5	81	6.7	83	276	20.4	74
5.2/25	86	6.8	79	279	20.8	75
LSD (0.05)	ns	0.5	6	21	1.9	4
	Sweet pepper					
2.5/5	96	14.0	147			
3.7/5	96	13.5	141			
3.7/12.5	90	12.5	139			
5.2/5	85	11.7	138			
5.2/25	80	11.1	139			
LSD (0.05)	9	1.3	4			
	Cucumber crop 1			*Cucumber crop 2*		
2.5/5	50	24.7	498	20	10.2	523
3.7/5	47	23.0	494	20	10.0	513
3.7/12.5	45	22.3	496	20	10.2	510
5.2/5	43	20.7	486	20	9.9	506
5.2/25	41	20.3	495	17	8.6	512
LSD (0.05)	3	1.5	ns	2	1.0	ns

The data of the different fruit quality characteristics are listed in Table 2.4. Blossom-end rot in tomato and sweet pepper increased with increasing EC values. In sweet pepper the disorder was specifically associated with high NaCl. Apart from blossom-end rot, the external fruit quality was generally improved by increasing EC values. This is apparent from the longer shelf life, the higher colour index, and the decrease of russetting and green spot. The higher acid content and the higher refraction with increasing EC value can be considered as improvements of the internal quality. The effect on the vitamin C content was not consistent.

Table 2.3. Salinity threshold values (c_t) and salinity yield decrease values (SYD) of kg marketable fruit calculated from the data of Table 2.2.

Experiment	c_t (dS m^{-1})	SYD (% per dS m^{-1})
Tomato crop 1	2.5	2.3
crop 2	2.9	7.2
Sweet pepper	2.8	7.6
Cucumber crop 1	2.3	5.8
crop 2	3.5	5.6

The differences in water uptake of the crops between treatments were marginal. The water absorption averaged over the treatments is listed in Table 2.5. The absorption of Na and Cl by the crops was strongly affected by the concentration of these elements in the root environment, as is shown by the data in Table 2.5. Nearly always Cl was absorbed in greater quantities than Na. The Na absorption of sweet pepper was generally lower than that of other crops and seemed to be noticeable only during the first months of growing. Later on, there was hardly any absorption of Na by this crop.
The Na and Cl contents of the plant tissues (Table 2.6) clearly reflect the different absorptions found in the different crops and treatments. The low Na contents in the sweet pepper tissues are striking.

2.4 Discussion

In general the marketable yield of the crops tested was not specifically affected by high concentrations of NaCl in the root environment. This is in agreement with results of other researchers (Maas and Nieman, 1978). However, the highest NaCl concentration in the second cucumber crop significantly reduced fruit yield as compared to the highest nutrient concentration. Slight specific yield reductions, though not statistically significant, were also found in the first crop. All this indicates a tendency to specific sensitivity for NaCl, which has also been found for soil grown cucumber (Sonneveld and Van Beusekom, 1974). The slight specific yield reductions of the sweet pepper crops might be explained by the higher percentage of fruits affected by blossom-end rot. Increasing NaCl concentrations lower the ratio $\alpha_{Ca} / \Sigma\alpha_{cation\ i}$, and may result in a lower Ca absorption if this ratio decreases (Bennett and Adams, 1970; Shear, 1975) and induce blossom-end rot. Sweet pepper is very prone to blossom-end rot, as has been found also in experiments with soil grown crops (Sonneveld, 1988a). So, with increasing Na concentrations in the root environment an increase in the Ca concentration may be necessary for this crop in order to maintain an adequate ion activity ratio.

Table 2.4. Fruit quality as affected by the treatments

Treatment EC/NaCl	*Tomato crop 1*					*Tomato crop 2*				
	BER (%) tion	shelf life (days)	russet- ting index	acid (mmol kg^{-1})	refrac- tion (%)	BER	shelf (days)	russet- life index	acid ting kg^{-1})	refrac- (mmol (%)
2.5/5	3.9	11.1	1.18	69	5.1	1.9	7.7	2.3	68	4.7
3.7/5	9.9	13.8	0.77	71	5.4	2.1	9.5	2.2	74	5.1
3.7/12.5	5.5	14.6	0.72	72	5.2	1.9	7.8	2.3	73	5.0
5.2/5	7.9	16.5	0.56	75	5.5	3.1	9.3	1.8	70	4.9
5.2/25	8.2	16.5	0.45	78	5.6	3.0	9.8	1.7	74	5.1
LSD(0.05)	2.5	1.7	0.21	4	0.3	ns	0.9	0.2	2	0.1

Treatment EC/NaCl	*Sweet pepper*					
	BER (%)	deformed (%)	(%)	russetting (%)	green spot (mg g^{-1})	vit C
2.5/5	2.1	3.1	23.0	7.2	1.94	
3.7/5	3.1	4.2	18.4	5.5	1.84	
3.7/12.5	7.5	4.9	19.3	3.7	1.70	
5.2/5	7.0	3.7	18.4	2.7	2.10	
5.2/25	12.6	3.2	14.7	2.1	1.80	
LSD(0.05)	2.6	ns	5.4	2.9	0.31	

Treatment EC/NaCl	*Cucumber crop 1*			*Cucumber crop 2*		
	deformed (%)	colour index	shelf life (days)	deformed (%)	colour index	shelf life (days)
2.5/5	<0.1	6.7	12.7	21.2	6.6	11.4
3.7/5	<0.1	6.8	13.7	22.6	6.9	13.3
3.7/12.5	<0.1	6.6	11.6	19.8	7.0	14.4
5.2/5	<0.1	7.3	16.0	19.5	7.6	16.1
5.2/25	<0.1	7.3	15.8	22.0	7.5	14.4
LSD(0.05)	ns	0.4	ns	ns	0.6	2.1

Maximal yield of rockwool grown crops can be obtained with nutrient concentrations resulting in an EC value of 1.5 dS m^{-1} in the root environment (Sonneveld, 1988b). This means that if the usual EC value of 3.0 dS m^{-1} is maintained in the root environment, the difference between 1.5 and 3.0 dS m^{-1} can be substituted by NaCl and that Na and Cl concentrations of about 12 mmol l^{-1} are still acceptable. Using water rich in NaCl, the accumulation of Na will be more critical than that of Cl, as Na is absorbed less readily than Cl. At a concentration in the root environment of

12 mmol l^{-1}, about 1.0, 0.3 and 1.3 mmol per litre water is absorbed by tomato, sweet pepper and cucumber respectively. Higher Na concentrations will cause a rapid accumulation and necessitate leaching. The required leaching fraction can be calculated by the following equation:

Table 2.5. Total water absorption during the experimental period in l m^{-2} and Na and Cl absorption expressed in mmol per l water absorbed.

Crop	Water absorbed l m^{-2}	Na and Cl absorbed (mmol l^{-1})					
		Concentration of NaCl in root environment(mmol l^{-1})					
		<5		12.5		25	
		Na	Cl	Na	Cl	Na	Cl
Tomato 1	180	0.3	0.4	0.9	1.0	1.3	1.5
Tomato 2	480	0.6	0.7	1.1	1.4	1.4	1.7
Sweet pepper	495	0.2	0.3	0.3	0.8	0.6	1.3
Cucumber 1	225	0.2	0.4	1.2	1.6	2.0	2.4
Cucumber2	130	0.4	0.2	1.4	2.1	3.2	5.0

Table 2.6. Contents of Na and Cl in young fully grown leaves and mature fruits expressed as mmol per kg dry matter.

Crop	Tissue	Element	NaCl concentration in root environment (mmol l^{-1})		
			<5	12.5	25
Tomato	leaf	Na	41	104	172
		Cl	77	122	164
	fruit	Na	31	71	106
		Cl	136	198	201
Sweet pepper	leaf	Na	3	3	3
		Cl	12	17	23
	fruit	Na	3	6	9
		Cl	9	24	36
Cucumber	leaf	Na	25	93	166
		Cl	32	154	350
	fruit	Na	61	172	336
		Cl	68	197	286

$$LF = (c_{w(Na)} + c_{f(Na)} - c_{u(Na)})/(c_{d(Na)} - c_{u(Na)})$$

in which LF is the leaching fraction, $c_{w(Na)}$ the Na concentration of the irrigation water, $c_{f(Na)}$ the increase of the Na concentration in the irrigation water by impurities of fertilizer addition, $c_{u(Na)}$ the Na absorption of the crop expressed as mmol per litre water absorbed and $c_{d(Na)}$ the Na concentration of the drainage water. Guide values for $c_{u(Na)}$ and $c_{d(Na)}$ are traced in the present research. $c_{f(Na)}$ can be calculated by the fertilizer impurities. Thus, LF can be calculated on basis of $c_{w(Na)}$.

The data presented for tomato contradict those of Adams (1987). He found that Na concentrations in the root environment of a soilless culture system could increase up to 37 mmol l^{-1} without any yield reduction. His data showed that yields were even slightly higher at Na concentrations of 22 and 37 mmol l^{-1} than at low concentrations. Corresponding EC values for low Na and 37 mmol l^{-1} Na were 2.0 and 6.2 dS m^{-1}, respectively. In other words, according to the work of Adams (1987) the salinity threshold value for tomato would be beyond 6.2 dS m^{-1}. A salinity threshold value for tomatoes between 2.5-2.9 dS m^{-1}, as presented in this paper, is reasonably in agreement with values generally found. In a review of crop salt tolerance, Maas and Hoffman (1977) gave a threshold value based on saturation extracts of 2.5 dS m^{-1}. This value can be converted to a value of 3.8 dS m^{-1} in the soil solution (Sonneveld et al., 1990). The contradiction referred to may be caused by differences in growing conditions. Under climatical conditions promoting vegetative growth, tomato plants may grow too vigorously and then high salinity will improve fruit formation. The data of Adams (1987) suggest such an effect. In our data the low SYD value of tomato crop 1 (Table 3) may also be explained by a vigorous growth, for this crop starting in full summer showed such a development.

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3. Salt tolerance of flower crops grown in soilless culture

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Published in: Journal of Plant Nutrition 22, 1033-1048

Abstract
Gerbera, carnation, rose, aster, bouvardia and lily were grown in a hydroponic system at different levels of salinity. The EC and sodium (Na) and chloride (Cl) concentrations maintained in the root environment solution were tuned at the expected salt sensitivity of the crops grown. The target values for the EC were between 1.7 and 5.2 dS m^{-1} (25^{0}C) and the Na and Cl concentrations between 0 and 30 mmol L^{-1}. All experiments had one treatment in which the EC was increased through addition of nutrients instead of sodium chloride (NaCl).
The calculated salinity threshold values were between 1.1 and 4.3 dS m^{-1} and the salinity yield decrease (SYD) values between 2.1 and 16.8% per dS m^{-1}. For aster no values could be calculated, because the highest EC value of 4.2 in this experiment did not affect the production level. However, the regrowth of this crop after the first harvest was strongly hindered by the EC in the root environment, especially when the EC was increased with NaCl. The flower production of the bouvardia crop was specifically decreased by the addition of Na. Post harvest quality characteristics of the flower crops were not affected by the treatments. The relationships between the Na and Cl concentrations in solution and the uptake concentrations of these elements were determined for the different crops. Mostly, a linear relationship was found, for Cl sometimes a curvilinear relationship showed a better fit.

3.1 Introduction

In the Dutch greenhouse industry, an important part of the flower production is performed in soilless culture (Proefstation voor Bloemisterij en Glasgroente, 1997). Different substrates are used as growing medium, such as expanded clay, perlite, granulated foams, peat mixtures, volcanic gravels, glasswool and rockwool. Salinity problems may occur in soilless culture systems by accumulation of salts from the irrigation water used (Voogt and Sonneveld, 1997). Accumulation of salts in the root environment has been a problem in the Dutch greenhouse industry since the crops were grown in the greenhouse border soil. Many types of water used for irrigation had too high salt concentrations (Sonneveld, 1993). Salinity is even more serious in the small root volumes generally used in soilless cultures, because accumulation of salts may occur very quickly. Especially, when crops are grown in closed growing systems the accumulation of salts in the root environment occurs rapidly. The use of such systems is greatly promoted by Dutch governmental policy, because of prevention of environmental pollution (Ministerie van Verkeer en Waterstaat, 1994). That's why at the Research Station for Floriculture and Glasshouse Vegetables a special study has been conducted on the effects of salinity on the performance of flower crops in closed soilless culture systems. Detailed results of the experiments with carnation and gerbera have been already published (Baas et al., 1995). Besides these crops, other flower crops were examined in the study. In this paper, the results of the other flower crops will be compared, with special attention to salinity effects on total fresh flower productions. Some of the data of carnation and gerbera will be used in this comparison.

3.2 Materials and methods

Experimental Design

Gerbera, carnation, rose, aster, bouvardia and lily were grown in a hydroponic system at different salinities. Six treatments with different EC values in the nutrient solution in the root environment were compared in each experiment (Table 1). With the exception of the second bouvardia experiment, the different EC values in the treatments 1 to 5 were realized by addition of NaCl. The EC in Treatment 6 was assessed by addition of extra nutrients up to the EC of Treatment 5, thus keeping the ratios between the nutrient elements constant. In the second bouvardia experiment, the EC values were not realized by addition of NaCl, but just by addition of Na or Cl, while two treatments were included in which the EC was increased by addition of extra nutrients. In the treatments where either Cl or Na was increased, nutrient anions and cations were replaced by the addition of these elements, respectively. In all cases the mutual ratios between the nutrient anions and cations were kept constant. The levels of the EC values, and Na and Cl concentrations realized in the experiments were different for crops. They were tuned to the expected salt sensitivity of the crop under investigation. The EC values and Na and Cl concentrations aimed at in the different experiments are listed in Table 3.1.
The treatments were laid out in four parallels. The experimental plots had a size of 3 - 6 m^2, depending on crop and growing system available. Two plots were connected with one recirculation basin. So, each of the treatments had two basins each supplying two plots with nutrient solution.

Table 3.1. Target EC values (dS m^{-1} 25^0 C) and NaCl concentrations (mmol L^{-1}) in the root environment in the different treatments of the experiments. The values are given as EC/NaCl.

Nr	Gerbera	Carnation	Rose	Aster	Bouvardia 1	Bouvardia 2	Lily
1	1.8/0	1.7/0	1.9/0	1.8/0	2.2/0	2.0/0	1.5/0
2	2.2/4	2.6/7½	2.5/5	2.4/5	2.8/5	2.0/10Cl*	1.8/3
3	2.7/8	3.5/15	3.1/10	3.0/10	3.4/10	3.0/10Cl*	2.2/6
4	3.2/12	4.3/22½	3.7/15	3.5/15	4.0/15	2.0/10Na*	2.5/9
5	3.7/16	5.2/30	4.5/20	4.2/20	4.6/20	3.0/10Na*	2.8/12
6	3.7/0	5.2/0	4.5/0	4.2/0	4.6/0	3.0/0	2.8/0

* not NaCl, but just mmol Cl or Na L^{-1} in the root environment, respectively.

Growing System

The crops were grown in a heated greenhouse of 150 m^2, in which set point temperatures were maintained for heating and ventilation related to the crop requirements. During day time, especially in summer, temperatures increased depending on radiation. Furthermore, the growing conditions were adjusted to the crop and the equipment available in the greenhouse. The nutrient solution in the growing systems was recirculated.
Gerbera plants were raised in rockwool cubes and placed on polyurethane strips in gullies. The planting density was 6¼ plant m^{-2}. The water was supplied by ebb and flow. Carnation, rose and aster plants were propagated in small plastic containers filled with perlite or rockwool. The

containers were placed in holes in polyethylene covers on gutters. The planting density for carnation, rose and aster was 37½, 15 and 12½ plants m^{-2} ,respectively. The water was supplied by ebb and flow. From September until May, with light intensities below 100 W m^{-2} the rose crop was given supplementary artificial lighting from 4.00 to 20.00 h. The growing and the irrigation systems for the bouvardia plants in the first experiment were the same as for carnations, rose and aster. In the second experiment the plants were raised in rockwool plugs which were planted out on rockwool slabs of 0.07 m height. The water was given by a lay flat tube system. The planting density was 25 plants m^{-2}. The photoperiod was adjusted by lighting and screening to get the plants flowering on the planned date. For lily gutters were filled with a 0.10 m layer of perlite granules of a size between 0.6 - 2.5 mm. The perlite was put on a screen 20 mm from the bottom, to get a free space for drain water. The water was given by lay flat tubes and the planting density was 30 plants m^{-2}. The growing period of the crops and the cultivars used are listed in Table 3.2.

Table 3.2. Growing periods of crops and cultivars used in the experiments.

Crop grown	Cultivars used	Growing period	Duration of the experiment (months)
Gerbera	Beauty	Jul 1991-Jun 1992	12
Carnation	Adelfie	Dec 1991-May 1993	18
Rose	Europa	Dec 1991-Sep 1993	22
Aster	Monte Casino	Jul 1992-Feb 1993	7
Bouvardia 1	Van Zijverden	Mar 1993-July 1993	5
Bouvardia 2	Van Zijverden	Feb 1994-Nov 1994	9
Lily	Star Gazer	Mar 1995-Jun 1995	4
	Connecticut King	Mar 1995-May 1995	3

Nutrient Solution

To achieve an optimal nutrient status in the root environment, the nutrient concentrations were adjusted to crop requirements, following the current recommendations for growers (Sonneveld and Straver 1994). In this way, the EC maintained for the nutrient supply in the solution in the root environment varied between 1.5 and 2.2 dS m^{-1}. To keep the mutual ratios between the nutrient elements within the recommended limits and the Na and Cl concentration constant, the recirculating solution was sampled and analyzed regularly and the composition of the nutrient solution was then adjusted by additions of water, nutrients, Na or Cl. The water used in the experiments was rainwater. The EC of this water was lower than 0.1 dS m^{-1} and the Na and Cl concentrations were about 0.3 mmol L^{-1}.

Crop Observations

Number and fresh weight of the marketable flowers were determined.The quality characteristics determined depended on the crop. With gerbera vase life, flower shape and flower size (area) were determined. With carnation vase life was determined and with rose also flower bud opening and flower diameter at the end of the vase life**.** With lily number of buds and number of misshapen buds were counted. With the cultivar Connecticut King also vase life was determined.

In the storage room a temperature of 20^0C and a relative humidity of 60% were maintained. The light intensity was 1.5 W m^{-2} for 12 h day^{-1}. Vase life was considered terminated at loss of turgor of the flowers.

Sodium and Chloride

The total absorption of Na and Cl was calculated from the total dry matter production, taking the crop residu into account, and the respective tissue concentrations. Mostly at the end of the experiments, but also at times if crop reaction to salinity gave occasion to it, samples of plant tissues were gathered and after drying analyzed for Na, Cl and nutrient elements.

Statistical Analysis

Flower weights were analyzed statistically using linear regression according the model of Maas and Hoffman (1977). Absorptions of Na and Cl were related to root environment concentrations using linear and curvilinear equations.

3.3 Results

The total flower weights are given in Table 3.3. With respect to the NaCl additions, generally the weights were highest in the treatments with the lowest or second lowest NaCl concentrations in the root environment. The weights decreased with increasing NaCl concentrations, but this was not the case for the aster crop. Between the other crops big differences in salt sensitivity appeared. Carnation seemed to be rather tolerant, because the high NaCl additions resulted in marginal yield reductions with increasing concentrations. Rose and lilies cv Connecticut showed to be only a little more sensitive. Gerbera and lily cv Star Gazer had a moderate position in this respect, while the yield reductions of the bouvardia crop were relatively highest.

The decrease of the total flower weights of gerbera and rose was affected relatively more by a decrease in the number of flowers than by a decrease of the stalk weight. For carnation and bouvardia the opposite was the case. With lily the number of stalks was fixed by the number of bulbs planted out. The decrease of the total flower weight was thus related to a decrease of the weight per flower.

For most crops the flower weights in the treatments in which the EC value was increased with nutrients were the same as in the treatment with a comparable EC achieved with NaCl. This was not the case with the bouvardia crop, of which the flower weight in the Treatment 4.6/20 was much lower than that in the Treatment 4.6/0. This crop showed to be specifically sensitive to NaCl. With carnation the total flower weight in Treatment 5.2/0 tended, however, not significantly, to be lower than in Treatment 5.2/30; indicating an effect opposite to that with the bouvardia crop.

With respect to the specific sensitivity of bouvardia for NaCl, it is clear from the second bouvardia experiment that Cl hardly affected growth, but that mainly Na was responsible for the growth reduction. At the same EC, addition of 10 mmol Cl L^{-1} reduced growth with 6% and with the same Cl concentration but an increase of the EC to 3.0 with nutrient elements the growth reduction was 9 %. The increase of the EC with one unit was thus responsible for a growth reduction of 3 % (9%- 6%). This was in good agreement with the yield of Treatment 3.0/0, which was only 3% lower than that of Treatment 2.0/0. The addition of Na, however, had a different effect on growth. Addition of 10 mmol Na L^{-1} with identical EC value and by this low concentrations of nutrient cations, reduced the growth with nearly 50%. At the same Na concentration but with a higher EC value, through higher nutrient concentrations, growth reduction was restricted to only 20%. Thus, the Na effect was partly eliminated by a higher supply of nutrient cations. This should be explained either by cation competition which will restrict the uptake of Na or by setting aside a limited uptake of a cation essential for plant growth caused by Na competition or by the decreased concentration of such a cation in the root environment resulting from the increased Na concentration in Treatment 2.0/10Na. To study these effects in more detail, tissue samples were gathered at specific times and analyzed for uptake of minerals. The results are listed in Tables 3.4 and 3.5. Chloride was absorbed in much bigger quantities than Na. The contents of Na and Cl were clearly affected by the addition of these elements as well as by the nutrient level. The total top mass showed higher Na and Cl contents than the fully expanded leaves (Table 3.4). The contents of nutrients on whole plant basis after harvest of the second flux of flowers (Table 3.5) was reduced strongly by the Na addition in treatment and lowered nutrient cations, as will be clear from comparing the data of the Treatments 2.0/0 and 2.0/10Na. The reduction by Na, however, was eliminated by a higher nutrient level in the root environment as is clear from the results of Treatment 3.0/10Na. With aster it was striking that many plants did not show regrowth after harvest. The number of plants with regrowth decreased strongly with increasing NaCl addition (Table 3.6). The results strongly suggest that this was mainly a NaCl effect, because increase of the EC to 4.2 dS m^{-1} with nutrients decreased the regrowth plants only to 75.8%, while at the same EC achieved with NaCl regrowth was only 39.7%.

Table 3.3. Total flower weights (kg m^{-2}) of the crops and EC (dS m^{-1}) realized in the root environment in the different experiments.

EC/NaCl	kg m^{-2}	EC/NaCl	kg m^{-2}	EC/NaCl	kg m^{-2}	EC/NaCl	kg m^{-2}
Gerbera		*Carnation*		*Rose*		*Aster*	
1.8/0	5.12	1.7/0	14.8	1.9/0	13.4	1.8/0	0.35
2.2/4	4.74	2.6/7½	14.0	2.5/5	14.0	2.4/5	0.38
2.7/8	4.62	3.5/15	14.0	3.1/10	12.6	3.0/10	0.35
3.2/12	4.04	4.3/22½	14.0	3.7/15	12.4	3.5/15	0.36
3.7/16	4.22	5.2/30	13.7	4.5/20	12.4	4.2/20	0.37
3.7/0	4.47	5.2/0	12.0	4.5/0	12.7	4.2/0	0.39
Bouvardia 1		*Bouvardia 2*		*Lily cv Connecticut*		*Lily cv Star Gazer*	
2.2/0	1.31	2.0/0	6.49	1.5/0	3.55	1.5/0	3.43
2.8/5	1.20	2.0/10Cl	6.08	1.8/3	3.65	1.8/3	3.24
3.4/10	0.99	3.0/10Cl	5.90	2.2/6	3.65	2.2/6	3.26
4.0/15	0.84	2.0/10Na	3.40	2.5/9	3.38	2.5/9	3.24
4.6/20	0.78	3.0/10Na	5.27	2.8/12	3.52	2.8/12	3.04
4.6/0	1.18	3.0/0	6.32	2.8/0	3.20	2.8/0	3.08

With respect to the quality characteristics (data not shown) it was found that the vase life of gerbera, carnation, rose and lily was not significantly affected by the salinity treatments. The flower shape of gerbera was not affected by the treatments but the flower size was decreased with increasing salinity, proportionally to the decrease of the weight. The flower bud opening and the flower diameter of the roses at the end of the vase life period were not significantly affected by salinity and neither was the number of lily buds per stem. The number of misshapen buds showed a tendency to decrease with increasing NaCl.

Table 3.4. Na and Cl concentration of plant tissues (mmol kg^{-1} dry matter) from the second bouvardia experiment.

Treatments	Before 1th flush*		Before 2nd flush*		After 2nd flush*		After 2nd flush**	
EC/Na or Cl	Na	Cl	Na	Cl	Na	Cl	Na	Cl
2.0/0	19	54	0	69	4	34	7	64
2.0/10Cl	13	140	0	168	2	179	6	230
3.0/10Cl	7	80	0	134	5	156	9	250
2.0/10Na	28	52	37	88	nd***	nd***	151	82
3.0/10Na	16	46	4	73	4	45	96	64
3.0/0	4	63	0	68	3	79	8	142

* Fully grown leaves before the first, before the second and after the second flush of flowers
** Total top mass after the second flush of flowers
*** Not determined, because of insufficient material

Table 3.5. Nutrient concentrations (mmol kg^{-1} dry matter) in the total top mass of bouvardia after the second flush of flowers of the second experiment.

Treatments	Minerals in plant tissue							
	N	NO_3	P	K	Ca	Mg	Na	Cl
2.0/0	2164	433	192	907	363	126	7	64
2.0/10Na	1685	93	128	559	213	85	151	82
3.0/10Na	2176	389	202	838	339	157	96	64

Table 3.6. Percentages regrowth of aster plants after the first harvest.

EC/NaCl	% regrowth
1.8/0	86.5
2.4/5	75.8
3.0/10	63.5
3.5/15	52.2
4.2/20	39.7
4.2/0	75.8

The average Na and Cl concentrations realized in the root environment are listed in Table 3.7. The 0 level of NaCl never has been realized, as the water that was used in the experiments contained small quantities of Na and Cl. Moreover, the fertilizers used contained some Na and Cl. The Cl concentration in the root environment was kept more or less on a stable level between 0.2 and 2.1 mmol L^{-1}. With regard to Na a clear accumulation occurred at the 0 level. The average levels in the root environment varied between 0.7 and 3.0. With the other treatments the Na concentration was always higher than the Cl concentration, indicating that Cl was preferently taken up in higher amounts from NaCl than Na. The target concentrations were mostly rather well reached. In some situations, see for example the result with gerbera, the Cl concentration was too low. This especially occurred when there was a substantial difference between uptake of Na and Cl. In such cases the NaCl addition to the nutrient solution apparently has been better focused on the Na than on the Cl concentration in the root environment.

Table 3.7. Average Na and Cl (Na/Cl) concentrations (mmol L^{-1}) realized in the root environments of the different experiments.

NaCl*	Crops Gerbera	Carnation	Rose	Aster	Bouv 1	Bouv 2	Lily
0	1.7/0.2	2.7/0.2	3.0/2.1	1.2/0.6	1.3/1.0	1.0/0.2	0.7/0.3
3							2.9/2.6
4	4.2/0.9						
5			6.2/4.9	5.1/4.1	5.6/4.8		
6							6.1/6.0
7½		8.4/4.0					
8	7.9/4.2						
9							9.2/9.0
10			11.2/9.7	9.8/8.9	9.5/9.3	11.4/ 10.6	
12	11.5/8.9						12.1/11.6
15		15.9/13.1	15.6/13.7	14.0/12.9	14.7/14.5		
16	14.9/12.6						
20			20.2/18.2	18.9/17.9	19.2/19.2		
22½		23.5/20.6					
30		31.5/29.1					

* Target concentration mmol L^{-1}

In Table 3.8 the quantities of Na and Cl absorbed by the crops are given, expressed as mmol L^{-1} water absorbed, thus as "uptake concentrations". Mostly the influx of Cl was higher than that of Na, except for lily at the high NaCl concentrations and for aster at the lowest concentration. There seemed to be a relationship between the influx of Na and that of Cl. Crops with a relatively low influx of Na, like rose, had also a relatively low influx of Cl. Aster had a high Na absorption and also a high influx of Cl. With lily only the average influx for both cultivars could be calculated, because they were grown in the same experimental plots; it was therefore not possible to determine water uptake of the individual cultivars. However, there was a real difference between the cultivars. The tissue analysis (data not shown) learned that the Na absorption of cv Star Gazer was two to three times higher than that by cv Connecticut King. The Cl uptake by cv Star Gazer was about 65% of that of cv Connecticut King. So, with the lily cultivars the uptakes of Na and Cl were contrastive.

Table 3.8. Na and Cl absorption (Na/Cl) of flower crops expressed per L of water absorbed.

NaCl*	Crops

	Gerbera	Carnation	Rose	Aster	Bouv 1	Bouv 2	Lily**
0	0.17/0.59	0.13/0.35	0.00/0.09	0.24/0.16	0.03/0.11	0.02/0.32	0.15/0.40
3							0.40/0.70
4	0.51/1.71						
5			0.00/0.11	0.38/0.64	0.06/0.18		
6							0.70/0.80
7½		0.31/0.61					
8	0.64/2.00						
9							0.90/0.80
10			0.01/0.15	1.18/1.52	0.13/0.33	0.35/0.86	
12	0.61/2.14						1.20/0.90
15		0.39/0.72	0.01/0.18	2.79/3.15	0.16/0.36		
16	1.31/2.65						
20			0.01/0.22	3.72/4.01	0.16/0.36		
22½		0.60/0.93					
30		0.88/1.13					

* Target concentration in the root environment in mmol L^{-1}
** Average values of both cultivars

3.4 Discussion

With the data presented in Table 3.3 salinity threshold (c_t ; dSm^{-1}) values and salinity yield decrease (SYD; % per dSm^{-1}) values of the total flower weights can be calculated, following the model of Maas and Hoffman (1977). Slope and threshold value of this model were unknown, so the following equations have been developed based on the formulae given by Van Genuchten and Hoffman (1984):

$$SYD = 100/n \sum_{1}^{n} (Y_i - Y_{i-1})/Y_m(c_i - c_{i-1}) \qquad (3.1)$$

$$c_t = 1/n \sum_{1}^{n} c_i - (Y_m - Y_i) /(SYD*Y_m) \qquad (3.2)$$

in which Y_i is the yield, Y_m the maximum possible yield without salinity effects on the crop, c_i the EC realized in the root environment, i the running number of a treatment and n the number of observations.
In most cases Y_m was derived from the treatments with the low EC in which no NaCl was added and which were thus not affected by salinity. In some cases there were salinity treatments with yields equal to or higher than these treatments. In such cases another estimation of Y_m was made according to:

$$Y_m = 1/n \sum_{1}^{n} Y_i \qquad \text{for all } Y_i \geq Y_1 \qquad (3.3)$$

The results of the calculations are summarized in Table 3.9. The data of the second bouvardia experiment were not included, for the object of this experiment was different from the others and not tuned to the calculations of SYD and threshold values. In the other experiments the data of

Treatment 6, in which the EC was increased with nutrients, were not included in the calculations, because of the fact that the results of this treatment sometimes deviated from the others. It is likely that the flower yield of Treatment 1 (EC value 1.7) in the experiment with carnation was accidentally high, because the yields of the Treatments 2, 3 and 4 (EC values 2.6, 3.5 and 4.3) were equal. If the high yield of Treatment 1 was taken into account in the calculations, the threshold value tended to the EC of Treatment 1, but when this high yield was ignored the threshold value tended to the EC value of Treatment 4.
The threshold value for gerbera is in good agreement with the value of 2.0 given by De Kreij and Van Os (1989). The SYD value of 2.5% calculated from their data is much lower than the 9.8% found in our experiment. The comparison of two EC values with gerbera in rockwool culture in the study of De Kreij et al. (1986) showed a SYD value of 9.7%. From a study with a soil grown crop (Sonneveld and Voogt 1983) a SYD value for the soil solution of 6.2% was calculated for the cv "Mandarine" and of 10.2% for the cv "Fabiola". The conversion from saturation extract to soil solution for these calculations was made by the data of Sonneveld et al. (1990). The data of the soil grown crop were not suitable for an exact calculation of a threshold value. All these latter SYD values are in good agreement with the value found in our experiment.

Table 3.9. SYD values (% per dS m^{-1}) and salinity threshold values (c_t) calculated for total flower weights on basis of the data presented in Table 3.

Crops	SYD	c_t
Gerbera	9.8	1.5
Carnation	2.1	1.1
Carnation*	3.9	4.3
Rose	5.3	2.1
Aster**	n.d	>4.2
Bouvardia 1	16.8	2.1
Lily Conn.King	4.6	1.6
Lily Star Gazer	9.6	1.6

* ignoring the high yield in Treatment 1
** at t ≥ 4.2 calculation of SYD is not possible

For carnation Baas and Wertwijn (1995) made a comparison between two EC values with a rockwool grown crop. The SYD value derived from this experiment was 7.2%. With the data of Sonneveld and Voogt (1983) for soil grown carnations, a SYD value of 2.0% for the cv "Scania" and of 1.6% for the cv "Nora Barlo" was calculated for the soil solution. A threshold value for both cv's of 8.1 dS m^{-1} was obtained, which is high in comparison with the 1.1 - 4.3 dS m^{-1} found in our study. The data of Ishida (1979a) found with a carnation crop grown in sand and soil cultures are not a good basis for comparison with other salinity studies, for in this experiment sea water was used to increase the salinity. Sea water contains bromide (Br), for which carnation is specifically sensitive. The sea water concentration in his experiment ran to 15% and thus the Br concentration must have reached levels up to 125 µmol L^{-1} (Stumm and Morgan 1996). This concentration can be tolerated by carnation for a period of several weeks only (Hoffmann and Malkomes, 1979), but for longer growing periods concentrations > 50 µmol L^{-1} are already toxic to this crop (Van den Bos, 1991).
De Kreij and Van den Berg (1990) found in a rockwool grown rose crop a threshold value of 2.4 dS m^{-1} and a SYD value of 6.9%. In another experiment (De Kreij and Van den Berg, 1987) they

found no difference in yield between EC values in the root environment of 2.5 and 4.2 dS m^{-1}. From the data of Feigin et al. (1989), who investigated the effect of Cl, a threshold value was calculated of about 1.0 dS m^{-1} and a SYD value of 3.3%. Zeroni and Gale (1989) conducted an experiment with roses in volcanic cinder, from which data a threshold value of about 1.0 and a SYD value of about 10% was calculated at ambient carbon dioxide (CO_2) level. At higher CO_2 levels both a higher salinity threshold and SYD value was obtained. The results of pot experiments by Ishida et al. (1979b) with rose crops grown in soil, do not allow calculation of a threshold value. Calculation of SYD values is possible on basis of the data given for the 1:5 w/w soil-water extraction. These data were converted to soil solution following the procedure of Van den Ende (1989). In this way for the cuttings and the grafted material included in the experiments, SYD values of 3.6 and 10.3% were found, respectively. The data of Ploegman (1973) with a soil grown crop in pots were also not suitable for calculation of a threshold value. The SYD value calculated for the soil solution was 6.2%. Hughes and Hanan (1978) mentioned a threshold value of 1.8 in experiments with roses grown in gravel. From the data of Yaron et al. (1969) with a soil grown crop a threshold value of 2.9 and a SYD value of 14.1% was calculated. From the data of field grown experiments of Bernstein et al. (1972) a SYD value for the soil solution of 20% was calculated.

For aster and bouvardia no relevant literature about salinity has been found. For lily only data of a field grown crop for bulb production are available (Ploegman and Boontjes, 1981). These data show that irrigation with saline irrigation water especially affected the main bulb production. A threshold value of about 1.0 was given and a SYD value of 3.2%.

It is not clear what effect was responsible for the huge growth reduction in bouvardia by the Na addition at the standard EC value (Treatment 2.0/10Na). The Na concentrations in the plant tissues increased by the addition of Na and extra addition of nutrients reduced the uptake of Na to the original value (Table 3.4). So the Na concentrations of the tissues were in a way in agreement with the effects on the growth. However, the concentrations of nutrients were also affected by the Na addition (Table 3.5). The total N concentration of the tissue of Treatment 2.0/10Na is 22% lower than that of the control Treatment (2.0/0). This difference can be explained for 70% by the difference between the nitrate (NO_3) concentrations. The absorption of the other nutrients was reduced by 30 - 40% in Treatment 2.0/10Na. This reduction was more or less completely compensated by the higher addition of nutrient elements in Treatment 3.0/10Na. Thus the concentrations of nutrient elements interacted with the Na concentrations in the tissue. However, it is clear that a combination of high Na and low nutrient cation concentrations in the root environment is highly detrimental to bouvardia.

The uptake of Na and Cl per litre of water absorbed by the crops increased with increasing Na and Cl concentrations in the root environment (Table 3.8). Relationships were calculated between the Na and Cl concentration in the root environment and the uptake concentration of Na and Cl. Linear relationships calculated did not always fit well, therefore also exponential relationships of the model $y = a\ x^b$ were calculated. The results of these calculations are summarized in Table 3.10. For the uptake of Na by rose no relationships were calculated, for the uptake concentration was more or less zero over the whole range of Na concentrations. For Cl for gerbera, bouvardia and lily crops the correlation coefficients for the exponential functions are significantly higher than those for the linear functions. This indicates that the relationships for Cl are stronger curvilinear than those for Na, which is in agreement with the exponents found in the exponential functions for Cl, generally being lower than those for Na.

The salinity threshold values found in these experiments indicate that EC values of solutions in the root environment higher than 2.0 dS m^{-1} soon cause growth reduction for all tested flower crops. The high threshold value found for aster concerns the first flush of flowers only, because high NaCl concentrations caused problems with the regrowth. Threshold values derived from literature are also mostly below 3.0 dS m^{-1} with only a few exceptions. This means EC values in the solution in the root environment should not exceed a value of 2.5-3.0 dS m^{-1} in order to prevent strong growth reductions. Taking into account that for the supply of nutrients to the crop an EC value of 1.5 dS m^{-1} is necessary, the room for salt accumulation in the root environment is 1.0-1.5 dS m^{-1}, i.e. equivalent to 8-12 mmol NaCl L^{-1}. With this NaCl concentration of about 10 mmol L^{-1} in the root environment flower crops studied absorbed quantities of Na between 0.0 -1.2 mmol L^{-1} and Cl concentrations of 0.2 - 2.1 mmol per litre water absorbed. The maximum acceptable concentrations for irrigation water suitable for flower crop production in closed substrate systems should thus not exceed these values. However, in many cases water with higher Na or Cl concentrations will be used and then part of the solution should be drained out. With the data presented in this study, drain fractions can be calculated by the equation given by Sonneveld and Van der Burg (1991).

Table 3.10. Relationships between Na and Cl concentrations realized in the root environment ($c_{ss(Na)}$ and $c_{ss(Cl)}$) expressed as mmol L^{-1}, and Na and Cl uptake ($c_{u(Na)}$ and $c_{u(Cl)}$) expressed as mmol L^{-1} water absorbed by the crop.

Crop	Element	Linear	r	Exponential	r
Gerbera	Na	$c_{u(Na)} = 0.070\ c_{ss(Na)} + 0.09$	0.865	$c_{u(Na)} = 0.103\ c_{ss(Na)}^{0.88}$	0.858
	Cl	$c_{u(Cl)} = 0.122\ c_{ss(Cl)} + 1.16$	0.788	$c_{u(Cl)} = 1.369\ c_{ss(Cl)}^{0.25}$	0.909
Carnation	Na	$c_{u(Na)} = 0.025\ c_{ss(Na)} + 0.06$	0.981	$c_{u(Na)} = 0.038\ c_{ss(Na)}^{0.90}$	0.975
	Cl	$c_{u(Cl)} = 0.025\ c_{ss(Cl)} + 0.42$	0.973	$c_{u(Cl)} = 0.430\ c_{ss(Cl)}^{0.26}$	0.946
Rose	Na	nd*		nd	
	Cl	$c_{u(Cl)} = 0.008\ c_{ss(Cl)} + 0.07$	0.999	$c_{u(Cl)} = 0.056\ c_{ss(Cl)}^{0.46}$	0.979
Aster	Na	$c_{u(Na)} = 0.212\ c_{ss(Na)} - 0.42$	0.960	$c_{u(Na)} = 0.042\ c_{ss(Na)}^{1.54}$	0.982
	Cl	$c_{u(Cl)} = 0.235\ c_{ss(Cl)} - 0.20$	0.981	$c_{u(Cl)} = 0.123\ c_{ss(Cl)}^{1.22}$	0.986
Bouvardia 1	Na	$c_{u(Na)} = 0.008\ c_{ss(Na)} + 0.03$	0.923	$c_{u(Na)} = 0.026\ c_{ss(Na)}^{0.64}$	0.947
	Cl	$c_{u(Cl)} = 0.015\ c_{ss(Cl)} + 0.13$	0.888	$c_{u(Cl)} = 0.111\ c_{ss(Cl)}^{0.43}$	0.945
Lily	Na	$c_{u(Na)} = 0.089\ c_{ss(Na)} + 0.12$	0.995	$c_{u(Na)} = 0.175\ c_{ss(Na)}^{0.76}$	0.996
	Cl	$c_{u(Cl)} = 0.037\ c_{ss(Cl)} + 0.50$	0.849	$c_{u(Cl)} = 0.543\ c_{ss(Cl)}^{0.20}$	0.977

* not determined, because uptake concentrations were close to zero.

High absorption rates of Na and Cl by crops seem to be an advantage, as it counteracts accumulation of these elements in the root environment. The results obtained in this study, however, suggest that such high absorption rates are not always really an advantage, This is clear from the high adsorption of Na and Cl by the aster crop; the poor regrowth of this crop after the first harvest is possibly linked with it.

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4. Response of tomatoes *(Lycopersicon esculentum)* to an unequal distribution of nutrients in the root environment

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Published in: Plant and Soil 124, 251-256

Key words: electrical conductivity, fruit quality, *Lycopersicon esculentum* Mill., nutrient distribution, split root, substrate sampling, tomato yield, water absorption

Abstract

Tomato *(Lycopersicon esculentum* Mill.) plants were grown in a split root system. The plants were rooted in two separate cubes of rockwool, which were subsequently irrigated with nutrient solution of equal (control) or different EC values. Besides optimal values, too low and too high values for maximal production were included.
The yield was determined by the EC value considered optimal for plant nutrition if present in one of both rockwool cubes. The quality of the fruits was primarily determined by standard EC values available in part of the root environment. Water was preferably taken up from the low EC compartment, nutrients from the high EC compartment. Samples of leaves and fruits were analyzed to get information about uptake and translocation of nutrients in the plant.

4.1 Introduction

In the Dutch greenhouse industry many crops are grown in rockwool slabs. As the nutrient solution is supplied by means of a trickle irrigation system, great differences occur in the nutrient levels from spot to spot. Generally, the concentrations of nutrients at spots between emitters are higher than at spots under emitters, just like in soils (Bernstein and Francois, 1975; Hoffman, 1986; Oster *et al.,* 1984).
When a sample of solution is gathered for analysis, the question arises how the effect of this heterogeneity in nutrient concentration in the root environment must be interpreted in terms of yield and fruit quality. In two experiments, effects of an unequal distribution of nutrients in rockwool slabs were studied. The test crop was tomato. Besides, the effects on yield, effects on fruit quality and on uptake of water and nutrients were investigated.

4.2 Methods and materials

Experiments

In the experiments each tomato plant was grown in two rockwool cubes with length, width and height of 0.15, 0.10 and 0.10 m, respectively. The two cubes were separated by placement in different gullies as shown in Figure 4.1. Each cube was provided with a dripper so that it was possible to realize different nutrient levels in the cubes. The nutrient solutions were recirculated. The quantity of nutrient solution supplied was 20 L per m^{-2} greenhouse area per day. In the first experiment it was found that transport of nutrient solution from one to the other growing cube was possible, through the propagating cube. So, in the second experiment the propagating cubes were placed on small polystyrene strips, to prevent such transport.

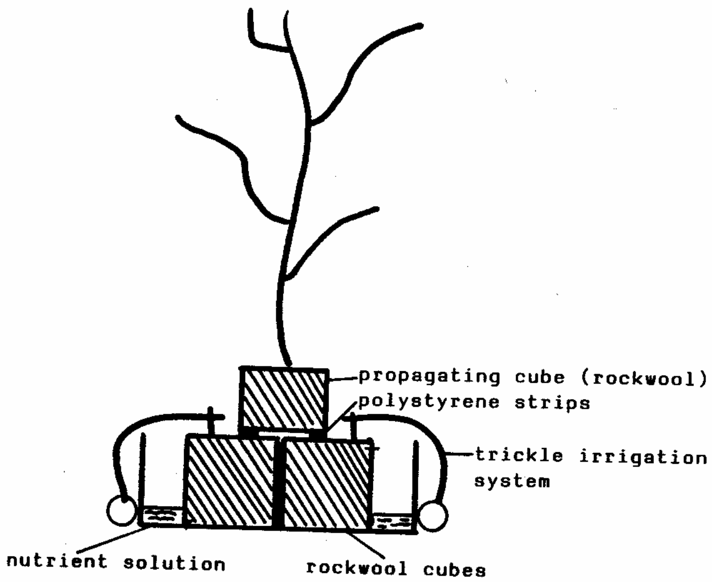

Fig 4.1. The growing system used

The tomato crops were grown from January till August. For some time after planting out, all cubes were supplied with the same nutrient solution having an EC value of 2.5-3.0 $dS.m^{-1}$ (25°C). Thus each plant was enabled to develop equal root parts in the two cubes. The treatments were set up in the beginning of March.
In both experiments five treatments were laid out in four parallels in a youden scheme. The EC values maintained in the pairs of rockwool cubes were as follows.

Experiment 1: 0.75/0.75, 2.5/2.5, 5.0/5.0, 0.75/2.5 and 2.5/5.0 $dS.m^{-1}$ (25°C).
Experiment 2: 0.75/3.0, 3.0/3.0, 5.0/3.0, 7.5/ 3.0 and 10.0/3.0 $dS.m^{-1}$ (25°C).

In experiment 1, the round Dutch tomato cultivar Counter was grown and in experiment 2 the beefsteak type cultivar Dombito. The experiments were carried out in a greenhouse in which as setpoint for heating 15°C was maintained during night and 19°C during day. The ventilation temperature was 24°C.

Nutrient solution

At an EC value of 3.0 in the recirculation basin, the nutrient solution contained following ions in mmol. L^{-1} NO_3 17, H_2PO_4 1, SO_4 5, K 7, Ca 7, Mg 3.5, which values are operative for tomato growing in rockwool (Sonneveld and De Kreij, 1987). The different EC values were realized through proportionally higher or lower concentrations of nutrient elements. Measurements of EC values in the rockwool cubes showed no differences with the values in the recirculation basins, which is understandable in view of the ample supply of nutrient solution.
Micro elements were added proportionally to the macro elements. At an EC value of 3.0 following concentrations in μmol. L^{-1} were pursued: Fe 15, Mn 7, Zn 7, B 50, Cu 0.7, Mo 0.5. The pH was roughly controlled by additions of NH_4NO_3 and adjusted by additions of HNO_3 or a mixture of KOH and $Ca(OH)_2$ (mol ratio 2:1). On average NH_4 was added in a ratio to NO_3 of 1:7.
The water used in the experiment was rainwater or demineralized water, with an EC value of about 0.3 $dS.m^{-1}$ and a concentration of sodium chloride of 0.5 mmol L^{-1}.

Absorption of water and nutrients

In the second experiment the uptake of water and nutrients was determined over the period March-July. The composition of the recirculating nutrient solution was checked frequently and kept constant by addition of fertilizers and water. The absorption of water and nutrients was calculated from the quantities of water and nutrients needed to keep volume and ionic composition constant. The nutrients present in the raw water were taken into account.

Tissue analysis

The nutrient status of the tomato plants was checked by analysing samples of laminae and fruits. The samples were gathered in the second part of the growing period, thus at a moment that the plants had grown for a rather long period under treatment conditions. The samples were rinsed in a detergent solution, dried, ground and analysed. The analytical methods used are described by De Bes (1986).

Crop observations

At harvest, the number and weight of fruits were determined. Fruit colouring was expressed in terms of number of days elapsing between picking and reaching colouring stage 100% orange. Shelf life was expressed as the number of days between 100% orange and fruit softening. In the fruit sap, EC value, acid content and refraction were measured and expressed as $dS.m^{-1}$ (25°C), mmol. L^{-1} and percentages Brix, respectively. Russetting, gold specks and irregular colouring were judged visually. The index used for russetting and gold specks ranged from 0, unaffected, till 3, heavily affected fruits. Irregularly coloured fruits, being the fruits with insufficiently regular colouring at picking stage for first class quality, were expressed as percentages.

4.3 Results

Fruit yields of both experiments are listed in Table 4.1. In experiment 1, yield was highest for plants grown, completely or partly, at an EC value of 2.5 in the root environment. At a value of 0.75, yield was not significantly reduced by the low nutrient status in the root environment, but at a value of 5.0 yield was substantially reduced by the low osmotic potential. In experiment 2, no significant differences between yields were found. Fruit weights tended to be highest where EC values in the root environment were completely or partly low.
The data of fruit quality characteristics are summarized in Table 4.2. For treatments in which an equal EC value was maintained in the root environment, quality was improved by increasing EC values, for such an increase shortened the colouring period, extended shelf life, increased EC values, acid content and refraction of the fruit sap and decreased the indexes for russetting (not significant) gold specks and the percentage irregularly coloured fruits. With different EC values in the root environment, in experiment 1 the quality characteristics tended to adjust to the standard EC value of 2.5. In experiment 2, the EC value of 0.75, supplied in part of the root environment, tended to affect fruit quality negatively.

Table 4.1. Yield and fruit weight of tomato in both experiments

Experiment 1			Experiment 2		
EC value	Yield ($kg\ m^{-2}$)	Fruit weight (g)	EC value	Yield ($kg.m^{-2}$)	Fruit weight (g)
0.75/0.75	22.7	82	0.75/3.0	23.8	188
2.5 /2.5	24.0	77	3.0 /3.0	24.0	180
5.0 /5.0	21.1	71	5.0 /3.0	25.1	177
0.75/2.5	24.2	83	7.5 /3.0	24.6	178
5.0 /2.5	23.7	80	10.0 /3.0	23.6	173
LSD 0.05	2.4	ns	LSD 0.05	ns	ns

Analytical data of tissue samples gathered in experiment 1, are listed in Tables 4.3 and 4.4. With equal EC values in the root environment, the Na, Ca, Mg and Cl contents of leaves were higher at EC = 0.75 than at EC = 2.5. The P and K contents on the contrary were lower. At EC = 5.0, especially Ca content was low. As to fruits, a high Na content and a low P content were found at the low EC value and a low Ca content at the high EC value.
In the treatments in which a low or a high EC value was maintained in part of the root environment, element contents in laminae and fruits tended to adjust to those at the standard EC value. In experiment 2, high P contents were found in plant tissues of the treatments with high EC values (5-10) in part of the root environment. In comparison with the other two treatments, the tissue contents were on average 27% higher. As to the other elements, plant tissue contents did not show real differences between treatments.

Table 4.2. The effect of variation in EC values in the root environment on quality of tomato fruits

Characteristics	EC values					LSD
	0.75/0.75	2.5/2.5	5.0/5.0	0.75/2.5	2.5/5.0	0.05
Experiment 1						
Colouring in days	4.3	3.9	3.4	4.0	3.6	0.3
Shelf life in days	6.2	6.6	9.1	7.0	7.4	1.4
EC fruit sap, $dS.m^{-1}$	4.5	5.1	5.5	5.0	5.1	0.2
Acids in fruit sap, $mmol.L^{-1}$	5.9	6.6	7.6	6.4	6.8	0.3
Refraction fruit sap, %Brix	4.1	4.1	4.6	4.1	4.2	0.1
Russetting index	0.44	0.43	0.28	0.43	0.42	ns
Gold specks index	1.82	2.27	1.17	2.36	2.34	0.63
Irregular colouring, %	21	17	2	10	11	14
	EC values					LSD
	0.75/3.0	3.0/3.0	5.0/3.0	7.5/3.0	10.0/3.0	0.05
Experiment 2						
Colouring in days	3.3	2.9	2.9	2.8	2.9	0.4
Shelf life in days	4.1	5.1	5.5	5.5	5.4	1.3
Russetting index	1.30	1.21	1.20	1.28	1.25	ns
Gold specks index	1.24	0.84	0.96	0.95	0.85	0.29
Irregular colouring, %	42	12	9	12	14	ns

Table 4.3. Analytical data of laminae of young leaves of tomato grown in experiment 1. Element contents are expressed as $mmol.kg^{-1}$ dry matter and dry matter content as % of fresh material

Elements	EC values				
	0.75/0.75	2.5/2.5	5.0./5.0	2.5/0.75	2.5/5.0
Na	193	58	39	73	55
K	658	953	1080	888	972
Ca	858	794	587	698	748
Mg	274	161	160	184	156
C1	66	32	57	47	31
N	3340	3476	3738	3561	3545
P	137	192	210	190	191
S	483	473	423	442	440
Dry matter	11.0	10.4	10.8	10.8	11.0

Table 4.4. Analytical data of tomato fruits grown in experiment 1. Element contents expressed as mmol. kg^{-1} dry matter and dry matter content as % of fresh material

Elements	EC values				
	0.75/0.75	2.5/2.5	5.0/5.0	2.5/0.75	2.5/5.0
Na	59	20	18	28	21
K	940	1116	1086	1107	1123
Ca	34	36	26	34	32
Mg	65	64	60	66	68
C1	86	60	70	62	60
N	1300	1298	1302	1368	1443
P	128	169	160	170	175
S	56	56	51	54	57
Dry matter	4.4	4.6	5.2	4.6	4.9

The quantitative uptake of water and nutrients in the treatments of experiment 2 is shown in Table 4.5. Water absorption was strongly reduced by EC values above the standard value of 3.0. The uptake of nutrients was mostly highest in root halves with EC values above the standard value. At the low EC value (0.75), nutrient absorption appeared to be very low. For some elements, not any absorption at all was found in that root half. As for calcium, even a negative value was measured.
In both experiments, the root development was judged visually at the end of the growing period. No differences were visible between treatments and between root halves within treatments.

Table 4.5. Absorption of water and nutrients by the different root parts in the treatments of experiment 2. The quantity of water is expressed as L per m^2 greenhouse area per day and the quantity nutrients in mmol per m^2 greenhouse area per day. Mean values over 150 days

Elements	EC values				
	0.75/3.0	3.0/3.0	5.0/3.0	7.5/3.0	10.0/3.0
Water	1.1/ 1.5	1.3/ 1.3	0.5/ 2.1	0.4/2.2	0.2/2.4
NO_3	2 /20	11 /11	8 /14	16 /6	14 /8
P	0.5/ 2.8	1.6/ 1.6	2.4/ 1.8	3.5/0.7	3.7/0.5
K	2 /15	8 / 8	7 /10	13 /4	13 /4
Ca	-0.4/ 5.4	2.5/ 2.5	1.6/ 3.4	4.5/0.5	4.1/0.9
Mg	0.0/ 1.4	0.7/ 0.7	0.2/ 1.2	1.1/0.3	0.6/0.8

4.4 Discussion

Results of both experiments described in this paper showed that tomatoes grown under an unequal distribution of nutrient concentrations in the root environment primarily responded to standard nutrient levels available in part of the root environment. Sometimes effects of the low EC value dominated. This seemed to be the case with the fruit weight. Although no significant differences were found, the fruit weight was highest in the three treatments in which an EC value of 0.75 was present in the root environment (Table 4.1). In experiment 2, this was accompanied by some negative effects on fruit quality. Effects of high EC values did not occur at all where a root half had the disposal of a standard EC value. However, in experiment 2 phosphate absorption was aggravated by a local high EC value. In experiment 1, such an effect on phosphate uptake was not found. This difference might be due to the cultivars grown (Howell and Bernard, 1961; Zijlstra *et al.,* 1987).

Nutrient and water absorption differed strongly between root halves of different EC value. Water was preferably absorbed from spots of low concentration, which is in agreement with results of salinity experiments (Bingham and Garber, 1970; Kirkham *et al.,* 1969; Lunin and Gallatin, 1965). For nutrient uptake the reverse was the case. These findings lead to the conclusion that plants absorb water and nutrients independently, which is in agreement with results of Allerton (1954), who stated that tomatoes make a double root system in his special "container-gravel" culture.

In treatments in which the roots had the disposal of both standard and low concentrations, only a restricted absorption of nitrate, phosphate and potassium and no absorption of calcium and magnesium were realized from the low concentration root part. The negative value found for calcium could indicate transport of calcium from one root to the other. Nutrient transport from one root to the other is possible indeed (De Jager, 1984), but not likely for calcium. So, the negative value for this ionic species is considered as a measuring error. For root halves with high EC values, the quantity of nutrients absorbed per unit water taken up appeared to be very high. So, for the root half grown at an EC value of 10, it was 70, 18, 65, 20 and 3 mmol per litre for nitrate, phosphate, potassium, calcium, and magnesium, respectively.

The tomato yield did not respond to high EC values in 50% of the root environment. This is in agreement with the work of Klapwijk and Wubben (1989), who removed a large part of the roots of a full grown tomato crop on rockwool and could not observe any crop reaction. This points to an overcapacity of root activity, making the plant less sensitive to stress situations in part of the root system.

Returning to the question posed in the introduction, on which spot a sample of solution must be gathered, the information presented suggests random sampling. This means that a sample should be composed of solution gathered from sufficient different spots selected at random, for a sample gathered in this way best reflects the quantity of nutrients available in the rockwool slabs. Avoidance of high concentrated spots between emitters seems to be incorrect, for such spots probably play an important role in nutrient absorption. With respect to fruit quality low concentrations have to be avoided in the nutrient solution supplied via the emitters, thus preventing spots of low EC values, which may adversely affect fruit quality.

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5. Response of cucumber (*Cucumis sativus L.*) to an unequal distribution of salts in the root environment

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Published in: Plant and Soil 209, 47 - 56

Key words: Cucumus sativus L., electrical conductivity, nutrient distribution, nutrient uptake, split root, substrate sampling, water absorption

Abstract

Plant response to salinity as affected by an unequal distribution of salts in the root environment was studied with cucumber (*Cucumis sativus L.*) as a test crop. In a series of six experiments use was made of a split root system, in which the plants were grown in separated rockwool strips irrigated with nutrient solutions with equal or different EC values, predetermined by different concentrations of either nutrients or NaCl.
From low to standard EC values the uptake of nutrients was highest in the root parts with the highest concentration of nutrients. In root parts with concentrations of nutrients >4 dS m^{-1}, the uptake decreased rather quickly. Nutrient uptake from one root part with high NaCl concentrations was also retarded, if the NaCl concentration supplied to the other root part was low. If both root parts were supplied with high NaCl concentrations, the plant was able to adjust and absorbed adequate amounts of nutrients, despite the high NaCl concentrations.
Water was preferably absorbed from the root part with the lowest EC. However, if no nutrients were supplied in one of the root parts the water uptake from that root part was retarded. Effects of high NaCl concentrations in specifically retarding the water uptake were not established from the data of the experiments.
The results are discussed in relation to existing models predicting effects of spatial variation of salinity in the root environment under growing conditions in the glasshouse industry and in relation to the experiences previously gained with tomato.

5.1 Introduction

Plant response to salt stress can differ greatly depending on factors which affect growth. One of these factors is the distribution of salts in the root environment and to this respect different models have been developed and tested to estimate effects of salinity in relation to spatial variations of salts (Meiri, 1984). In the glasshouse industry many crops are grown in substrates, of which rockwool slabs have an important place. Salinity in such growing system is often accompanied by high concentrations of nutrients in the root environment. Salts and nutrients are supplied with the irrigation water by trickle irrigation systems. This method of water supply can easily lead to an uneven distribution of salts and nutrients in the root environment in soil grown crops (Bernstein and Francois, 1975; Hoffman, 1986; Oster et al., 1984) as well as in rockwool grown crops (Van Noordwijk and Raats, 1980), the latter substrate growing system often being used in the North-West European glasshouse industry for the production of many crops, where trickle irrigation is the solely used irrigation system. The large spatial differences in concentrations of salts and nutrients in the root environment of such growing systems raise questions of where sampling should take place and the interpretation of analytical data of routine tests of the nutrient solution in the root environment.

In previous experiments Sonneveld and Voogt (1990) studied the response of tomatoes to a varied nutrient distribution in the root environment. In relation to yield and fruit quality, tomato seems to be very resistant to huge local differences in the concentrations of nutrients and even EC values up to 10 dS m^{-1} in one part of the root environment there was no clear negative effect on crop development. It is well known, however, that tomato is salinity-resistant, so that we wished to test the view that the ability to tolerate local variations in salt concentration in the root environment is related to the overall salt tolerance. For this purpose cucumber was chosen, since it is more salt sensitive and root development is different, both new growth and dying off of roots being more rapid than in tomato. Additionally, in the previous study the experiments were carried out solely with nutrients in the root environment and only under spring-summer growing conditions, whereas in the present study attention is also paid to the effects of NaCl in the root environment and summer-autumn growing conditions. In this way the experiences previously gained with tomato and in the present study with cucumber can be used as basis for broader interpretations. The present study with cucumber thus focused on:

- the reaction of a cucumber crop to an unequal distribution of nutrients in the root environment and the results obtained compared with those gained with tomato.
- effects of NaCl on the uptake of water and nutrients in relation to an unequal distribution of salts in the root environment.
- effects of growing conditions. Cucumbers in the experiments were grown in spring-summer as well as in summer-autumn, to test for any effects of the growing conditions in relation to the unequal distribution of salts.

5.2 Methods and Materials

Experiments

In the experiments each cucumber (*Cucumis sativus L.*) plant was grown in two rockwool strips of 75 mm width and 75 mm height in two experiments (1 and 2) and in strips of 100 mm width and of 75 mm height in four experiments (3-6).The two strips were separated by placement in different gullies. They were provided with separated drip systems so that it was possible to obtain different nutrient and NaCl concentrations in the strips. The nutrient solutions in the system were recirculated and the quantities of nutrient solution supplied were about ten times the water use of the crop to ensure an equal distribution of NaCl and nutrients within the strips. The cucumber plants were raised in rockwool cubes and, when spaced out in the experimental glasshouse, were placed in such a way that rooting in both separated rockwool strips was possible. The propagating cubes were placed on small polystyrene or polyethylene strips laid on the rockwool strips to prevent water transport through the cubes from one rockwool strip to the other. A scheme of the experimental equipment is shown in Figure 5.1.

The cucumber crops were grown in different seasons of the year, common for cucumber production the Netherlands. Cultivars used and length of the growing period were tuned to those customary with Dutch growers (Table 5.1). After planting, all strips in the experiments were supplied with the same nutrient solution with an EC-value of about 2.5 dS m^{-1} (25^0 C). In this way plants were enabled to develop equal root parts in both strips. Different EC values in the separated rockwool strips were established 2-3 weeks later. The cultivars used, the growing period of the crop and the number of days of experimentation are listed in Table 5.1.

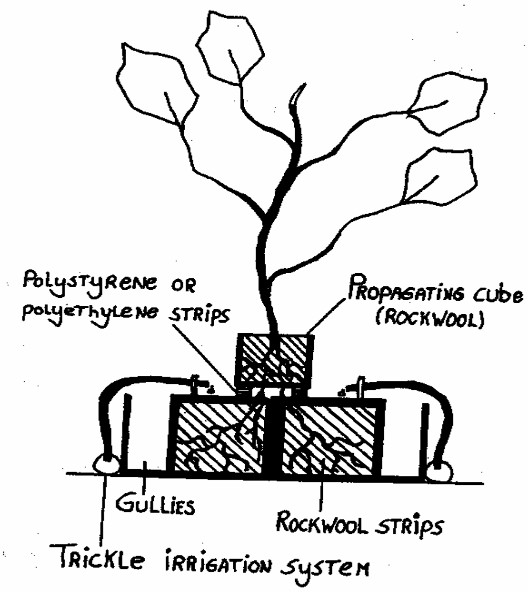

Fig 5.1. **Plant growth system.**

Table 5.1. General data of experiments carried out.

Number of experiment	Cultivar	Growing period	Number of days of experimentation
1	Ventura	Apr-Aug 1992	92
2	Aramon	Mar-Jun 1993	64
3	Tyria	Sep-Dec 1993	45
4	Aramon	Jun-Sep 1994	86
5	Aramon	Feb-Jun 1995	74
6	Cum Laude	Jul-Aug 1995	24

Six experiments were carried out in which the treatments were laid out with six replicates in a randomized block. The replicates of the treatments were connected to one circulation tank. A description of the experiments following the aims stated in the Introduction are given below:

Experiment 1. Comparison of equal and different concentrations of nutrients, i.e. EC values, in the pairs of rockwool strips.

Experiments 2 and 3. Comparison of a series of increasing EC values in one rockwool strip while in the other strip all treatments had a standard EC value. The crop in experiment 2 was grown in spring-summer and that in experiment 3 in autumn.

Experiment 4. Different combinations of high and low EC values were chosen in such a way that three treatments had an average EC value of 2 and another three an average value of 5 dS m^{-1} in the root environment.

Experiments 5 and 6. The effects of different high EC values realized either with nutrients or NaCl.
The EC values in the separated rockwool strips of a treatment are referred to as EC_x /EC_y, which means the maintainance of an EC in one rockwool strip of EC_x and in the other strip an EC of EC_y. In Table 5.2 a review is given of the EC values aimed at, following the design of the different experiments. In the tables with the experimental data the average EC values are given as calculated from weekly measurements in the recirculating solution during the experimental period.
The experiments were carried out in a glasshouse in which a heating set point of 22/20 ^{0}C day/night was maintained and a ventilation set point of 23/22 ^{0}C day/night

Table 5.2. Target EC values (dS m^{-1}) in the treatments of the different experiments. The values are given as EC_x /EC_y, which denote the values in both root parts. For EC values realized see Table 5.3.

Experiments					
1	2	3	4	5	6
0.75/0.75	2/0	2/0	0/4	1.5/1.5	2/2
3/3	2/1	2/1	2/2	1.5/4.5	2/2+1Na*
6/6	2/2	2/2	1/3	1.5/1.5+3Na*	2/2+2Na*
0.75/3	2/4	2/4	2/8	4.5/4.5	2/4
0.75/6	2/6	2/6	3.5/6.5	1.5/7.5	4/4
3/6	2/8	2/8	5/5	1.5/1.5+6Na*	2+2Na*/2+2Na*

* The EC value realized by addition of NaCl.

Nutrient solution

The nutrients were added to the recirculation tank in ratios in accordance with those recommended for cucumber growing in rockwool (Sonneveld and Straver, 1992). At an EC value of 1.7 the concentrations of major elements in the nutrient solution added were in mmol L^{-1} : NO_3 12, SO_4 1, H_2PO_4 1, K 6.5, Ca 2.75 and Mg 1. In treatments in which the different EC values were realized by different levels of nutrients, proportionally higher or lower concentrations of nutrients were added. In treatments in which the EC values were partly increased by NaCl, 8.5 mmol L^{-1} of this salt was given for an increase of 1 dS m^{-1}. During the growing period the recirculating nutrient solutions were sampled and analysed weekly. The analytical data were compared with the standards set up for cucumber (IKC, 1994) and if necessary the addition of the nutrients was adjusted to prevent undesirable high or low concentrations.
Si and micronutrients were added in all treatments in equal concentrations. For Si 0.75 mmol L^{-1} was applied and for micronutrients the following concentrations in µmol L^{-1} were added to the water: Fe 15, Mn 10, Zn 5, B 25 Cu 0.75 and Mo 0.5.
The pH was roughly controlled by additions of NH_4NO_3 and further adjusted by addition of HNO_3.
The water used in the experiments was rainwater or demineralized water. The average EC value was 0.3 dS m^{-1} and the NaCl concentration about 0.5 mmol L^{-1}. The quantity of nutrient solution available in both parts of the rockwool strips was 4 to 5 L m^{-2}, while a storage of about 3 L m^{-2} was available in the recirculation tank. Therefore, the total quantity of nutrient solution in the recirculation system was 7-8 L m^{-2} together on both sides of the plants. The plant density was 1.5 m^{-2}.

Absorption of water and nutrients

The absorption of water and nutrients in the experiments was determined over the periods that the target EC values in the treatments were obtained. This was done by calculations according to the following formula:

$$U = (a + b - c) / \Delta t \qquad (5.1)$$

in which is

- U - average uptake rate (L m^{-2} day^{-1}) of water or nutrients (mmol m^{-2} day^{-1})
- Δt - number of days from beginning till the end of the experimental period
- a - the quantity of water or nutrient element in the root environment at the start of the experimental period
- b - the quantity of water or nutrient added during the experimental period
- c - the quantity of water or nutrient available in the root environment at the end of the experimental period

Crop observations

Fruits were harvested three times a week. The number and weight of fruits and the number of misshapen fruits were determined. In the fifth experiment the shelf life of the fruits was determined, as the number of days between harvest and colour stage 5 (Janse and Welles, 1984).
In experiments 5 and 6 the crop growth of some treatments was affected by *Pythium*. This happened shortly after planting out in the greenhouse and the affected plants were replaced by new ones. This, however, clearly affected the yield, but not the ratios between the water uptake in the different root parts during the experimental period. The amount of water absorbed of the affected treatments are given but not the yields.

Statistical analysis

Yield data were statistically analysed by analysis of variance. Such was not possible for the data of water and nutrient uptake, because the replicates of the treatments were connected to one recirculation tank. So, these data were verified by weekly calculations of balances of water and nutrient uptake.

5.3 Results

EC values

The EC values as realized in the recirculating nutrient solution of the different experiments are shown in Table 5.3. Comparison of the EC values in Table 5.3 with those in Table 5.2 shows that generally designed EC values were reasonably realized in the experimental periods. In the root parts in which an EC value of 0 was aimed at, the values sometimes stayed too high after the start of the experimental period. In these cases the EC value was established mainly by Ca, Mg and SO_4 remaining in the root environment from the starting period. Examples are the treatments 2/0 of experiment 3 and 0/4 of experiment 4. In a few cases one or both EC values turned out too high, as in the treatments 3/6 of experiment 1 and 4/4 of experiment 6.The main reason for these aberrations was the relatively large root volume available in the experiments, which made fine regulation of the EC value difficult. Interpretation of the crop response, however, was carried out on the basis of realized values.

Table 5.3. Yield of cucumbers expressed as kg m^{-2} as affected by an unequal salt distribution (EC value) in the root environment. The EC values are expressed as dS m^{-1} in two root parts. Values in the same column followed by the same letter do not differ significantly at P= 0.05.

Experiment 1		Experiment 2		Experiment 3	
EC	Yield	EC	Yield	EC	Yield
0.9/0.9	30.9 a	2.1/0.2	27.5 ab	2.2/0.8	4.6 a
3.1/3.1	30.0 a	2.0/1.2	28.1 a	2.3/1.4	4.6 a
6.5/5.8	23.5 c	2.0/2.0	26.5 bc	2.4/2.4	4.8 a
1.2/3.1	31.1 a	2.2/4.3	26.3 bc	2.5/4.3	4.7 a
1.1/5.2	32.0 a	1.9/6.2	25.5 cd	2.6/6.2	4.6 a
4.8/6.0	27.2 b	2.2/7.7	24.2 d	2.4/7.8	4.6 a
Experiment 4		Experiment 5		Experiment 6	
EC	Yield	EC	Yield	EC	Yield
1.0/3.1	28.8 a	1.5/1.6	29.8 a	2.4/2.4	7.1 a
2.1/2.1	26.5 ab	1.5/3.9	nd**	2.7/3.3Na*	nd**
1.6/4.0	28.8 a	1.6/4.1Na*	29.5 a	3.0/3.9Na*	nd**
2.1/7.4	24.9 b	4.7/4.7	25.7 c	2.6/4.1	7.6 a
3.6/6.4	24.0 b	1.8/6.8	30.5 a	4.8/5.6	5.9 b
5.1/5.9	18.7 c	1.5/6.8Na*	27.8 b	4.6Na*/5.0Na*	5.3 b

* Means that the EC value is realised partly by addition of NaCl.
**Yield could not be determined, because of root diseases.

Yield

The yields of the cucumbers in the different experiments are given in Table 5.3. In experiment 1 no significant differences were shown between treatments 0.9/0.9 and 3.1/3.1, thus at an EC value of about 1 and 3 in the whole root environment. With an EC value of about 6 in the whole root environment (treatment 6.5/5.8) the yield was 23% lower. The negative effect of such a high EC value disappeared completely if part of the roots was supplied with a low EC value (treatment 1.1/5.2). A somewhat lower EC value than 6 in one part of the root environment, e.g. treatment 4.8/6.0, counteracted the negative effect only partly. This was to be expected, because of the fact that an EC value of 4.8 is above the salinity threshold value, being the maximum allowable EC without yield reduction (Maas and Hoffman, 1977), and it is to be expected that yields will not exceed the highest possible yield at the lowest EC value in part of the root environment.
The yield in experiment 2 showed significant differences only if the EC value in one of the root parts became higher than 6, (treatments 1.9/6.2 and 2.2/7.7). This crop was grown in spring-summer and the same EC values in an autumn crop, experiment 3, did not show any significant difference in yield.
The yield in experiment 4 in the treatments with a low average EC value was not affected by the distribution. In the treatments with a high average EC value, yield was clearly affected by the distribution. A partly low and a partly high value was less detrimental than a moderate value of about 5.5 in both parts; compare for example the yields of the treatments 5.1/5.9 and 3.6/6.4.

The missing value of the yield treatment 1.5/3.9 in experiment 5 is not a big handicap, for the yields of the treatments 1.5/1.6 and 1.6/4.1Na were the same. This means that in the lower EC range the yield was not negatively affected if a high NaCl concentration occurred in a part of the root environment, as was the case in the very high range of NaCl supply. The yield of treatment 1.5/6.8Na was lower than those of treatment 1.8/6.8. Such a NaCl effect was also found in experiment 6, in which the yield of treatment 4.6Na/5.0Na showed a tendency to be lower than that of treatment 4.8/5.6. This effect, however, was not significant. In the low range of this experiment no conclusions are possible, because of the missing data
The data on the number of fruits and the number of misshapen fruits did not provide additional information about the effects of both types of salinity and are not given in this paper. The shelf life was determined twice in experiment 5 and was longest for treatment 4.7/4.7 in both cases. The differences, however, were not significant.

Water absorption

The water absorption as found in the different root parts is listed in Table 5.4. The total water uptake in the different treatments in the same experiment was mostly equal, independent of the distribution of the EC in the root environment. Only in those cases where yield was reduced strongly, was the average total water absorption per day lower. In cases where the crop was affected by *Pythium,* water absorption was also lower.
The data show that the water absorption between root parts may differ strongly, if there are differences in EC value. Generally, the uptake was highest in the root part with the lowest EC value. There was only one exception, viz. in experiment 2. The water uptake in the root parts of treatment 2.1/0.2 of this experiment was lowest in the root part with the EC value of 0.2. With such a low EC value roots may become deficient in certain nutrient elements, for the redistribution of many nutrients from one root to another is poor (De Jager, 1984). Water absorption may then be restricted by a deficiency of essential elements. It is striking that in the high range of EC values with relatively small differences between the EC values of the different root parts, big differences in the water absorption occurred. See for example the water absorption in the root parts of treatments 6.5/5.8 of experiment 1 and 5.1/5.9 in experiment 4. In the lower range of EC values the differences were often less pronounced.

Nutrient uptake

The uptake of nutrients by the different root parts showed more or less the same pattern in the different experiments. From low to standard EC values, 2-3 dS m^{-1}, in root parts there was an increase in the quantities of nutrients absorbed by the crop from such root parts, if the concentration in the other root part was rather low. With higher values, however, the quantities of nutrients absorbed from those root parts decreased strongly if there was a root part with a low EC value available. The effects are discussed with the aid of the data gathered in experiment 2, as listed in Table 5.5.

Table 5.4. Water uptake of cucumbers expressed as L m^{-2} day^{-1}, as affected by an unequal salt distribution (EC-value) in the root environment expressed as dS m^{-1} in two root parts.

Experiment 1		Experiment 2		Experiment 3	
EC	Water	EC	Water	EC	Water
0.9/0.9	1.9/2.1	2.1/0.2	2.6/1.7	2.2/0.8	0.5/0.7

3.1/3.1	2.0/2.1	2.0/1.2	1.7/2.8	2.3/1.4	0.4/0.7
6.5/5.8	1.0/2.3	2.0/2.0	2.1/2.0	2.4/2.4	0.6/0.5
1.2/3.1	2.2/1.8	2.2/4.3	3.4/0.6	2.5/4.3	1.0/0.2
1.1/5.2	3.4/0.9	1.9/6.2	3.6/0.3	2.6/6.2	0.9/0.1
4.8/6.0	2.0/1.6	2.2/7.7	3.6/0.2	2.4/7.8	0.9/0.1
Experiment 4		Experiment 5		Experiment 6	
EC	Water	EC	Water	EC	Water
1.0/3.1	2.9/1.0	1.5/1.6	1.7/1.8	2.4/2.4	2.1/2.0
2.1/2.1	2.1/1.9	1.5/3.9	2.2/0.9	2.7/3.3Na*	1.5/1.0
1.6/4.0	2.3/1.6	1.6/4.1Na*	3.2/0.3	3.0/3.9Na*	1.2/0.8
2.1/7.4	3.6/0.4	4.7/4.7	1.5/1.7	2.6/4.1	2.7/1.2
3.6/6.4	2.7/1.0	1.8/6.8	3.4/0.3	4.8/5.6	2.0/1.2
5.1/5.9	1.8/1.0	1.5/6.8Na*	3.0/0.2	4.6Na*/5.0Na*	1.4/1.3

* Means that the EC value is realised partly by addition of NaCl.

Table 5.5. Uptake of nutrients by cucumbers as affected by an unequal distribution of nutrients in the root environment in experiment 2. Quantities are expressed as mmol m^{-2} day^{-1}, over a period of 64 days from April 21 - June 24.

EC-values	NH_4	K	Ca	Mg	NO_3	SO_4	P
2.1/0.2	5.5/1.6	20.3/0.0	7.2/0.0	2.5/0.0	35.3/1.4	2.2/0.0	2.5/-0.2
2.0/1.2	3.8/3.6	11.2/8.6	3.8/3.1	1.2/1.1	19.8/16.1	1.2/1.1	1.4/1.1
2.0/2.0	3.0/3.1	9.5/9.5	3.4/3.1	1.1/1.1	17.0/16.9	1.1/1.1	1.2/1.1
2.2/4.3	4.7/1.4	16.7/4.2	6.1/-0.9	2.0/0.2	29.2/6.4	2.0/0.2	2.0/0.6
1.9/6.2	5.8/0.8	17.0/2.3	6.2/-0.6	2.2/0.0	31.2/0.9	2.0/-0.2	2.0/0.5
2.2/7.7	5.9/0.6	19.7/-1.1	7.2/-1.9	2.3/-0.5	33.4/-3.8	2.3/-0.3	2.5/0.0

The data show that the differences between the total uptake of nutrients of the treatments are more or less negligible. The absorption over the treatments on average was in mmol m^{-2} day^{-1}: NH_4 6.6, K 19.6, Ca 6.1, Mg 2.2, NO_3 34.0, SO_4 2.2, P 2.4. However, for all nutrients except P there was a tendency to a somewhat lower uptake in the treatments with a high EC value in one of the root parts. This can be explained by a reduction of the yield and other non harvestable plant parts in these treatments. For Mg, NO_3 and SO_4 the decrease was relatively of the same order of magnitude as the yield reduction. For Ca the reduction in uptake was relatively bigger than the yield reduction and that for K relatively smaller. These latter effects may be explained by the fact that with proportionally increasing concentrations of nutrients many crops absorb relatively more K than Ca (Bakker and Sonneveld, 1988; Charbonneau et al., 1988; Sonneveld and Welles, 1988; Sonneveld and Voogt, 1993). The relatively high absorption of P in the treatments with a high EC value in one of the root parts should be considered as luxury absorption, which easily occurs with this element (Asher and Loneragan, 1967; Zijlstra et al., 1987).
Highest nutrient absorptions per root part were found under conditions where the other root part was not supplied with nutrients or where the uptake in the other root part was depressed because of a high EC value. In the root part with the high concentration of treatment 2.2/7.7 a “negative absorption” was found for most of the nutrients, indicative of nutrient exudation. It is striking that this exudation was relatively highest for Ca, the value representing about one third of the total

taken up. For Ca, exudation was also found in root parts of treatments with lower EC values than 7.7. It is true that redistribution of nutrients between roots is possible, but Ca is not easily redistributed within plants and so it is not so likely that Ca is first to be exuded (De Jager, 1984). Exudation of Ca has also been measured in a previous experiment with tomatoes (Sonneveld and Voogt 1990), but in this case it was found in root parts with a low EC value. Measurements of NH_4 absorption in the root parts could not be done in relation to the EC value, for NH_4 was used to adjust the pH, so that NH_4 was added to the different root halves in relation to the pH changes measured. It is clear from the data that the pH changes induced by the ion uptake of the crop in the different root halves were more or less parallel with the nutrient uptake in that part. High NaCl in root parts can block the uptake of nutrients completely. This is shown by the data of experiment 5, listed in Table 5.6. The relatively small uptakes of the nutrients from the high EC root part of treatment 1.8/6.8 were completely stopped if the nutrients in the high EC root part (6.8 dS m^{-1}) were partially replaced by NaCl, as in treatment 1.5/6.8Na. Even if the NaCl content was fixed at a lower level, as in treatment 1.6/4.1Na, the absorption of nutrients in the root part with Na was strongly depressed and lower than in the root part with the high EC value of treatment 1.8/6.8.

Table 5.6. Uptake of nutrients by cucumbers as affected by an unequal distribution of nutrients and NaCl in the root environment in experiment 5. Quantities are expressed as mmol m^{-2} day^{-1}, over a period of 74 days from March 24 - June 6.

EC values	NH_4	K	Ca	Mg	NO_3	SO_4	P
1.8/6.8	2.4/0.1	19.1/3.6	7.2/1.5	2.4/0.4	30.8/5.7	2.3/0.1	2.7/0.8
1.5/6.8Na	3.2/0.1	19.2/-0.1	7.0/0.0	2.3/0.1	31.4/0.0	2.3/-0.1	2.7/0.0
1.6/4.1Na	3.8/0.5	18.5/1.4	6.9/0.3	2.3/0.1	30.8/2.0	2.2/0.0	2.6/0.3

5.4 Discussion

Nutrient uptake

Earlier experiments with tomato as test crop showed, that when part of the roots was exposed to total nutrient concentrations up to 10 dS m^{-1} the uptake of nutrients from that part was substantial (Sonneveld and Voogt, 1990). Supplementary experiments showed that the uptake of nutrients was reduced at a local EC value of 12 dS m^{-1} (Sonneveld et al.,1991). The present study with cucumbers confirms the findings with tomato only to a certain extent. From "low" to standard EC values (2-3 dS m^{-1}) an increased uptake of nutrients in the root parts with the highest concentration of nutrients was also found. However, in root parts with somewhat higher concentrations, the absorption of nutrients decreased rather quickly to low values. The decrease of nutrient absorption in root parts with high concentrations thus occurred with cucumber at much lower (>4 dS m^{-1}) concentrations than with tomato (>12 dS m^{-1}). In experiment 2 (Table 5.5) even negative uptakes were measured in root parts with EC values of about 7 dS m^{-1}, possibly indicating exudation of nutrients by the root parts high in nutrient concentrations. It is striking that this "exudation" was relatively highest for Ca, an element with a low mobility in plants. An "exudation" as mentioned here was not measured with comparable EC values in the root environment in experiment 5 (Table 5.6 treatment 1.8/6.8), so, it seems that "exudation" effects will vary depending on growing conditions.

NaCl and nutrient uptake

The data of experiment 5, listed in Table 5.6, show a strong effect of NaCl on nutrient absorption. The uptake of nutrients in the high EC part was stopped if part of the nutrients was replaced by NaCl up to a concentration of about 50 mmol L^{-1}. However, even at a concentration of about 25 mmol L^{-1} (Table 5.6 treatment 1.6/4.1Na), nutrient uptake is mostly prevented and it seems that the presence of NaCl in the root environment is a real hindrance to the uptake of nutrients. On the other hand, the plant apparently was able to adjust for the depressing effect of NaCl on the nutrient uptake if the entire root system was subjected a to high NaCl concentration, as in treatment 4.6Na/5.0Na of experiment 6, where nutrient uptake in both root parts (data not shown in the text) was equal and adequate for normal plant development.

K/Ca change and spatial variation

Cucumber plants were not able to utilize the spatial variation of nutrient concentrations to adjust for the change in uptake between K and Ca which usually occurs with high nutrient concentrations in the root environment. This is remarkable in view of the fact that this plant so easily changed the uptake of water and nutrients between root parts. The phenomenon e.g clearly shown with the data of treatment 2.2/7.7 in Table 5.5, occurred in the first place by the high "exudation" of Ca in the high concentration part and the relatively high uptake of K in the low concentration part.

Water absorption

Water absorption by the cucumber crop was mainly directed by the osmotic potential, EC value, in the root parts. The cucumber plants preferably absorbed the water from the root part with the low EC value, which is in agreement with the findings in comparable experiments with tomato (Sonneveld and Voogt, 1990) and also with the findings in salinity experiments (Bingham and Garber, 1970; Lunin and Gallatin, 1965; Shalhevet and Bernstein, 1968). It is not clear whether water absorption is specifically retarded by the availability of NaCl in part of the root environment. In experiment 5 e.g. the water absorption in the high EC part of treatment 1.6/4.1Na was only 8% of the total water uptake, which is very low in comparison with the absorption of 29% in the root part with the high EC value of treatment 1.5/3.9 of this experiment. This observation lends support to a specific retardation of NaCl to the water absorption. Such a retardation, however, was not found in the difference between the relative water uptake in the highest EC parts of the treatments 1.5/6.8Na and 1.8/6.8 in the same experiment, the values being 6% and 8% respectively. Also the data of experiment 6 did not support specific retardation of NaCl to the water absorption.

Interpretations

Cucumber did not show the very high ratios between the absorption of nutrients and water as was found for tomato in the root part with high EC values in former study (Sonneveld and Voogt 1990). This indicates that the absorption of water and nutrients in root parts with higher EC values is retarded more or less proportionally. Highest ratios between the absorption of water and nutrients with cucumber were noticed in the root half with standard nutrient concentrations in the

absence of nutrient supply in the other root half. In this case the ratios were 7.8, 2.8, 1.0, 13.6, 0.8 and 1.0 mmol L^{-1}, for K, Ca, Mg, NO_3, SO_4, and P, respectively.
The data of the yield in the present paper do not fit well with the models developed for spatial variations in salinity in the root environment (Meiri, 1984). All these models calculate linear functions of the salinity of the soil solution in space and consequently a yield reduction is calculated for any part of the root environment with high EC values. This conflicts with the data in the present paper. For example, the yield of treatment 1.1/5.2 in experiment 1 was not negatively affected by the high EC value of 5.2, while this value is certainly above the salinity threshold value. The shortcoming in the existing models is also clear from the data of experiment 3. The very high values in part of the root environment in some treatments of this experiment did not show any effect on yield.
The data of the present experiments indicate that with variations of salinity in space the salinity threshold value and the salinity yield decrease value (the slope) in the Maas/Hoffman model (Maas and Hoffman, 1977) are changed. The threshold value as well as the slope varies with crops, cultivars and growing conditions, as in the case of crop growth in a uniform saline space (Sonneveld and Van der Burg, 1991). For Dutch summer growing conditions the salinity threshold value for root parts with a high salinity in the case of variations in space should be estimated between 2 and 4 dS m^{-1} as can be concluded from the data of experiment 2. Under Dutch autumn/winter conditions this value is possibly higher than 8 dS m^{-1}, as found in experiment 3. In a former study with an equal salt distribution, values of 2.3 and 3.5 have been found for Dutch summer and winter conditions respectively (Sonneveld and Van der Burg, 1991). The slope calculated for experiment 2 (summer) on basis of the high salinity half of the root environment is about 2% per dS m^{-1}. For experiment 3 (winter) no calculation of the slope is possible. In a former study with an uniform distribution, values for the slope between 5 and 6% per dS m^{-1} have been found for summer and winter growing conditions (Sonneveld and Van der Burg, 1991).
The problems concerning about sampling and interpretation of analytical data of routine testing posed in the introduction, have not been fully resolved by the present study. As with tomatoes (Sonneveld and Voogt, 1990), it is clear that for the uptake of water, spots of low concentration are most important and that spots of high nutrient concentrations are really important with respect to nutrient supply. The presence of NaCl in part of the root environment greatly affects the availability of nutrients in such parts, but the reasons for it are not fully understood in the experiments presented and further study is needed. The same is true for the high “exudation” found. More experiments directed to this subject with more detailed observations are necessary.

The tendency found that the shelf life of cucumber fruits was controlled by spots of low concentration is in agreement with the effects on quality found with tomatoes (Sonneveld and Voogt, 1990). This means that growers using the EC value in the root environment as a tool for adjustment of the fruit quality should pay more attention to the low concentration spots than to the high concentration spots. Thus, for fruit quality the EC value of the drip solution (lowest) is of greater importance than that of the drainage solution (highest).

Acknowledgements

The authors are grateful to ir W. H. K. Post for the careful carrying out of the experiments and to Dr E. A. Kirkby for his constructive remarks and improvement of the English usage.

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6. Yield and quality of rockwool-grown tomatoes as affected by variations in EC-value and climatic conditions

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Published in: Plant and Soil 111, 37-42

Key words: climatic conditions, EC-values, quality, tissue analysis, tomato yield

Abstract

Tomato *(Lycopersicon esculentum)* was grown on rockwool at different EC-regimes. The experiments were carried out under different climatic conditions. The EC-regimes were realized by varying the quantities of nutrient elements supplied. The ratios between the elements were kept constant.
The maximum value of the EC in the root environment at which no yield depression occurred was about 2.5 $dS.m^{-1}$ at 25°C. Higher EC-values decreased the yield with 5 to 7% per $dS.m^{-1}$. However, a decrease of 10% was found in an experiment with a very high humidity level. High EC-values under poor light conditions did not affect yields adversely to any extent. It could therefore be concluded that in calculations of EC-induced yield reductions from data of experiments with varying EC-values, both the lengths of the EC-intervals and the light intensity during the intervals have to be taken into account.
Fruit quality was improved by increased EC-values. Potassium contents in the leaves were increased and calcium and magnesium contents were decreased. The effect on the nitrate and the phosphate contents was different for young and old leaves.

6.1 Introduction

At the Glasshouse Crops Research Station several tomato experiments were carried out in which the effects of different EC-regimes in the root environment were compared. The purpose of these experiments was to investigate effects of variation in EC-values on tomato plants grown in soilless cultures. The advantages of high EC-values are more generative plants with early stages of production especially at low light conditions, and an improved fruit quality later on. A disadvantage of high EC-values is the risk of yield reduction.
It may be assumed that EC-effects interact with climatic effects. Therefore the experiments were carried out largely under varying climatic conditions. A greenhouse with 10 compartments was available for that purpose. The results of seven experiments will be presented in this paper.

6.2 Methods and materials

Experimental design

In a glasshouse with several compartments the effects of variation in EC-regime in the root environment on fruit quantity and quality were studied under different climatic conditions (Experiments 1-4). In the Experiments 5-7 different EC-regimes were compared without variation in climatic conditions. The tomato plants in the Experiments 1-6 were grown on rockwool slabs placed in a gutter in which the nutrient solution circulated. In Experiment 7, however, the plants were grown in a nutrient film system (Graves, 1983). The details of both variables, EC and climatic conditions, were as follows.

Experiment 1. A fall crop was grown under five different climatic conditions, in combination with six different EC-regimes in the root environment. Three EC-regimes were started at a value of about 2.5 $dS.m^{-1}$ (25°C) and in the three other at a value of about 5.0. In two regimes the EC-value was kept constant at values mentioned. In four regimes the value was changed after 60 or 90 days. Values of about 2.5 were increased to about 5.0 and the other way round.

Experiment 2. A spring crop was grown under five different climatic conditions, with five different EC-values, varying between 1.7 and 6.4, during the first five weeks from planting. After five weeks the EC-value was brought to 2.4 for all treatments.

Experiment 3. A spring crop was grown under five different climatic conditions, with two EC-values. An EC-value of 2.6 was compared with a value of 3.5.

Experiment 4. A fall crop was grown under five different climatic conditions with four EC-regimes. In one treatment an EC-value of 2.9 was maintained continuously. In two other treatments a value of 2.9 at the start was increased to 5.0 after 60 and 90 days, respectively. The fourth treatment started at a value of 2.9, which value was raised to 6.8 after 90 days.

Experiment 5. A spring crop was started with three EC-values, namely 5, 7 and 10 which values were gradually lowered to 2.5, 3.5 and 4.5, respectively, after six weeks.

Experiment 6. For a spring crop an initially high EC-value of 5.9 was maintained over different periods before it was lowered to a value of 2.6.

Experiment 7. In a fall crop four EC-values between 1.7 and 4.6 were maintained continuously.

Growing conditions

The spring crops were grown from the end of December till June-July and the fall crops from July till November. The setpoint for heating was 15°C during night and 19°C during the day. The ventilation temperature was 24°C.

The differences in climatic conditions were realised by use of single or double glass covers, by use of polythene thermal screens, by heating and ventilation and by artificial evaporation of water. With fall crops (Experiments 1 and 4) differences in climatic conditions developed especially in the second part and with the spring crops (Experiments 2 and 3) especially in the first part of the growing period. Between the beginning of April and the end of September no crucial differences existed in climatic conditions, except the different light conditions. Under double glass light intensity was 18% lower than under single glass. In the period mentioned high radiation necessitated ventilation or removal of the screens in all compartments. In Experiments 1 and 2 the differences in vapour pressure deficit (vpd) were marginal, which was caused by malfunctioning of parts of the equipment. In Experiment 3 the average vpd of the treatments ranged from 0.35-0.52 kPa and in Experiment 4 between 0.38-0.60 kPa.
In Experiment 4, beefsteak tomatoes, cultivar Vision, were grown. In all other experiments the usual round Dutch cultivars like Abunda, Angela or Calypso were grown.
CO_2 was kept constant at 340 vpm.

Nutrient solution

At an EC-value of 1.7 the nutrient solution used in the experiments contained the following ions in mmoles L^{-1}: NO_3 10.5, H_2PO_4 1.5, SO_4 2.25, NH_4 0.5, K 7.0, Ca 3.5, Mg 1.0 and the following ones in µmoles L^{-1}: Fe 35, Mn 20, Zn 4, B 20, Cu 0.5, Mo 0.5. The different EC-values were realised through proportional addition of the nutrient elements. Mostly adjustments were made for certain growth stages of the crop like is recommended to growers (Sonneveld and Welles, 1984). In an early growing stage, 1.5 mmol calcium nitrate more than usual was added and in periods of heavy fruit bearing, calcium was lowered with 1 mmol L^{-1} while potassium was increased with 2 mmol L^{-1}.
The EC-value in the root environment was calculated by averaging the EC-values of incoming and outgoing nutrient solutions.

Tissue analysis

The nutrient status of the tomato plants was determined by analysing leaf and fruit samples. The samples were gathered in the Experiments 1 and 6 about 75 days after planting, except for fruit samples of Experiment 6 which were taken a hundred days after planting. The leaves were separated in laminae and petioles. The fruit samples consisted of fruits ready for picking. The samples were dried, ground and analysed for macro-nutrient elements. The analytical methods used are described by De Bes (1986).

Crop observations

At harvest, the numbers and weights of fruits were determined. Fruit shape was judged visually. The index used for this judgment ranged from 5, a rather poor, till 8, a very good fruit shape. Colouring was expressed in terms of number of days elapsing between picking and reaching colouring stage 100% orange. Shelf life was expressed as the number of days between 100%

orange and fruit softening. In the fruit sap, EC, acid content and refraction were measured and expressed as $dS.m^{-1}$ (25°C), mmol L^{-1} and percentages Brix, respectively.

6.3 Results

The results of the experiments in which interactions between EC-values in the root environment and climatic conditions were studied (Experiments 1-4) are listed in Tables 6.1-6.4.

Table 6.1. The effect of different EC-regimes in the root environment on the yield of tomatoes. Experiment 1

EC-values			Fruit yield. m^{-2}		
	Average				
0-60 days	60-90 days	90-120 days	Number	kg	fruit weight g
4.6	4.6	4.6	161	9.2	57
4.5	4.5	2.9	163	9.5	58
4.4	2.6	2.6	153	9.5	62
2.4	2.4	2.4	164	10.4	64
2.6	2.6	4.9	165	10.2	62
2.7	5.0	5.0	174	10.2	59

Table 6.2. The effect of high EC-values in an early growth stage on yield of tomatoes. Experiments 2 and 6

Experiment 2			Experiment 6		
EC-values		Yield	Number of days		Yield
0-35 days	35-200 days	kg m^{-2}	EC 5.9	EC 2.6	kg m^{-2}
1.7	2.4	16.5	0	190	20.2
2.8	2.4	16.6	35	155	21.7
3.8	2.4	16.6	50	140	22.4
5.0	2.4	17.1	65	125	22.8
6.4	2.4	16.2	80	110	21.8

Fruit yield in Experiment 1 was mainly determined by the EC-value during the first 60 days of growth. The confidence limit (P) for the interaction between EC-value and climatic conditions was not significant (>0.10). The results of Experiment 2 did not show significant ($P > 0.05$) differences in fruit yield at the EC-regimes maintained. The yield differences between EC-values compared in Experiment 3 were significant. These differences, however, showed interaction with climatic conditions in the various glasshouse compartments ($P < 0.05$). A significant yield reduction caused by the higher EC-value was found only when humidity was high either during day or night, or continuously (Table 6.5). Furthermore with the higher EC-value in the root environment a lower fruit weight, a longer shelf life and a higher EC-value and acid content in the fruit sap were found (Table 6.3). In Experiment 4 fruit yield in the treatment with the early rise in EC-value was significantly ($P < 0.01$) lower than yields in the other treatments. The lower yield was caused by a lower fruit weight.

Table 6.3. The effect of variation in EC-values in the root environment on yield and quality of tomato. Experiment 3

Characteristics	EC 2.6	EC 3.5
Number of fruits m^{-2}	224	222
Fruit yield, kg m^{-2}	12.7	11.9
Average fruit weight, g	56	54
Fruit shape index	6.4	6.6
Colouring in days	4.4	4.1
Shelf life in days	17.5	19.2
EC fruit sap dS m^{-1}	5.8	6.2
Acids in fruit sap, mmol L^{-1}	75	84
Refraction fruit sap, % Brix	4.8	5.0

Table 6.4. The effect of different EC-regimes on the yield of beefsteak tomatoes. Experiment 4

EC-values			Fruit yield m^{-2}		Average fruit weight
0-60 days	60-90 days	90-130 days	Number	kg	
2.9	2.9	2.9	56	9.8	175
2.9	5.0	5.0	56	9.1	163
2.9	2.9	5.0	55	9.6	173
2.9	2.9	6.8	55	9.5	171

Table 6.5. Calcium deficiency symptoms and yield of tomatoes in Experiment 3

Glass cover	Humidity		Ca-deficiency[a]	Yield, kg.m^{-2}	
	Day	Night		EC 2.6	EC 3.5
Single	ambient		0.05	13.4	13.6
Double	high	high	1.61	11.2	10.0
Double	low	high	0.38	12.5	11.4
Double	high	low	0.12	13.0	11.7
Double	low	low	0.09	13.2	13.0

[a] Index Ca-deficiency: 0—no symptoms and 4—severe symptoms.

The results of the Experiments 5-7 are listed in Tables 6.6, 6.2 and 6.7 respectively. Continuously high EC-values lowered fruit yields significantly ($P < 0.01$) but improved scores for fruit quality as shown by the results of Experiments 5 and 7 (Tables 6.6 and 6.7). However,

blossom-end rot was increased by high EC-values (Experiment 7). Initially high EC-values did not affect yields negatively in Experiment 6 (Table 6.2), not even if maintained for 80 days from planting. However, an initially low EC-value lowered yield in this experiment ($P < 0.05$), caused probably by a too rapid plant growth.
Analytical data of tissue samples gathered in the Experiments 1 and 6 are listed in Tables 6.8 and 6.9 respectively. In all plant tissues the potassium contents were higher at the higher EC-values. This was of interest especially in old laminae and petioles. Calcium and magnesium contents were virtually always lower at higher EC-values. Nitrate contents of leaf parts were much higher in the spring crop (Experiment 6) than in the fall crop (Experiment 1). High EC-values increased the nitrate contents in young leaf parts and decreased the contents in old leaf parts. High EC-values reduced phosphorus contents in young leaf parts and fruits, but not in old leaf parts. Generally, dry matter contents were higher at higher EC-values.

Table 6.6. The effect of different EC-regimes in the root environment on yield and quality of tomatoes (Experiment 5)

EC regime	% dry matter	Fruit yield m^{-2} Number	kg	Average fruit weight g
5-2.5	4.9	206	14.4	68
7-3.5	5.0	206	13.3	64
10-4.5	5.3	201	11.7	58
	Shape index	Shelf life days	Acids mmol l^{-1}	Refraction % Brix
5-2.5	6.8	12.5	66	5.0
7-3.5	7.0	14.6	76	5.2
10-4.5	7.7	16.1	84	5.3

Table 6.7. Yield of tomatoes as affected by the EC of the circulating solution. The numbers of fruits affected by blossom-end rot and by blotchy ripening are expressed as percentages of the total numbers of fruits (Experiment 7)

EC	Yield $kg.m^{-2}$	Blossom-end rot, %	Blotchy ripening %
1.7	15.9	0.3	4.6
2.6	16.0	0.3	4.0
3.6	15.3	0.6	2.8
4.1	14.2	2.0	1.9

Table 6.8. Analytical data of laminae and petioles of young leaves and of fruits as affected by variation in EC-value in the root environment. Nutrient contents expressed as $mmol.kg^{-1}$ dry matter and dry matter as % of fresh material. Results of Experiment 1

Nutrient	Plant parts					
	EC value					
	Laminae		Petioles		Fruits	
	2.4	4.6	2.4	4.6	2.4	4.6
K	961	1032	1711	1712	1049	1107
Ca	847	842	699	697	34	27
Mg	145	123	135	121	65	63
NO_3	68	77	297	326	25	25
P	193	166	184	121	151	142
Dry matter	9.9	10.5	7.0	7.6	4.8	5.4

6.4 Discussion and conclusions

High EC-values in the root environment of tomato improved fruit quality, but lowered fruit yield. The salinity threshold value appears to be an EC-value of about 2.5, as may be concluded from the results of Experiment 7. Salinity yield decrease (SYD) values can be calculated from the experiments in which EC-values in the root environment were kept constant. The results of such calculations are summarized in Table 6.10. The SYD-values ranged from 5.2 to 7.0% per $dS.m^{-1}$.

Under poor light conditions at early growth high EC-values in the root environment usually did not adversely affect long term production, as shown in Experiments 2 and 6. The same was true for high EC-values under poor light conditions at late growth, as found with treatments 3 and 4 in Experiment 4. Too early an EC rise, however, lowered yield seriously, as was found with treatment 2 of this experiment.

These findings justify the conclusion that high EC-values are less detrimental under poor light conditions than with ample light. This is understandable, as under Dutch climatic conditions light intensity and growth (yield) are more or less linearly related. It can be hypothesized that an ECeffect on the yield of a crop is not plainly related to the length of a period over which a certain EC-value is maintained (Meiri, 1984), but is also related to the production level in such a period. The validity of this hypothesis can be tested with the results of Experiments 1 and 4. The yields obtained in these experiments were related to the weighted mean of the EC-values, calculated over the lengths of the periods that EC-values were maintained (EC_t) and calculated over the product of the lengths of the periods that EC-values were maintained and the radiation in the periods (EC_R). EC_t and EC_R are defined as follows:

$$EC_t = \frac{\Sigma\, d_i\, EC_{di}}{\Sigma\, d_i} \qquad (6.1)$$

$$EC_R = \frac{\Sigma\, d_i\ R_i\ EC_{di}}{\Sigma\, d_i\, R_i} \qquad (6.2)$$

in which d_i is a certain day, R_i the radiation on that day in Joules cm^{-2}, EC_{di} the EC-value maintained in the root environment and i the running number of days from planting. The results of the calculations are listed in Table 6.11. The correlation coefficients for the relationships with EC_R as independent variable are much higher than those with EC_t. This finding confirms the hypothesis raised.

Table 6.9. Analytical data of plant tissues of tomatoes grown at standard (EC = 2.6) and high (EC = 5.9) EC-value in the root environment. Nutrient contents expressed as mmol kg^{-1} dry matter and dry matter (DM) as % of fresh material. Results of Experiment 6

Plant part	K		Ca		Mg	
	EC value		EC value		EC value	
	2.6	5.9	2.6	5.9	2.6	5.9
Young laminae	972	993	663	661	164	161
Young petioles	2178	2437	648	621	228	213
Old laminae	1116	1400	1284	1115	231	202
Old petioles	1952	2404	1004	760	363	285
Fruits	1625	1661	47	47	70	61
	NO_3		P		DM	
	EC value		EC value		EC value	
	2.6	5.9	2.6	5.9	2.6	5.9
Young laminae	410	452	258	226	10.1	10.6
Young petioles	1838	1947	258	252	5.8	6.1
Old laminae	637	590	231	249	9.1	9.4
Old petioles	2247	2017	280	339	7.4	7.4
Fruits	26	24	233	214	4.9	5.4

Table 6.10. Calculation of salinity yield decrease (SYD) values of experiments with constant EC-values

Experiments	Range of EC-values	Range of relative yield	SYD %
1	4.6-2.4	100-88.5	5.2
3	3.5-2.6	100-93.7	7.0
7	4.6-2.6	100-88.5	5.6

Increases in EC-value led to higher dry matter contents of plant tissues, as appears from data of Tables 6.8 and 6.9. Hence, the effect of variation in EC-value on dry matter production is less than on fresh material production. However, no data were gathered on dry matter production in the experiments described in this publication.
The nature of the interaction observed between EC-value in the root environment and climatic conditions in Experiment 3 differed from the one met in other investigations. Mostly, in salinity studies EC-induced yield reductions are higher at low than at high humidity (Hoffman and Rawlins, 1971; Magistad *et al.,* 1943). In our study, however, EC-induced yield reduction was highest at high humidity (see Table 6.5).

Table 6.11. Regression equations and correlation coefficients for relationships between yield (y) on the one hand and average EC-values weighted over time (EC_t) and over the product of time and radiation (EC_R) on the other hand

Experiments	Regression equation	Correlation coefficient
1	$y = - 4.9\ EC_t + 112$	- 0.797
	$y = - 5.1\ EC_R + 113$	- 0.944
4	$y = - 4.2\ EC_t + 112$	- 0.788
	$y = - 9.5\ EC_R + 128$	- 0.950

In most salinity studies crops grown under standard climatic conditions are compared with crops grown at very low humidity. In Experiment 3 of our study standard glasshouse conditions were compared with a very humid climate. The continuously maintained high humidity reduced the calcium content of the young leaves to about 50% of that observed at standard climatic condition, causing plants that considerably suffered from calcium deficiency in the leaves (see Table 6.5) and that produced lower yields.
In the other treatments with a high humidity maintained a part of the natural day, calcium deficiency was evident as well. It is, therefore, likely that the nature of the interaction is a function of the calcium status of the plants (Thomson, 1985). However, the present experiments provide no proof for this assertion. Further study in this field is necessary.
In the other experiments with varying climatic conditions, no interaction was found between the effects of such conditions and those of EC-values. The absence of an interaction may find its cause in the lower humidity levels imposed and in the absence of calcium deficiency.
The interaction observed in Experiment 3 strongly affects the SYD-value. The value of 7% calculated for all treatments (Table 6.10) is an average of the value of 10.9% per $dS.m^{-1}$ for the high humidity treatments and that of 0% for the low humidity treatments (Table 6.5).

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7. Discussion

7.1 Introduction

The main objective in greenhouse cultivation, as in other industries, is low cost production of a given quality with minimum environmental effects. The environmental effect in the greenhouse industry concerning this study is the output of nutrients by drainage water. This output is determined by the quantity of drainage water and the ion concentrations in it. The aim with respect to the environment is the reduction of the quantity of the nutrient output with a special reference to the output of the quantities of N, P and K, being the ions with the strongest environmental impact. Output of salts by leaching is necessary if the concentration of any ion in the root environment becomes higher than acceptable for the production objectives and no other economically acceptable reduction in the supply of that ion is possible.
In view of this premises leaching should be focussed on minimum quantities of water with lowest acceptable concentrations of N, P and K. However, this should not conflict with the situation that a certain (high) EC level in the root environment is required with respect to the quality of the produce. The difference between the lowest acceptable EC with respect to the mineral nutrition of plants and the required EC with respect to the produce quality can be filled up by accumulation of ions that necessitate leaching. That way the accumulation of ions that necessitate leaching can be maximized and the quantity of water used for leaching minimized. However, it should be taken into account that interaction is possible between the level of accumulation of ions that necessitate leaching and the lowest acceptable concentrations of nutrients.
The provisions posed made clear that salinity may be considered as an extension of the field of plant nutrition. This is especially the case in the greenhouse industry, where intentionally or not high levels of nutrients are maintained in the root environment. The gradual change from proper conditions for plant nutrition to salinity stress necessitates a fine tuning between nutrient concentration and salinity indices in the external solution. This should be accentuated because of the small root volumes involved with substrate growing, being the system under discussion. In this concluding chapter a short review will first be given of the nutrient requirements of crops. Next the limits set by salinization will be discussed. The chapter will be concluded with indications and suggestions for a programme in which fertilization and salinity are fitted in such a way that optimum productions are ensured with minimum environmental consequences.
The management of ions in a substrate system can roughly be described by the following balance equation:

$$Sc_s - A - (S - U)c_d = 0 \qquad (7.1)$$

in which:

- S = rate of water supply in $l\ d^{-1}\ m^{-2}$
- c_s = concentration of any ion in the solution supplied to the system in $mmol\ l^{-1}$
- A = nutrient absorption by the crop in $mmol\ d^{-1}\ m^{-2}$
- U = rate of water absorption of the crop in $l\ d^{-1}\ m^{-2}$
- c_d = concentration of any ion in the drainage water in $mmol\ l^{-1}$

Furthermore, the following is defined:

$$c_u = A/U \qquad (7.2)$$

in which:

c_u = ratio between the uptake of ions and water, often denoted as uptake concentration, in mmol l^{-1}

From the definition can be derived that:

$$A = U\, c_u \qquad (7.3)$$

In equation (7.1) c_s can be written as:

$$c_s = c_f + c_w \qquad (7.4)$$

in which:

c_f = concentration of any ion from fertilizer supply

c_w = concentration of any ion in the primary water

For any ion in the system the following rule applies:

$$c_{ss} \leq c_{ss}\,(max) \qquad (7.5)$$

in which:

c_{ss} = concentration of any ion in the solution in the root environment

c_{ss} (max) = maximum acceptable concentration of that ion in the root environ ment

The value of c_{ss} (max) is determined by specific ion effects or by too high a contribution to the osmotic potential of the ion(s) involved. Written in formulae:

$$c_{ss}\,(max) \leq c\,(tox) \qquad (7.6)$$

$$c_{ss}\,(max) \leq c_t - c_n \qquad (7.7)$$

in which:

c (tox) = toxic concentration of the ion involved

$c_t - c_n$ = difference between the minimum concentration of plant nutrients necessary for optimum growth and the salinity threshold concentration (see equation 1.2)

If the concentration of any ion in the root environment solution (c_{ss}) becomes higher than the maximum acceptable concentration {c_{ss} (max)} for that ion, leaching is necessary. In case that the potential uptake of all elements is equal to or bigger than the supply (c_s) leaching is not necessary and the system can be kept "closed". Whenever leaching is necessary, this should be restricted as much as possible. This can be achieved by a well controlled supply (c_s) or by leaching at maximum acceptable concentrations in the root environment solution {($c_{ss} = c_{ss}$ (max)} of the ion involved. The supply of nutrients is controlled by fertilizer applications (c_f), however, some ions occur as impurities in fertilizer compounds. These quantities are of minor importance if high quality compounds are used. When ions in the supply are already present in too high

concentrations in the primary water ($c_w > c_u$), the control to the supply is difficult and mostly cannot be economically realized. Leaching only at maximum acceptable concentrations in the root environment contributes in two advantages with respect to restricting leaching as much as possible. Firstly, directly due to the fact that the concentration of the ion involved in the drainage water is as high as possible and thus, the quantity accompanying nutrients often primarily responsible for environmental pollution, like N and P, are minimized. Secondly, there is an indirect effect, because the uptake of some ions, like Na and Cl, is stimulated by increasing concentrations and an increased uptake will reduce the accumulation in the root environment and by this the need for leaching.
Furthermore, when an ion accumulates in the root environment the lowering of the concentration of other ions should be considered. In this way the total ionic concentration in the root environment and, therefore, the osmotic stress of plants will not be affected. In other words, if e.g. Na or Cl accumulates the nutrient cation or anion concentration, respectively could be lowered. The level of any nutrient should never be below the minimum concentration for optimum growth (c_n), see section 1.7. Interaction between the required nutrient concentration in the root environment and excess accumulation of any ion may occur and was part of this study.

7.2 Nutrient absorption

Nutrient uptake differs strongly among crops and is affected, in addition to the crop itself, by the ion composition of the external solution, the growth stage, the climatical conditions and the yield level. Growth stage and climatical conditions affect the mutual ratios and the rate of the nutrient uptake, respectively, during the growing period rather than the overall uptake over the whole (long) cultivation period (Voogt, 1993). Growth stage effects have clearly been shown for fruit vegetable crops. Tomatoes for example absorb K and Ca at a (mol) ratio of about 4, while at heavy fruit load this ratio reaches values up to 7 (Voogt, 1988). With respect to climatic conditions, it is evident that global radiation is the main factor determining the absorption of nutrients (Schacht and Schenk, 1990), because of its effect on plant growth and the nutrient requirement resulting from this. The ion composition of the external solution affects the nutrient absorption of crops mainly at low and sub-optimum supply of nutrients, for crops under these conditions show reduced nutrient concentrations. With optimum and luxurious supply of nutrients the nutrient concentrations in plants are generally rather constant over a relatively wide concentration range of the external solution. In substrate systems and glasshouse soils, generally, the nutrient concentrations in the external solution are in the optimum or luxurious range. So, in glasshouse industry total nutrient uptake mainly depends on crop type and yield level.
In a study at the Research Station for Floriculture and Glasshouse Vegetables (Sonneveld, 1997) data were gathered about nutrient absorption of greenhouse crops from experiments at the Research Station and from observations of Dutch greenhouse holdings. With most crops a close relationship has been found between yield and total nutrient uptake. In Table 7.1 such relationships are shown for cucumber and chrysanthemum. All regression equations for cucumber show a substantial intercept, while this is not the case with chrysanthemum. The intercepts with cucumber more or less reflect the uptake during the vegetative stage of the crop. At harvest of the first fruits substantial amounts of nutrients have already been taken up during the vegetative development of the plant, and these amounts only gradually increase with increasing yield. With chrysanthemum no intercepts have been found, because the total plant shoot is included in the harvest. Also with sweet pepper, tomato, radish and lettuce close relationships were found between yield and total nutrient uptake (Sonneveld, 1997). The relationships for pepper and tomato show high intercepts, just as found with cucumber. With rose no relationships were found

between yield and total nutrient uptake. The residual rose shoot parts that remain on the nursery will fluctuate strongly, which is maybe a reason for the poor correlations found between yield and total nutrient uptake.

Table 7.1. Relationships between fresh fruit yield of cucumber and fresh flower weight of chrysanthemum (x) on the one hand and the uptake of nutrients (y) on the other hand. Fruit yield and flower weights are given as kg m^{-2} and uptake of nutrients in kg ha^{-1}. The relationships are given as linear functions y = ax + b. Data from Sonneveld (1997).

Element	Parameters					
	Cucumber			Chrysanthemum		
	a	b	r	a	b	r
N	14.5	60.8	0.939	40.3	- 3.4	0.975
P	2.4	23.7	0.721	5.8	1.2	0.905
S	2.2	8.6	0.813	2.7	0.1	0.881
K	21.3	129.2	0.866	70.0	- 8.1	0.971
Ca	8.8	72.1	0.826	11.6	2.0	0.964
Mg	1.9	12.6	0.773	3.7	- 1.6	0.887

The data in Table 7.1 clearly demonstrate the huge absorption of nutrients in the greenhouse industry. So, for cucumbers can be calculated that at an annual yield of 60 kg m^{-2} the absorption of N and K is 930 and 1410 kg ha^{-1} y^{-1}, respectively. This accentuate again the need for a precise regulation of the fertilizer supply by fertigation, keeping in mind the small quantities of nutrients available in the root environment in substrate systems (Table 1.1).Therefore the total uptake is a poor basis for fertilizer supply in substrate systems, but the nutrient uptake in relation to the water absorption is a better basis for the daily supplies.

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7.3 Uptake concentration

Both crop yield and water absorption are strongly related with radiation input. As outlined before, total nutrient uptake and crop yield are strongly related. Thus, a more or less stable ratio between the absorption of nutrients and water can be supposed. This ratio, often referred to as uptake concentration, has no physiological basis, because absorption of water and nutrients by plants are independent processes (See chapters 4 and 5). However, the variations in the uptake concentrations are less than those in the absolute values of nutrient uptake (kg ha^{-1}) of crops (Savvas and Lenz, 1995), because both processes determining the uptake concentration are driven by the radiation. Therefore, the uptake concentration is a rough basis for fertigation in substrate systems.

In Table 7.2 uptake concentrations found for a number of nutrients and greenhouse crops are listed. There are huge differences between crops, but also the growing conditions strongly affect the uptake concentration, as is shown for radish. The uptake concentration for a winter grown crop is about four times higher than for a summer grown crop. Such differences arise primarily from differences in the water absorption and rarely from differences in the nutrient uptake as has been found by Sonneveld and Van den Bos (1995) with a radish crop and by Terada et al. (1997) with a rose crop. The water use of a radish crop grown in winter was about one quarter of that of a crop grown in summer. This low water use under poor light conditions of the Dutch winter should be explained by a relatively high and low energy use for photosynthesis and transpiration, respectively, compared with crops grown in summer. Indicating a high light efficiency under low light conditions, as also has been found by Ho and Adams (1994) with cucumbers. With very high transpirations in summer a further decrease of the uptake concentration can be expected (Kläring et al., 1997).

Table 7.2. Uptake concentrations (c_u) for greenhouse crops. Data gathered from experiments at the Research Station for Floriculture and Glasshouse Vegetables, Aalsmeer/Naaldwijk and from Dutch greenhouse holdings. Concentrations expressed as mmol l^{-1} water absorbed.

Crops	Nutrients					
	N	P	S	K	Ca	Mg
Cucumber	12.2	1.0	0.9	6.6	2.7	0.8
Sweet pepper	9.7	0.8	0.6	4.5	1.9	0.7
Radish (summer)	8.6	0.4	0.4	4.5	1.2	0.4
Radish (winter)	31.5	1.0	1.7	16.4	5.4	1.6
Tomato	9.6	1.1	1.2	6.1	2.2	0.9
Rose	5.2	0.4	0.4	1.9	0.9	0.3
Gerbera	10.2	0.7	0.4	7.0	1.6	0.5

In substrate systems the concept of uptake concentrations is a helpful tool in estimating nutrient supply to the irrigation water, to keep the nutrient concentrations in the root environment at levels required for optimum productions. However, it cannot be applied as such to concentrations of nutrients required in the root environment for a sufficient uptake of nutrients. The ratio between the concentration of an ion in the root environment and the uptake rate differs strongly among ions. K, NO_3, NH_4 and H_2PO_4 are easily absorbed by crops and can thus be supplied to the crop at relatively low concentrations, while Ca and Mg are absorbed with more difficulty and should, therefore, be available in relatively high concentrations in the root environment (Marschner, 1997; Sonneveld and Voogt, 1985; Sonneveld and Voogt 1986; Wild et al., 1987). Thus, recommendations for balanced nutrient solutions in the root environment for crops grown in substrate are generally characterized by relatively high Ca and Mg concentrations (Sonneveld and Straver, 1994).

Over the whole growing period of substrate grown crops the input of plant nutrients should at least meet the demand for absorption by the plant plus the nutrients drained out. In systems with a free drainage the average input concentration can be calculated as:

$$c_s = (W_u\, c_u + W_d\, c_d)/W_s \qquad (7.8)$$

in which:

W_s = water supplied l m^{-2}
W_u = water absorbed by the crop l m^{-2}
W_d = water drained to waste l m^{-2}
c_s = concentration of a nutrient in the water supplied mmol l^{-1}
c_u = uptake concentration of the nutrient mmol l^{-1}
c_d = concentration of the nutrient in the drainage water mmol l^{-1}

In a recirculating system are no losses, which means that in (7.8) the term $W_d\, c_d = 0$ and thus follows:

$$c_s = W_u\, c_u / W_s \qquad (7.9)$$

In a closed substrate system an equilibrium develops between supply and uptake. This is in agreement with formula (7.9), the input concentration (c_s) is equal to the uptake concentration (c_u), because W_s is equal to W_u. Apart from water losses by transpiration of the crop, in a closed system there are no other water losses. Not even by evaporation from the surface, because in such systems the substrate is wrapped in plastic sheeting. In principle, it can be concluded from equation (7.8) that in a free drainage system optimum productions can be gained with input concentrations lower than the uptake concentrations. The total nutrient uptake W_uc_u will be supplied with quantities of water larger than the quantities absorbed by the crop. Thus $W_u/W_s < 1$ and so $c_s < c_u$. However, in practice the total input of nutrients, generally, will be much higher than the uptake by the crop, due to the fact that a substantial part of the nutrients are drained out (see section 1.3).

Uptake concentrations for Na and Cl are important with respect to judgment of the water quality. They strongly depend on the crop and the concentrations of Na and Cl in the external solution, as is shown in Tables 2.5 and 3.10. Sometimes the uptake concentration can be expressed as a percentage of the concentration in the external solution, when the relationship between the uptake concentration and the external concentration is linear and no significant intercept is calculated (See Table 3.10). Otherwise, the uptake concentration should be experimentally determined or assessed using more complex equations. Table 7.3 summarizes the uptake concentrations from the experiments carried out in this study and from research data elsewhere. The uptake concentrations for Cl are generally higher than those for Na. There are two exceptions, radish and lily. Crops with a low Na uptake generally also show a low Cl uptake. Summer grown radish shows much lower uptake concentrations than a winter grown crop, because of the lower water absorption in winter with a more or less equal ion absorption. The very low uptake concentrations for rose and bouvardia are striking and such crops when grown in a closed system require water more or less completely free from NaCl.

7.4 Nutrient concentrations in the root environment

It is well known that plants are able to take up sufficient nutrients for optimum growth and development at very low concentrations in the root environment (Clement et al., 1978; Ingestad, 1970; Massey and Winsor, 1980; Siddiqi et al., 1998; Voogt, 1992; Wild et al., 1987). With such low concentrations a high flow rate and intensive monitoring of the chemical composition of the nutrient solution are necessary to ensure continuous availability of nutrients. Such systems are not realistic in commercial production systems. In commercial systems the rate of the solution mostly does not exceed 2. In a free drainage system the rate is the ratio between the water supplied (W_s) and the water absorbed by the crop (W_u); a leaching fraction (LF) of 25% corresponds with a rate of 1.3. In closed systems the rate is the ratio between the water supplied (W_s) + the water reused (W_{rs}) and the water absorbed by the crop (W_u). With a leaching fraction of 50% the recirculation rate is 2.

Table 7.3. Uptake concentrations of Na and Cl for greenhouse crops. Concentrations expressed as mmol l^{-1} water absorbed by the crop.

Crops	Element	Ext. concentration		References
		<5 mmol	10 mmol	
Vegetables				

Tomato	Na	0.4	0.8	Chapter 2
	Cl	0.6	1.0	id.
Sweet pepper	Na	0.2	0.3	id.
	Cl	0.3	0.6	id.
Cucumber	Na	0.3	1.0	id.
	Cl	0.3	1.5	id.
Radish (summer)	Na	0.3	-.-	Sonneveld, 1997
	Cl	0.5	-.-	id.
Radish (winter)	Na	1.8	-.-	id.
	Cl	0.9	-.-	id.
Flowers				
Gerbera	Na	0.2	0.8	Chapter 3
		1.7	2.4	id
Carnation	Na	0.1	0.3	id
	Cl	0.5	0.8	id
Rose	Na	0.0	0.0	id
	Cl	0.1	0.2	id
Aster	Na	0.2	1.5	id
	Cl	0.4	2.0	id
Bouvardia	Na	0.1	0.1	id
	Cl	0.2	0.3	id
Lily	Na	0.4	1.0	id
	Cl	0.6	0.9	id

With free drainage systems the leaching fraction should be restricted as much as possible to limit the environmental pollution, while in recirculation systems a high recirculation rate of the nutrient solution is expensive, because costly sterilisation is often necessary before the drainage water can be reused in a recirculating system (see section 1.5).
It has been reported that different crops grown on reasonably balanced nutrient solutions with total ion concentrations below 1.5 dS m^{-1} often show growth reduction. With gerbera De Kreij and Van Os (1989) noticed a 16% decrease of the flower production when the EC in the external solution was lowered from 1.8 to 0.9 dS m^{-1}. With rose De Kreij and Van den Berg (1990) found a 12% reduction in flower production at an EC of 1.0 compared to production at 1.9 dS m^{-1}. With sweet pepper De Kreij (1999) noticed a yield reduction of 14% when the EC of the external solution was decreased from 2.0 to 1.0 dS m^{-1}. Gislerød and Selmer-Olsen (1980) found a 10% reduction of the fresh weight of chrysanthemums when the EC of the external solution was reduced from 2-4 to 1-2 dS m^{-1}. Udagawa (1995) reported fresh plant weights of dill and thyme at 1.2 dS m^{-1} that were about 30% of those at 2.4 dS m^{-1}. Also Ingestad (1972) claimed for maximum growth rate of cucumber nutrient requirements corresponding with an EC in the external solution of at least 1.5 dS m^{-1}. In a series of experiments Sonneveld and Van den Bos (1995) and Van den Bos (1994a, 1994b, 1995, 1996a, 1996b, 1996c, 1997) compared six levels of solution concentrations with different vegetables and flowers as test crops. The crops were grown in sand as well as in granulated rock wool. The lowest concentration with an EC in the substrate solution between 1.0 and 1.5 dS m^{-1}, was supposed to be sub optimum. The second lowest concentration with an EC between 2.0 and 2.5 dS m^{-1}, was supposed to be optimum. The drainage water from the system was reused and the foreseen leaching fraction was 30% and this varied under the experimental conditions between 10 and 50%, depending on crop, growing conditions, and treatment. Highest yields were always obtained with one of the two lowest

concentrations. In Table 7.4 the EC of the irrigation water and the drainage water of both treatments are listed, together with the relative crop yields. The second lowest concentration is used as a standard.

Table 7.4. Relative yields of vegetable and flower crops at suboptimum and optimum concentration in the substrate solution. Data from Sonneveld and Van den Bos (1995) and Van den Bos (1994a; 1994b; 1995; 1996a; 1996b; 1996c; 1997).

Crops	Yield characteristics	EC		Relative yields***	
		Irr*.	Drw**	Sand	Rockwool
Radish (summer)	Plant weight	1.0	0.9	83	42
		1.8	1.7	100	100
Radish (winter)	Plant weight	1.4	1.3	42	52
		2.3	2.2	100	100
Lettuce (summer)	Head weight	1.3	1.2	81	77
		2.1	2.3	100	100
Lettuce (autumn)	Head weight	1.3	1.2	70	77
		2.1	2.1	100	100
Kohlrabi	Tuber weight	1.3	1.3	41	33
		2.1	2.2	100	100
Chrysanthemum	Flower weight	1.0	1.3	85	88
		1.8	2.5	100	100
Aster	Flower weight	1.2	1.8	114	111
		1.8	4.3	100	100
Freesia	Flower weight	1.2	1.8	97	97
		1.9	3.3	100	100
Lily	Flower weight	1.1	1.3	108	110
		1.8	2.6	100	100
Hippeastrum	Bulb weight	1.1	1.4	121	115
		2.0	3.4	100	100

* Irr - irrigation water, ** Drw - drainage water and *** Yield relative to the second concentration.

With vegetables the lowest nutrient concentration (EC 1.0 - 1.4 dS m^{-1}) was always too low to achieve maximum production (Table 7.4). Flower crops reacted differently. Chrysanthemum more or less reacted like the vegetable crops and with freesia the differences between the flower weights at the two nutrient levels were marginal. At the lowest concentration, the average EC in the root environment (average of irrigation and drainage water) for this crop was 1.5 dS m^{-1}. With the other flower crops, aster, lily and hippeastrum, highest flower and bulb weights were gained at the lowest nutrient levels, having average EC values between 1.2 and 1.5 dS m^{-1}. It is remarkable that for these crops an increase of the EC to an average value between 2.2 and 3.0 resulted in yield reductions between 8 and 21%. The crop reaction was not related to differences in the leaching fractions achieved with the different crops.

The maximum production is often observed at concentrations in the external solution higher than the uptake concentration. From the ion compositions from Table 7.2 it can be calculated that the uptake concentrations vary from 0.6 dS m^{-1} for a rose crop to 1.5 dS m^{-1} for cucumber under

current Dutch growing conditions. At low transpiration rates, the uptake concentrations substantially increase. With radish for example (Table 7.2) the EC of the uptake concentration is 0.9 dS m^{-1} in summer and 3.0 dS m^{-1} in winter. Thus, the experimental data show that supply of nutrients at uptake concentrations do not sufficiently ensure nutrient uptake for maximum productions, but that certain concentrations in the root environment are required to effectuate such an uptake.
If crops were able to take up all nutrients supplied to a substrate system, then it should be sufficient to supply nutrients at a concentration equal to following concentration:

$$c_s = (1 - LF)\, c_u \qquad (7.10)$$

in which:

c_s = concentration in the solution supplied, the input concentration mmol l^{-1}
c_u = uptake concentration at optimum production mmol l^{-1}
LF = leaching fraction

This, however, will never be the case, because the concentration of nutrients in the drainage water of substrate systems will never become zero. Such is clear from the EC of the drainage water in the experiments presented in Table 7.4. Even at sub optimum supply of nutrients the EC of the solution supplied and those drained out are more or less equal. The concentration of nutrients in the drainage water varies strongly and depends on factors like the concentrations in the solution supplied, the leaching fraction and the absorption by the crop, as follows from the data presented in Table 7.5 (Van den Bos 1994a and 1994b). In the system considered, crops were grown in a 15 cm substrate layer. The uptake concentrations at optimum growth were 11.6 N and 6.1 K mmol l^{-1} for kohlrabi and 7.2 N and 6.2 K mmol l^{-1} for chrysanthemum. At low nutrient levels plants seem to be able to absorb 80 to 90% of the N and K supplied, as shown with kohlrabi at an optimum nutrient supply where the nutrients were given at concentrations more or less equal to the uptake concentration. On the other hand it is clear that even at a low supply of nutrients the kohlrabi crop was not able to absorb all N and K supplied. With chrysanthemum low efficiencies were observed because of the high leaching fraction, especially when concentrations supplied were higher than the uptake concentrations, for example with the N uptake. At an optimum growth of chrysanthemum, however, an optimum K uptake can be reached with a high leaching fraction at a concentration lower than the absorption concentration.

Table 7.5. Supply and absorption of water, N and K by kohlrabi and chrysanthemum from a nutrient solution with low or optimal nutrient level in a one-off run in a substrate. Water application and return in l m^{-2} and N and K in mmol l^{-1}. Data Van den Bos (1994a and 1994b).

Crop/nutrient	Applications			Leaching			Efficiencies*		
level	Water	N	K	Water	N	K	Water	N	K
Kohlrabi									
low	144	4.7	2.8	42	1.6	0.9	0.71	0.90	0.91

optimal	140	10.8	5.7	26	7.6	3.8	0.81	0.87	0.88
Chrysanthemum									
low	571	3.4	1.5	310	1.0	0.4	0.46	0.84	0.86
optimal	574	8.4	3.8	305	9.1	2.8	0.47	0.41	0.61

* calculated as 1 - W_d / W_s and 1- W_d $c_{d(x)}$ / W_s $c_{s(x)}$ for water and nutrients respectively.

On the basis of the data presented it is possible to make a general concept for desired concentrations of easily absorbed nutrients like K and NO_3 in the root environment for stagnant systems. For example a stagnant system considered here can have a leaching fraction of about 0.25, being the minimum fraction necessary to correct the uneven water distribution and the uneven water absorption by crops (Sonneveld, 1993). Furthermore, nutrient uptake will be at an optimum level if the concentration of the drainage water is about 50% of the uptake concentration and the efficiency of the nutrient should not exceed 0.85. These values are widely chosen compared with the values shown in Table 7.5, to be ensured that no depletion will occur. Under these conditions the input concentration will be calculated as follows:

$$c_s = (1 - LF)\ c_u + LF\ c_d \qquad (7.11)$$

under conditions that:

$$E = (1 - LF)\ c_u / c_s < 0.85 \qquad (7.12)$$

in which:

- LF = leaching fraction of the system
- E = efficiency of the nutrients
- c_s = input concentration of the system mmol l^{-1}
- c_u = uptake concentration mmol l^{-1}
- c_d = concentration in the drainage water

From (7.11) and (7.12) can be derived

$$E = (1 - LF)\ c_u / [(1 - LF)c_u + LF\ c_d\ ] \qquad (7.13)$$

and if E is fixed on < 0.85 and $c_d = 0.5\ c_u$ follows:

$$E = (1 - LF) / (1 - 0.5LF) < 0.85$$

From this equation it can be calculated that L > 0.26 to keep E < 0.85. In this way it also possible to fix LF and adjust c_s and c_d.

Taking the data and calculations presented into account it can be suggested that in a stagnant system ions absorbed easily by crops should be supplied at concentrations in agreement with formula (7.11). This ensures a sufficient nutrient supply because the concentration in the drainage water is maintained at 50% of the uptake concentration. The leaching fraction to be chosen is 0.26, to keep as a safety that the efficiency should not be overestimated.

The starting points and foregoing calculations lead to the conclusion that the average concentration in the root environment should be about 69% of the uptake concentration, being the average of input concentration, calculated by formula (7.11) and drainage concentration, which was 50% of the uptake concentration.

Ions absorbed with difficulty by crops need to be available in the root environment at relatively high concentrations. Therefore these ions, mainly the bivalent cations, should accumulate in the root environment. In systems with an optimum supply of these cations the concentration in the drainage water was 2 - 3 times the concentration of those in the irrigation water (Sonneveld, 1981: Sonneveld and Voogt, 1985; Sonneveld and Voogt, 1986; Sonneveld, 1987; Voogt and Sonneveld, 1997). Therefore, the recommended concentrations of Ca and Mg in the root environment for optimum production generally are, respectively, equal to and half the concentration of K. The uptake concentrations of those ions are about 40% and 15% of those of K, respectively.
The total cation concentration in the root environment can be calculated from the uptake concentration by the following equation:

$$c_{ss(cat)} = (0.69c_{ss(K)} + 0.69c_{ss(Ca)} + 0.345c_{ss(Mg)})\, c_{u(K)} \qquad (7.14)$$

in which:

$c_{ss(cat)}$ = concentration of cations in the substrate solution in mmol l^{-1}
$c_{ss(X)}$ = respective concentrations of K, Ca and Mg in the substrate solution in mmol l^{-1}
$c_{u(K)}$ = uptake concentration of K in mmol l^{-1}

For a rough calculation of the EC of a nutrient solution, Sonneveld et al. (1999) have given the following formula:

$$EC = 0.1\ C^{+}\ dS\ m^{-1} \qquad (7.15)$$

in which:

C^{+}= the sum of protons in mmol l^{-1}

After substitution of (7.14) in (7.15) the EC of the solution can roughly be approximated by:

$$EC = 0.1\ (0.69 + 1.38 + 0.69)\ c_{u(K)}\ dS\ m^{-1} = 0.276\ c_{u(K)}\ dS\ m^{-1} \qquad (7.16)$$

This means, that in a stagnant system for optimum production crops with high nutrient uptake concentrations like tomato and cucumber with a K uptake concentration of about 6 mmol l^{-1}, the concentration of nutrients in the root environment needs to be about 1.7 dS m^{-1}. For rose with a K uptake concentration of 1.9 mmol l^{-1} an EC of about 0.5 would be sufficient. So, for tomatoes this is more or less in agreement with the experience under practical conditions and in experiments (Table 6.7) where an EC of about 1.5 dS m^{-1} was sufficient for maximum productions. With rose, however, the concentration calculated was too low for optimum production (De Kreij and Van den Berg, 1990) and under practical conditions an EC of 1.8 dS m^{-1} is recommended (De Kreij et al., 1997b).
It should be remembered that uptake concentrations for crops are not a stable factor. They can change with growing conditions and, generally, are higher in moderate climates like in the North-West European countries than in hot climates like in the Mediterranean. From autumn till early spring the uptake concentration in North-West Europe will be much higher than in full summer time. Furthermore, even the uptake concentration may vary from day to day. Therefore, it is imaginable that at such low concentrations in the root environment, as indicated for example for rose, one or more nutrient elements might become insufficient. This could easily occur by, for

example, changes in the uptake concentrations in the ratios of different nutrient elements. Therefore, for most crops total nutrient concentrations of at least 1.5 dS m^{-1} are recommended for commercial production, to prevent yield reductions caused by too low a concentration of any of the essential nutrient elements (Sonneveld and Straver, 1994). This is more in agreement with the results summarized in Table 7.4. Only with crops that are very sensitive to a high EC such as anthurium (Sonneveld and Voogt, 1993) and cymbidium low values of 1.0 and 0.8 dS m^{-1}, respectively, are recommended in the substrate solution (Sonneveld and Straver, 1994). This, however, does not answer the question whether it may be possible to grow a number of crops at lower than usual concentrations in the root environment. For this purpose, a finer regulation of the nutrient supply, better adjusted to the need of the crop involved, should be developed first.

7.5 Required and acceptable concentrations in the root environment

Formerly it was common practice to tune the levels of fertilization and salinity in the root environment to maximum yields. High levels of fertilization and salinity were exclusively connected with negative aspects of plant development. In the greenhouse industry where crops easily show a lush growth often connected with a poor produce quality, there was an early eye for positive effects of low osmotic potentials in the soil solution (Van den Ende, 1955). The lush growth of crops under greenhouse conditions especially appears at relatively high temperatures, reduced light intensity and ample water supply. Such conditions occur predominantly in winter in North-West Europe. Gradually, the osmotic potential of the soil solution became a tool for greenhouse growers to manipulate crop development. The use of substrates enhanced the availability of water in the root environment and thus accentuated the need of the osmotic potential as a tool for crop growth regulation. Substrate growing in fact offers excellent perspectives for such a regulation, because of the restricted root volume.

The osmotic potential of the nutrient solution affects plants in various ways. A general effect is the increasing dry matter content with increasing EC in the root environment (Hayward and Long, 1940-1941; Savvas and Lenz, 1994b; Schwarz and Kuchenbuch, 1997). Dry matter content may also decrease with increasing EC; this occurs in some crops where leaves become succulent when grown at high salt concentrations (Lüttge and Smith, 1984). Leaf succulence occurs often with NaCl salinity, but it is certainly not restricted to this type of salinity (De Jager, 1933). Succulence may be restricted to specific plant organs; it has been found that the dry matter content in leaves decreased, while it increased in fruits (Sonneveld and Van Beusekom, 1974). The effect, in fact, depends on crop species and on growing conditions (Salim, 1989). Another general consequence of increasing EC is a reduced Ca absorption (Adams and Ho, 1990; Bernstein, 1975; Bernstein, 1976; Geraldson, 1957; Selmer-Olsen and Gislerød, 1980; Shear 1975) or an inadequate xylem transport and redistribution of Ca (Adams and Ho, 1992; Ehret and Ho, 1986; Geraldson, 1957). Generally, the storage and consumption quality of fruits like cucumber, pepino, strawberry and tomato is improved by increasing salinity, So, a better colour and longer shelf life are reported (Janse, 1985; Sonneveld and Van Beusekom, 1974a; Table 2.4). Only at very high salinities a decrease of the shelf life was observed (Mizrahi, 1982). Also the consumption quality, in terms of increased sugar and acid contents and improved taste have been found at increased levels of salinity (Adams, 1991; Awang, et al., 1993; Cornish, 1992; Mizrahi and Pasternak, 1985; Mizrahi et al., 1988; Ohta et al., 1991; Petersen et al., 1998; Pluda et al., 1993; Verkerke et al., 1992). Salinity also reduces the occurrence of glassiness in crops (Proeftuin Noord Limburg, 1983; Van den Bos, 1996c; Maaswinkel and Welles, 1986). With radish, improved tuber development in winter and a decreased sponginess in spring/summer has been found with increasing salinity (Sonneveld and Van den Bos, 1995). Hippeastrum bulbs grown at a low EC in the root environment were sensitive to “soft rot” (Van den Bos, 1996c); probably caused by Phytophthora (Laboratorium voor Bloembollenonderzoek, 1995). In dill and thyme the essential oil concentration was strongly decreased at low EC in the root environment (Udegawa, 1995).

Negative quality aspects of increasing salinity in cut flowers are the reduction of flower size, decrease of length and thickness of stems, and leaf loss and discolouring of the leaves (Baas et al., 1994; De Kreij and Van Os, 1989; Ploegman, 1976; Urban et al., 1995). Vase life is usually not affected by salinity (De Kreij and Van Os, 1989; Urban et al., 1995), although some negative effects on vase life have been reported in relation to increasing salinity (De Kreij and Van der Berg, 1990; Ishida et al., 1981; Rutland, 1972).

The results in our study are in good agreement with those in literature. Lowest feasible EC in the root environment is not always the optimum with respect to produce quality. Apart from the growth reduction which appears both in flowers as well as in vegetables, there appears to be a difference in salinity response to quality characteristics between flowers and vegetables. In flowers, apart from the reduced flower size with gerbera, no negative effects have been found with increasing salinity (see section 3.3), while in vegetables positive side effects of increasing salinity on the quality of the produce dominate (see section 2.3). Nevertheless serious attention should be paid to negative side effects in vegetables. The increasing risk of Ca deficiency with increasing salinity (Table 2.4), for example, is a serious problem. On the other hand positive effects of salinity with flower crops should not be excluded in advance. Tissues of flower crops may become water-saturated at low EC in the root environment, which easily causes glassiness and rot.

The optimum EC levels for quality of crops may conflict with these for maximum production. For greenhouse production, high quality standards must be maintained to survive in the competition with field products. Therefore, sometimes higher levels of nutrients, which means a higher EC, are maintained than necessary for maximum production and sometimes an EC beyond the salinity threshold value is maintained.

It is not always unequivocal what criterion should be taken into account to assess the optimum level of the EC in the root environment. Up till now mostly fresh weight of the harvested produce or total shoot weight are used to determine threshold (c_t) and SYD values (Maas and Hoffman, 1977; Maas, 1986). In fact it is often the economic value that counts. For many field crops the fresh weight of the produce is directly related to its economic value. However, for a number of crops the dry matter production is more important and, as discussed before, many crops show an increased dry matter content under saline conditions. Thus for crops of which the economic value is determined by the dry matter production, the salt tolerance should be evaluated as being higher than that on the basis of fresh weight production. For cut flowers, the total weight of the harvested produce, being the result of both the number of flowers and the flower size can be accepted as a parameter for the economic value. Sonneveld and Voogt (1983) compared SYD-values for the economic yield and total flower weights and found a good agreement for two anthurium cultivars, while those for hippeastrum were less in agreement. For this crop the price per peduncle appeared to be determined by the number of calyces and not by their size, while calyx size obviously affects total weight. In such cases the economic value is less affected by the salinity than is the total flower weight. For ornamental shrubs, Aendekerk (1980) used shoot length as a parameter to assess salinity response. Bernstein et al. (1972), however, point to the fact that for ornamental shrubs and ground covers no maximum growth is needed. To achieve a more compact habit, growth reduction can even be an advantage. Leaf burn, leaf drop and shoot necrosis seem to determine the economic value rather than the shoot length or weight does. Also

for bedding plants a compact habit at an increased EC in the root environment has been recognized as an advantage (Van Leeuwen, 1994).
In soilless cultures of the North-West European greenhouse industry, the EC in the root environment is a tool in the management of crop production. In this management mostly different parameters of the crop should be taken into account and the choice of these parameters differs for crops and depends on the quality demands of the market. In the assessment for the required EC in the root environment, maximum growth and production may conflict with quality characteristics. Ultimately, the economic results will determine the acceptable limits in which both, the direct profits for the individual grower and the long term effects on the market should be considered.
With respect to the required EC in the root environment there are no arguments for EC-values lower than necessary for optimum nutrition of the crop. Such values easily reduce yield and quality negatively. The determination of required EC-values higher than necessary for plant nutrition is a complex process, in which yield and quality should be considered in relation to the demand on the market, crop characteristics and climatic conditions. In this process relationships between EC on the one hand and yield and positive as well negative aspect on quality on the other hand will be helpful tools. Quantitative relationships for EC and yield are rather well developed, but quantitative relationships for quality characteristics are underexposed. With the work of Petersen et al. (1998) a start has been made for tomatoes. A further development is necessary.
With the determination of the acceptable EC the accumulation of residual ions should be considered to a level as high as possible, to restrict leaching and with this environmental pollution. The residual ions accumulate in addition to the nutrients to a level not harmful to yield and quality of the crop, which means that in view of acceptable EC-values the total EC seldom will exceed the salinity threshold value (c_t) as defined in Figure 1.2.

7.6 Estimation of the salinity in the root environment

In the previous section arguments for required and acceptable EC-values in the root environment were considered but no attention was paid to its determination. Problems in this field can be distinguished in two steps: the sampling procedure and the determination of ion concentrations and osmotic potential in the sample at the laboratory. The sampling procedures are important with respect to the unequal distribution of ions in soils and substrates and the determination in the laboratory with respect to the methods used.

Sampling procedure

The purpose in knowing the chemical composition of the root environment can differ and the sampling procedure should be adjusted to that purpose. Estimations of the soil salinity are used to determine the necessity for leaching, but are also used for control on crop development. The first situation will mostly occur before planting and the second situation during crop growth.
Formerly greenhouse soils were randomly sampled over a certain depth, because sampling was carried out annually and measures to control salinity were carried out on the basis of this sampling strategy. Later on samplings were carried out during cultivation and often adjusted to irrigation method and crop position. Practices with sampling in substrate systems are more or less derived from practices developed for soil growing. Research on soil sampling for salinity to control crop growth is limited, and this is even more the case for substrate systems. Because of the great spatial ion gradients in the root environment of substrate systems, it is not realistic to collect samples at random. In this way the possibilities for plants to escape from unfavourable

growing conditions in the root environment are ignored. Therefore, sampling at random for determination of salinity in the root environment is a misconception, considering the ability of plants to escape from high salinity spots. However, there was insufficient information as to what extent plant ability reaches.

The experiments with tomato and cucumber described in the chapters 4 and 5, respectively, were carried out to get some information about the effects of spatial variation in salinity in substrate systems. The results clearly show that, with strong variations, the interpretations are not straightforward. First of all it should be remembered that absorption of water and nutrients by plants are two independent processes. Furthermore it was shown that plants are able to absorb sufficient nutrients by a restricted part of the root system, preferably from spots with rather high concentrations. This is also indicated by other researchers (Geraldson, 1990; Kasten and Sommer, 1990). But, on the other hand, plants are also able to absorb the necessary quantities of nutrients from lower concentrated spots. It is mainly the presence of nutrients in the root environment that counts, provided that concentrations and mutual ratios are acceptable for an optimum absorption of nutrients. From this point of view, samples for estimating the availability of nutrients should be taken at random, giving the best estimation of the quantity and the average concentration of nutrients in the root environment.

From the data of experiments with cucumber (chapter 5) there is some evidence that with unequal distributions of ions the different concentrations in the root environment exhibit different salinity threshold and SYD-values. The threshold value of the root part with the highest EC seems to be higher and the SYD-value lower than the respective values of the root part with the lowest EC. In other words, plants seem to be able to compensate in the low concentrated root part for the stress experienced in the high concentrated root part. This is in agreement with Lunin and Gallatin (1965), who found with corn and tomato that growth was unaffected when one third of the root zone was salinized and only slightly affected when two thirds of the root zone were salinized. Also the data of Cerda and Roorda van Eysinga (1981) with tomato and Bingham and Garber (1970) with corn and Shani et al., (1993) with grapevine support this compensation concept. However, Kirkham (1969) and Shalhevet and Bernstein (1968) recommended the mean salinity as estimator for salinity in the root zone for bean and barley and alfalfa, respectively. The water absorption from the different salinized root parts in the latter cases was, however, in agreement with our findings.

On the basis of the results of the experiments discussed in chapters 4 and 5, the models summarized by Meiri (1984) given in the equation 1.4, 1.5 and 1.6 need some adjustments, as suggested in the paragraph “interpretations” of section 5.4. Bearing the considerations of the paragraph in mind, the following model can be hypothesized to estimate effects of unequal distributed salinity in the root zone:

$$Y_r = 1 - SYD_l\,(c_l - c_{tl}) - SYD_h\,(c_h - c_{th}) \qquad (7.17)$$

in which:

Y_r	= relative yield
SYD_l and SYD_h	= SYD values of the lowest and highest salinity levels in the root environment, respectively
c_l and c_h	= lowest and highest EC in the root environment, respectively
c_{tl} and c_{th}	= threshold values for lowest and highest EC in the root environment, respectively

furthermore: $c_l > c_{tl}$

$c_h > c_{th}$

$SYD_l > SYD_h$

It should be taken into account that equation (7.17) is based on data of experiments with only two different salinities in the root zone, both covering 50% of the root volume. Under practical growing conditions a wide range of concentrations occur. All these different concentrations, however, will be related to the highest and the lowest concentration in the root environment. So, it appears to be reasonable that inclusion of the highest and the lowest concentration is sufficient to have a good estimator of the salinity of the root zone. For an exact proof of this statement a check on the effects of the different gradients as found under standard growing conditions should be necessary. Nevertheless, for many substrate systems can it be expected that measurement of the EC of the irrigation water and the drainage water, representing the lowest and the highest concentration in the root environment, respectively will strongly improve the interpretation. In case of ebb and flow irrigation the lowest and highest value are found in the irrigation water and the top-layer of the substrate, respectively (De Kreij and Straver, 1988; Otten 1994; Schwemmer, 1990).

An exact estimation of the parameters of equation (7.17) is difficult, because they are dependent on crops and growing conditions (Lunin and Gallatin, 1965), as are the parameters of the formula of Maas and Hoffman (1977), from which equation (7.17) is derived. From the data of experiment 2 in Table 4.1 the conclusion can be drawn that for summer-grown tomato $c_{th} > 10.0$ dS m^{-1}. The data of experiment 2 in Table 5.3 a c_{th} can be calculated as about 4.0 dS m^{-1} for summer-grown cucumber and a SYD_h of 2.8%. From the same table for the winter-grown cucumber of experiment 3, $c_{th} > 7.8$ and no calculation of SYD_h is possible. In the event that an SYD_h is calculated, only the highest EC is taken into account and not the average of both root parts. The calculations made were possible, because $c_l < c_{tl}$ and thus $(c_l - c_{tl}) \leq 0$. Furthermore, they are calculated under conditions that both EC-values were maintained in half of the root environment. The volume of different spatial salinities in the root environment will certainly affect the overall salinity effects on plant development (Lunin and Gallatin, 1965). Therefore it is not yet clear whether these studies made in substrate systems with a restricted root volume are usable for field interpretations. It is obvious that the total root volume and the size of the spatial variation compartments are important, but experiments in this field could not be realized within this study. With crop growth under practical conditions different salinities will never be manifest as clearly separated compartments, but as salinity gradients. Thus no distinctly separated salinity threshold and SYD-values as hypothesized in equation (7.17) will be found, but the Maas/Hoffman model (Maas and Hoffman, 1977) will appear with a salinity threshold value $c_t' > c_t$ and a $SYD' < SYD$, in which c_t and SYD are the salinity threshold and the SYD-values, respectively, based on an equally distributed salinity of the root zone and c_t' and SYD' are the threshold and SYD-values, respectively, based on an unequally distributed salinity of the root zone with on average the same salinity. The data of the experiments 1 and 4 In Table 5.3 confirm these suppositions.

Extraction methods

The estimation of the osmotic potential of samples from the root zone is carried out by the determination of the EC of the soil/substrate solution or in an extract of the substrate samples. For hydroponic or hydroponic-related systems, like rock wool, gravel or expanded clay systems, it is often easy to collect the substrate solution. With high circulation speed of the solution, samples can be taken from the recirculating solution. If the speed of the solution is low, solution can be collected from the substrate by low suction with a simple syringe and if this is not possible with a syringe, like with peaty substrates, by soil moisture samplers. For peaty substrates, however, a 1:1½ v/v substrate/water extraction method has been developed (Sonneveld and Van Elderen, 1994); the EC in such extracts is highly correlated with the EC of the substrate solutions. By CEN (CEN/TC 223, 1998) a 1:5 v/v substrate/water extraction method has been developed. This method is suitable for all types of substrates. The drawback of this last method is the strong and varying dilution of the substrate solution. The variation in the dilution makes it necessary to recalculate the results of the EC measurements by taking the dilution into account as done in equation (7.18).

$$EC_{ess} = EC_{ew} * 5 / RWV \qquad (7.18)$$

in which:

EC_{ess} = estimated EC of the substrate solution
EC_{ew} = EC of the water extract of a substrate
RWV = relative water volume of the substrate under field conditions

When the substrate contains sparingly soluble salts, the strong dilution which usually occurs with the CEN method easily leads to an over-estimation of the EC of the soil/substrate solution (Reitemeier, 1946; Van den Ende 1989).

7.7 Salinity: osmotic effects

The most common effect on plant growth of osmotic stress in the root zone is the reduction of shoot weight, often coinciding with a reduction of leaf area, plant height and stem thickness. The assessment of the osmotic stress is not unequivocal and will depend on the goal of plant production. From a plant physiological point of view, the total dry matter production of plants is an obvious estimator. This is, however, often not the best estimator for the effect of salinity on the economic production value of crops and certainly not of greenhouse crops. Fresh weight and quality characteristics are more important for the economic value of greenhouse products than the dry matter production. The impact of salinity is, therefore, strongly dependent on the demand of the market and this complicates the estimation of the effect of salt stress on the economic production value. (See also the remarks about this subject in sections 1.2 and 7.5) In the present paragraph parameters for salinity in relation to fresh weight production of crops will be discussed firstly and afterwards these parameters will be discussed in relation to quality requirements.
In this study salinity threshold values between 2.3 and 3.5 dS m^{-1} were found for substrate grown vegetable fruit crops. The SYD values varied between 2.3 and 7.6% per dS m^{-1} (Table 2.3). Our data show a tendency to a higher salinity resistance for summer-autumn grown crops in comparison with spring-summer grown crops. A low SYD value for tomato crop 1 and a high threshold value for cucumber crop 2 were found; both crops were grown in summer-autumn.

With hydroponically or substrate grown cut flower crops in this study (Table 3.9) salinity threshold values between 1.1 and 2.1 dS m^{-1} were found. One higher value of 4.3 was estimated for carnation, but could not be confirmed. The high value (>4.2) mentioned for aster was found for the first flush of flowers, but regrowth after the first harvest was strongly negatively affected by high salinities, indicating that for long production periods the threshold value would be lower, especially with NaCl salinity (Table 3.6). So, the results with this crop indicate that various processes in plant development can be affected differently. Starting with a young plant in a high NaCl containing medium seemed clearly different from sprouting of old root stocks in it, where most likely the young buds were damaged. With the exception of the aster crop, the SYD values found in the study with cut flowers varied between 2.1 and 16.8% per dS m^{-1}.

In this study no pot plants were included. In literature, results of salinity studies with these crops are poor and often not suitable for a standardised comparison on basis of EC-values in the substrate solution of the root environment. The measurements of the salinities are often carried out in non-standardized extracts, so that the relation with the substrate solution EC remains unclear. At the Research Station for Floriculture and Glasshouse Vegetables at Aalsmeer, salinity experiments with a series of pot plants were published, in which the EC of the substrate solution and the fresh plant weights were carefully determined. The plants were grown on flooded benches in containers filled with peaty substrate and the EC-values were maintained with different concentrations of nutrients in the irrigation water. The EC in the root environment was determined in the bottom two-third part of the container, either by *in situ* soil moisture sampling or by substrate sampling. In the latter case the EC was determined in the 1 : 1½ water extraction (Sonneveld and Van Elderen, 1994) and recalculated to substrate solution. Mostly different cultivars were compared and in a number of cases the experiments were carried out under winter as well as under summer growing conditions. Threshold and SYD-values calculated are presented in Table 7.6. In some experiments the range of EC-values in the root environment did not allow the assessment of threshold and SYD-values. Among the crops tested, threshold values were found in the range from 0.7 dS m^{-1} to beyond 3.8 dS m^{-1}. SYD-values ranged from 4.2 to 33.0% per dS m^{-1}. Kalanchoe, begonia and nephrolepis seemed to be much more sensitive to salinity under summer than under winter growing conditions, showing much higher SYD-values with the summer grown crops. Such a conclusion is not possible for cyclamen, but the summer experiment was carried out under different screening regimes, the data of which are listed in Table 7.7. In this experiment the growth of cyclamen as affected by high EC under standard growing conditions, a whitewash screen combined with a movable screen at a global radiation beyond 600 W m^{-2}, were compared with growth under conditions with three levels of less extreme screening. It is clear that under standard growing conditions the growth of cyclamen is not or even a little positively affected by a high salinity. With less screening, thus higher radiation, growth is reduced by the high EC and the higher the radiation the greater the reduction.

Table 7.6. Threshold (c_t) and SYD values of pot plants as calculated from data of a series of experiments carried out at the Research Station for Floriculture and Glasshouse Vegetables, Aalsmeer. The calculations are based on the EC of the substrate solution.

Crop	Cultivar	c_t	SYD	Ref *
Kalanchoe blossfeldiana (winter grown)	*'Debby'*	> 3.8	-.-	1
	'Mirjam'	2.6	7.6	1
	'Singapore'	> 3.3	-.-	1
Kalanchoe blossfeldiana (summer grown)	*'Debby'*	3.3	17.2	1
	'Mirjam'	2.4	28.0	1

	'Singapore'	1.5	9.6	1
Cyclamen persicum (autumn grown)	*'Sierra'*	> 1.6	-.-	2
	'Vuurbaak'	> 1.8	-.-	2
Cyclamen persicum (summer grown)	*'Julia'*	> 3.6	-.-	5
	'Louisa'	> 3.6	-.-	5
Dendranthema	*'Applaus'*	3.0	5.5	3
	'Regal Davis'	2.6	4.6	3
Adiantum raddianum	*'Fragrantissimum'*	> 1.6	-.-	4
Asplenium nidus		1.5	33.0	8
Asplenium nidus		> 1.1	-.-	4
Aechmea fasciata	*'Morgana'*	> 2.6	-.-	6
Guzmania	*'Empire'*	> 1.9	-.-	6
Vriesea	*'Splenriet'*	0.7	4.2	6
Begonia (winter grown)	*'Schwabenland'*	1.8	7.1	7
Begonia (summer grown)	*'Schwabenland'*	2.0	21.9	7
Nephrolepis exaltata (winter grown)	*'Teddy Junior'*	2.0	10.5	8
Nephrolepis exaltata (summer grown)	*'Teddy Junior'*	2.0	25.3	8
Nephrolepis exaltata		2.0	13.7	9

* Ref: 1: Verberkt et al., 1996; 2: Verberkt and De Jongh, 1995; 3: Bulle et al., 1996; 4: Mulderij and De Jongh, 1995; 5: Verberkt, 1997; 6: Mulderij, 1994; 7: Straver, 1991a; 8: Mulderij, 1993; 9: Straver 1991b.

The determination of the EC at the bottom two-third of the containers seems to be a right measure, because of the high EC which usually occurs in the top layer in flooded bench systems. This was also the case in the experiments discussed in Table 7.6. An example of such high ion accumulations is shown in Table 7.8 for the kalanchoe crop (Verberkt et al., 1996). The EC in the top layer can increase strongly, especially when the evaporation from the surface of the pot is high, as may be expected in summer. It did not seem realistic to take these high values into account in the measurements.

In Table 7.9 threshold and SYD-values for some bedding plants are summarized. The data are derived from experiments at the Research Station for Floriculture and Glasshouse Vegetables, where the crops were grown in containers filled with peaty substrate on flooded bench systems, and from Huang and Cox (1988) where they were grown in solution culture. In the experiments at the Research Station for Floriculture and Glasshouse Vegetables the different EC-values in the root environment were established by addition of different nutrients and in the experiments of Huang and Cox (1988) by addition of $CaCl_2$ and NaCl. With the flooded bench system the bottom two-third of the substrate layer was used to measure the EC of the substrate solution. The threshold values calculated for bedding plant range from 0.6 to 3.1 dS m^{-1} and the SYD values from 3.7 to 26.2% per dS m^{-1}. The threshold values as well as the SYD-values are more or less in the same range as the pot plants.

Table 7.7. SYD-values for shoot fresh weights (% per dS m^{-1}) between EC 1.5 and 4.0 dS m^{-1} in the root environment of summer grown cyclamen at different screening regimes (Verberkt, 1997).

Screening regime		Cultivars	
Fixed screen	Movable screen	*'Julia'*	*'Louisa'*
Whitewash	at 600 W m^{-2}	0	+ 4.6
No	at 300 W m^{-2}	- 5.4	- 4.0

No	at 600 W m^{-2}	-10.6	- 4.2
No	at 800 W m^{-2}	-12.0	- 9.9

Table 7.8. EC as found in the bottom two-third and the top one-third of the containers at the end of the experiment with kalanchoe cv *'Debby'* (Verberkt et al., 1996). The EC was determined at the end of the experiment by means of the 1:1½ water extract and expressed as dS m^{-1} of the extract.

Winter grown crop			Summer grown crop		
Addition	Bottom	Top	Addition	Bottom	Top
1.2	0.6	1.8	1.5	1.7	6.7
1.8	1.1	2.9	1.8	2.2	6.9
2.2	1.4	3.7	1.9	2.4	8.9
2.6	1.8	4.9	2.2	2.4	7.4

Table 7.9. Threshold (c_t) and SYD-values of bedding plants as calculated from data of the Research Station for Floriculture and Glasshouse Vegetables (Ref 1 and 2) and from literature (Ref 3).

Crop	Cultivar	c_t	SYD	Ref *
Impatiens	*'Impuls'*	1.4	4.9	1
Impatiens	*'Delias'*	1.8	26.2	2
Impatiens	*'Aglia'*	1.4	13.8	2
Impatiens	*'Thecla'*	0.6	14.2	2
Petunia grandiflora	*'Flash Blue'*	> 1.9	-.-	1
Pelargonium X	*'Jackpot'*	3.0	8.3	3**
Tagetes erecta L	*'First Lady'*	3.1	3.7	3**

* Ref: 1- Mulderij, 1998; 2- Verberkt and Van den Berg, 1993; 3- Huang and Cox, 1988.
** based on dry matter production.

Pot plants respond to salinity stress by reduction in size of the whole plant and with moderate salinities mostly no other negative quality aspects were shown. In the experiments at the Research Station for Floriculture and Glasshouse Vegetables careful attention was paid to the appearance and the shelf life of the plants. Only summer grown cyclamen showed a shorter shelf life with increasing salinity (Verberkt, 1997). With other crops no significant differences in shelf life have been found up to the maximum EC-values between 2 and 5 dS m^{-1} which were realised in the substrate solution.

With respect to flowering contradictory effects were found. With begonia flowering was delayed (Straver, 1991a), while kalanchoe flowered earlier at increasing EC-values (Verberkt et al., 1996). Chrysanthemum (*Dendranthema*) showed a better flower colouring when grown at higher EC, but exhibited a higher sensitivity to Botrytis (Bulle et al., 1995). Guzmania showed unequal leaf colouring at high EC (Mulderij, 1995). Nolan et al. (1982) showed that leaf necrosis with Maranta (*Maranta leuconeura* var.*kerchoviana*) was increased by NaCl salinity at a substrate solution EC of about 5 dS m^{-1} under low light intensity and of about 3 dS m^{-1} under high light intensity, and with Stromanthe (*Stromanthe amabilis*) at an EC of about 7 dS m^{-1} under low light

conditions and at 3 dS m^{-1} under high light conditions. Brassia (*Brassia actinophylla*) and Dieffenbachia (*Dieffenbachia amaculata*) grown under the same conditions did not show any necrosis at high substrate EC.
With respect to bedding plants, impatiens showed wilting and leaf burn at EC values in the substrate solution between 3 and 5 dS m^{-1} (Verberkt and Van den Berg, 1993). Marigold and geranium showed leaf injury by NaCl/$CaCl_2$ salinity at an EC of 7.4 dS m^{-1} (Huang and Cox, 1988).

7.8 Salinity: toxicity and nutrient disturbance

The assessment of toxicity and nutrient disturbance phenomena in salinity studies depends on the proper choice of a reference. This choice is debatable because the question is with which the specific ion in the experiments should be compared. With comparisons to discriminate between osmotic and specific salinity effects, soluble organic compounds with a high molecular weight are often introduced, because they are hardly or not absorbed by plants. The most common compound used for this purpose is polyethylene glycol (PEG).
The use of PEG is questionable since it is known that with long-term salinity it is mostly not the direct availability of water at low (negative) osmotic potentials that is responsible for the growth reduction of crops grown under saline conditions, but rather the adjustments made by plants to escape from this effect. Part of the adjustments made by crops will consist of uptake of extra ions. This uptake is promoted by higher concentrations of ions responsible for the salinity in the root environment. Also comparisons of increase of specific salts with a general increase of all nutrients does not ensure a strict discrimination between osmotic and specific ion effects. A good example of this difficulty has been shown in the experiments of West et al. (1980) with a series of ornamentals, comparing PEG and NPK iso-osmotic solutions. For a number of ornamentals, the osmotic stress in the PEG solutions was more severe than in the NPK solutions. Possible explanations for this phenomenon are (1) toxic effects of PEG absorbed by the plants, (2) toxic compounds as impurities in the PEG, (3) insufficient possibility for the plants in the PEG treatments to adjust for the osmotic stress, as indicated before, and (4) fertilization effects caused by too low fertilizer applications in the control treatment; part of the overdosed nutrients given in the high NPK treatments as osmoticum could have improved growth in these treatments, because of a sub optimum concentration of some nutrient in the control and PEG treatments.
The best method to discriminate between osmotic and specific effects are comparisons between series of salts, preferably different for only one ion and compared in different concentrations. However, such experiments are handicapped because of different valences of ions. It is impossible to prepare solutions of binary and tertiary salts of equal osmotic potential and different for one ion at equal concentrations. For example, preparation of Na and Ca in iso-osmotic solutions with Cl as accompanying ion in both cases, results in solutions in which the total ion concentrations consist of 50% of Na and 33_% of Ca, respectively. Another handicap in such comparisons are the different activities of ions, varying for ionic type and concentrations, so that solutions with an equal number of "ions" do not have an equal osmotic potential. In conclusion, mostly osmotic and specific salinity effects can only roughly be discriminated.
At the Research Station for Floriculture and Glasshouse Vegetables specific ion effects for greenhouse crops have been established on the basis of an equal concentration (equal number) of "ions" in the irrigation water (Sonneveld and Van den Ende, 1975; Sonneveld and Voogt 1978; Sonneveld, 1979; Sonneveld 1988). It was shown that yield responded mainly to the osmotic potential. Only the addition of bicarbonate caused huge specific yield reductions caused by

sodicity. With respect to quality characteristics, specific ion effects often play an important role. For greenhouse crops the following specific effects have been found.

Sodium chloride

Specific sensitivity to NaCl is a well known phenomenon (Greenway and Mums, 1980), but not frequently found in studies with greenhouse crops. Our study of salinity effects on vegetable crops grown in substrates (Chapter 2) allows the conclusion that cucumber is specifically sensitive to sodium chloride, because of the stronger yield reduction of this crop by addition of NaCl in comparison with addition of extra nutrients. Also in earlier experiments in soil grown crops, the sole addition of NaCl caused a stronger yield reduction in comparison with a mixture (Na, Cl, Ca, Mg, SO_4 and HCO_3) of salts (Sonneveld and Van Beusekom, 1974a). So far, it is not clear whether Na or Cl is responsible for this specific yield reduction. In another study with cucumber (Sonneveld and Voogt, 1978), no specific effects of NaCl were found. The specific sensitivity of bouvardia to NaCl found in our study (Chapter 3) could be attributed to an effect of Na. The problems with regrowth of aster after the harvest of the first flush of flowers in the same investigation were not studied in further detail, but are probably caused by Na, because this element often accumulates in roots and lower plant parts (Besford, 1978; Blom-Zandstra et al., 1998; Jacoby, 1979; Savvas and Lenz, 1996) and is toxic to plants (Bernstein, 1976). Absorbed Na can easily disrupt plant tissues (Maas and Nieman, 1978), often by interference of a reduction of the K absorption (Hecht-Buchholz, et al., 1979; Yeo and Flowers,1984), which is in full agreement with our result for bouvardia (Table 3.5). The NaCl effects with aster show that some salinity effects are only manifest in older crops and need to be investigated in long-term experiments. It is to be expected that more flower crops used in the greenhouse industry are specifically sensitive to NaCl.

Calcium

The reduced uptake and insufficient distribution of Ca is the most well-known specific ion effect occurring under saline conditions in greenhouse crops. The notorious occurrence of Ca deficiencies under greenhouse conditions can be related to the growth rate and the air humidity, both of which are sometimes high for longer periods under greenhouse conditions. These factors have been well identified as promoting Ca deficiency disorders in leaves (Adams and Ho, 1995; Bakker and Sonneveld, 1988; Collier and Tibbitts, 1984; Wiersum, 1965).
Ca disorders related to high salinity in fruits of vegetable crops are known as blossom-end rot (BER) in tomato (Adams and El-Gizawy, 1986; Adams and Ho, 1993a), eggplant (Savvas and Lenz, 1994a) and pepper (Chapter 2; Sonneveld en Van Beusekom, 1974), but are promoted by low humidity. Ca deficiency in fruit vegetable crops caused by high salinity may also occur in young leaves, as has been demonstrated by tomato and cucumber (Chapter 6; Ho and Adams, 1989; Ho and Adams, 1994). The phenomenon is especially evident in greenhouses, when a high growth rate of leaves (young plants) is combined with a high humidity (closed ventilators). Ca deficiency caused by high salinity levels is also well-known for leafy vegetables such as lettuce (Sonneveld and Van Beusekom, 1974a; Wiebe, 1967), celery (Geraldson, 1957) and chinese cabbage (Van Berkel, 1987), where it causes tipburn, black heart and tipburn, respectively. Besides the osmotic potential the ion composition of a soil/substrate solution may be of great importance in promoting the disorder (Geraldson, 1957; Sonneveld and Van den Ende, 1975; Sonneveld, 1988).

Ca applications can be too high as well. This has been demonstrated with cucumber, where it caused specific growth reduction and leaf chlorosis and necrosis (Abed, 1973; Shimida, 1973; Sonneveld and Voogt, 1978) and with tomato, pepper and eggplant fruits, where it caused gold speck (De Kreij et al., 1992), green spot (Janse and De Kreij, 1989; Voogt and Sonneveld, 1985) and calyx browning (Maaswinkel, 1988), respectively. Disorders promoted by too high Ca absorption in fruits can be controlled by increasing EC values (Chapter 2).

Potassium and magnesium

The addition of K and Mg mostly does not result in specific symptoms of toxicity in plants. An abundant application of these ions, however, reduces the uptake of Ca. The fact that K and Mg sometimes reduced stronger Ca uptake (Sonneveld and Voogt, 1978) and induced more Ca deficiency (Adams, 1991; Adams and Ho, 1993b) when compared with iso-osmotic concentrations of Na, can be explained by the fact that K and Mg are easier absorbed and transported to shoots than Na. This phenomenon, however, is not reported frequently and great differences among crops may occur (Sonneveld and Van den Ende, 1975; Sonneveld, 1979). In a study focussed on effects of absorbed cations on the incidence of tipburn in lettuce it has been found that increasing K as well as Ca concentrations of tissues reduced the appearance of tipburn, while Na and Mg promoted the incidence (Sonneveld and Mook, 1983). Extremely high applications of Mg in cucumber caused specific chlorotic and necrotic symptoms (Abed, 1973; Sonneveld and Voogt, 1978) and affected enzyme activity in the roots (Shimida, 1973).

Phosphorus

In most soils the P level in the soil solution is low and osmotically unimportant. However, salinity may interact with P, but this effect depends on plant species and concentration (Maas and Nieman, 1978; Cerda et al., 1977; Cerda and Bingham, 1978). For a restricted number of plant species the uptake of P may become too high and toxic, for some cultivars of sensitive crops even under field grown conditions (Howell and Bernhard, 1961), while the concentration in the soil solution is generally much lower than in substrates. Increasingly, P toxicity may be expected in substrate growing, where the P level in the root environment can become high, especially when EC-values are increased by nutrient supply. This was found with a cucumber cultivar (Zijlstra et al., 1987), but may certainly be expected with other crops. High salinity aggravates the uptake of P (Grattan and Maas, 1988a; Roberts et al., 1984), which is caused by synergy between P and Cl (Grattan and Maas 1988b). P can affect strongly the absorption of Ca, which was demonstrated with tomato. At low P levels Ca uptake is reduced, aggravating blossom-end rot (De Kreij, 1996) and high levels of P increased the Ca uptake and, consequently, the occurrence of gold speck (Voogt and Sonneveld-Van Buchem, 1989).

Nitrate and sulphate

NO_3 and SO_4 are not known as ions that cause specific toxicities at high concentrations. High SO_4 concentrations apparently are able to reduce the Ca uptake (Bernstein, 1976), but this was not confirmed with Na_2SO_4, when compared with other Na-salts (Sonneveld and Van den Ende, 1975). Replacement of NO_3 by Cl in nutrient solutions for tomato increased the Ca uptake (Voogt, 1992). It is not clear, what this phenomenon results from; the higher Cl, the lower NO_3, or a combination of both changed concentrations.

7.9 Interpretations for the EC in the root environment in relation to plant growth

In the foregoing paragraphs it has been made clear that crops show a wide range in their sensitivity to salts. It is, therefore, impossible to establish a general salinity threshold EC or a general maximum acceptable concentration for a specific ion below which optimum production and quality of different crops or even for a specific crop is ensured. Growing conditions have a substantial effect on salt sensitivity. On the other hand, this offers prospects for affecting the sensitivity of crops to salinity especially in greenhouses, because there the growing conditions can be more or less controlled. Discerning factors affecting salinity effects on crops are:

- supply of water and nutrients
- method of water supply
- air temperature and humidity
- evaporation rate
- CO_2 supply
- light intensity

That is why Gale and Zeroni (1984) stated that many greenhouse plants can be grown at an osmotic potential in the root environment of 1 - $2*10^5$ Pa, equivalent to an EC of 3 - 6 dS m^{-1}. These values are mentioned by authors in relation to what they call “controlled environment agriculture (CEA)” conditions, characterized by a constant ion concentration and high water potential around plant roots, low evapotranspiration potential, moderate temperatures, and carbon dioxide supply.
External factors that interact with salinity effects on plant development have been already identified decades ago. Magisted et al. (1943) grew several crops at different sites and salinities and concluded that for most crops relative yield was more depressed by salts in warm than in cool climates. The climates described by these authors differed not only in temperature, but also in humidity. More recently humidity has been recognized as a major factor. For different crops it has been found that growth reduction by salinity was alleviated by higher humidity (Hoffman and Rawlins, 1971; Kaminski und Lüdders, 1989; Salim, 1989). However, the very high humidity in experiment 3 described in chapter 6 showed a reverse effect. This is probably an exception caused by Ca deficiency in the leaves. The deficiency was already triggered by a high humidity and aggravated by an increasing EC in the root environment, as discussed in section 6.4. The data presented for kalanchoe, begonia and nephrolepis in Table 7.6 and for cyclamen presented in Table 7.7 confirm the general tendency found in literature that in cool and humid climates plants suffer less from high salinity.
The influence of temperature on salinity effects on crops is mostly not clear, perhaps because optimum temperatures are very crop specific. Lunt et al., (1960) found slight interactions between salinity and temperature with kidney beans; the SYD-value was increased by increasing temperature. The effect of light intensity on salinity effects on crops is not unequivocal either. Mostly, growth reduction by salinity is intensified at increased radiation levels, as has been found for radish and bean (Nieman and Poulsen, 1971) for strawberry (Awang and Atherton, 1994) and for tomato (Charbonneau et al.,1988). The effects found by Meiri et al. (1982) with muskmelon are not in line with this rule. The salinity threshold value in the saturation extract in the full sun was 3.1 dS m^{-1} and decreased to 0.8 dS m^{-1} under shaded conditions, which means 5.0 and 1.3 respectively in the soil solution. The SYD-value decreased for the shaded crop. However, the overall effect in their study was a higher salt resistance at higher radiation. Generally, CO_2 supply leads to increased salt tolerance, as was found for different crops (Feigin et al., 1989; Schwarz, 1984; Zeroni and Gale, 1989). Mavrogianopoulus et al. (1999) did not find an interaction

between NaCl salinity and CO_2 enrichment with melons. It should be emphasized that under practical growing conditions temperature, light intensity, and humidity are often strongly related. This implies that effects of the single environmental factors mentioned cannot always be clearly assessed; therefore it has been suggested to distinguish between "hot and dry" and "cool and humid" (Maas and Hoffman, 1977).

Another factor affecting salinity effects on crops is the method of water application. The differences resulting from different application methods are the ion distribution in the soil and the occurrence of leaf injury by overhead sprinkling with saline water. The sensitivity of crops to leaf injury differs strongly as has been reviewed by Maas (1985). The EC of the irrigation water that can be used safely for overhead sprinkling varies between < 0.5 and 3.0 dS m^{-1}. Also the frequency of sprinkling is important (Bernstein and Francois, 1975); a high frequency aggravated leaf injury and yield reduction. This, however, does not explain the great differences between furrow, drip and sprinkler irrigation as have been found by Bernstein and Francois (1973) with saline water. The effect was attributed to "osmotic shock" by flushing ions accumulated at the soil surface between irrigations into the root zone at next irrigation by the sprinkler and furrow irrigated plots. This explanation, however, paid insufficient attention to effects of the ion distribution as such. Drip irrigation allows crops an excellent osmotic escape. Frequent irrigations, usual with this method, ensure a stable equilibrium between a low concentrated spot at the dripping point and higher concentrations in surrounding areas. Plants are able to adjust with their root system to such a stable situation and react mainly on the low concentrated area, as has been shown in our study for tomato and cucumbers in chapters 4 and 5, respectively.

In conclusion, salinity threshold values and and SYD-values must be interpreted in relation to growing conditions. The values of 3 - 6 dS m^{-1} for greenhouse crops, as suggested by Gale and Zeroni (1984), seem to have a realistic basis under "cool and humid" climatic conditions, drip irrigation, and CO_2 supplementation. Such conditions can be realised in greenhouses in North-West Europe from autumn until early spring. Then they are in agreement with our findings in this study. For summer conditions in greenhouses in this area, the values for threshold and SYD found in the experiments described in the chapters 2 and 3 are more realistic. However, in the interpretations, more credit should be given to ion distribution in the root environment. The stable equilibrium as mentioned before, that occurs with drip irrigation between low and high concentrated spots also exists in substrate systems. The lowest concentrated spots usually will be found under the dripping points and the highest spots at drainage points This also creates an excellent osmotic escape for plants, which apparently strongly increases the "salinity resistance" of crops. To a certain extent interpretation of the salinity status of a substrate system based on the EC of the irrigation water is obvious. An "adjusted" basis for interpretation of the salinity status is also necessary for pot plants grown on flooded benches. The strong EC gradient from top to bottom (De Kreij and Straver, 1987; De Kreij 1995; Otten, 1994; Schwimmer, 1990) disturbs the relation between growth and average EC in the root environment. As in our studies, most of the water is absorbed from the low concentrated zones, thus in this case from the bottom parts (Otten, 1994). Therefore, plant growth will react mainly to the ion concentration at the bottom part of the containers. Sampling of such containers for routine soil testing after removal of the top layer of the substrate is common practice (IKC, 1994) and seems to be a right measure. However, this does not mean that the very high EC of 20-30 dS m^{-1}, as can be found in the top layer, would not affect growth at all. Our studies show that such high values in part of the root environment may indeed reduce plant growth. Besides growth reduction during production, the high values in the top layer may shorten shelf life, especially when the water supply pattern is changed from bottom-up in the benches to top-down by consumers (Bulle et al., 1996; Verberkt and Van den Berg, 1993). It should be emphasized that the sampling technique described only counts with

flooded bench irrigation. With watering from top an upside down ion distribution can be expected (Ku and Hershey, 1991). Then just the top layer is important for the water absorption and the sampling method should be adjusted to it.
A relation diagram for factors affecting salinity stress on plants is shown in Figure 7.1. The factors taken into account can aggravate the salinity effects (+) or diminish them (-).

7.10 Salinity and fertilization

Salinity and nutrient supply in the root environment are controlled to achieve optimum yield and quality combined with a maximum uptake efficiency of plant nutrients and a minimum environmental pollution. The ion distribution in the root zone is important, as has been shown in our studies described in the chapters 4 and 5. The ion distribution is mainly affected by the irrigation method, the leaching fraction, the substrate and substrate system properties, the water and nutrient uptake by the plant, and the ionic composition of the solution supplied. Furthermore, the evaporation can affect the ion distribution, but is excluded in many substrate systems by covering the surface. In substrate systems with accumulation of ions a gradual increase of the concentration from irrigation to drainage sites can be expected. The average ion concentration then mostly can be estimated as follows (Sonneveld and Voogt, 2001):

$$EC_{ss} \approx 0.5\ (EC_s + EC_d) \qquad (7.19)$$

in which:

EC_{ss} = estimation of the average EC of the substrate solution in dS m^{-1}
EC_s = EC of the irrigation water in dS m^{-1}
EC_d = EC of the drainage water in dS m^{-1}

Furthermore, the system obeys the following relationship:

$$EC_s = (1 - LF)\ EC_u + LF\ EC_d \qquad (7.20)$$

in which:

LF = leaching fraction of the irrigation water
EC_u = EC of the uptake solution in dS m^{-1}

Figure 7.1 Relation diagram for factors affecting salinity effects on plants

At a given EC_{ss} and EC_u the relationship between LF on the one hand and EC_s and EC_d on the other hand can be calculated. An example is shown in Figure 7.2 for an EC_{ss} = 4.0 dS m^{-1} and an EC_u = 1.5, data more or less representative for tomatoes (Table 7.2; Sonneveld and Straver, 1994).
The difference between EC_s and EC_d increases at decreasing leaching fraction, giving the plant the best osmotic escape. Thus, in case a high EC_{ss} is required for control on crop growth, a high leaching fraction is desirable to equalize the differences in the root environment, allowing the crop less osmotic escape. For plant nutrition the leaching fraction is not relevant, because the plant will absorb nutrients preferably from parts with a high concentration, but also low-concentrated spots may contribute, as long as the mutual concentrations are rather well balanced and the average total concentration in the root environment is 1.5 dS m^{-1} or higher, as has been discussed in section 7.4. When residual ions accumulate in the root environment, leaching is necessary. On the one hand leaching should be restricted as much as possible to prevent environmental pollution, but on the other hand adverse effects on plant development should be prevented. Thus the leaching fraction should be tuned to minimum values giving the plant an escape from osmotic stress injury around the irrigation point.

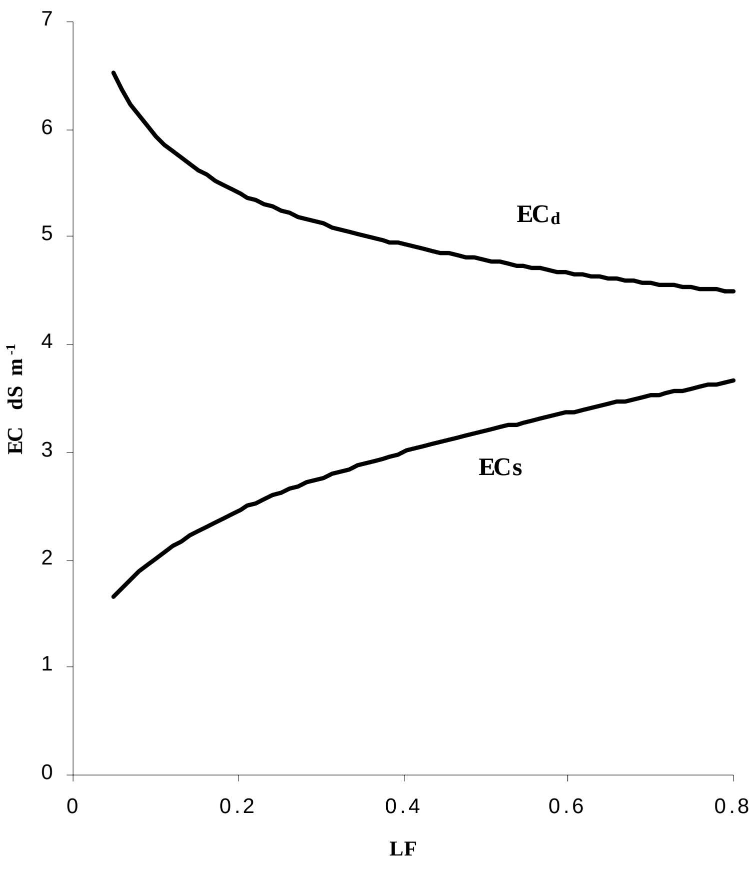

Figure 7.2 The relationship between the leaching fraction (LF) and the EC of the water supplied (EC_s) and the drainage water (EC_d) and the average concentration of the substrate solution (EC_{ss}) of 4.0 dS m^{-1} and a nutrient uptake corresponding with an EC of 1.5 dS m^{-1}.

When residual ions accumulate in the root environment, the nutrient level can be gradually reduced to an acceptably low level for plant nutrition. In a residual space in the substrate solution, ions may accumulate up till acceptable and must accumulate up till required total EC values. In such cases mostly plant development is not affected negatively. From this view-point EC_{ss} can be described as:

$$EC_{ss} = EC_{ss(Nu)} + EC_{ss(Re)} \qquad (7.21)$$

in which:

$EC_{ss(Nu)}$ = minimum EC required for plant nutrition in dS m^{-1}
$EC_{ss(Re)}$ = EC available for residual ions in dS m^{-1}

Following the model of equation (7.19), $EC_{ss(Nu)}$ and $EC_{ss(Re)}$ can be described as:

$$EC_{ss(Nu)} = 0.5\ (EC_{s(Nu)} + EC_{d(Nu)}) \qquad (7.22)$$

and:

$$EC_{ss(Re)} = 0.5\ (EC_{s(Re)} + EC_{d(Re)}) \qquad (7.23)$$

and thus:

$$EC_{ss} = 0.5\ (EC_{s(Nu)} + EC_{d(Nu)} + EC_{s(Re)} + EC_{d(Re)}) \qquad (7.24)$$

in which:

$EC_{s(Nu)}$ = EC caused by plant nutrients in the irrigation water in dS m^{-1}
$EC_{d(Nu)}$ = EC caused by plant nutrients in the drainage water in dS m^{-1}
$EC_{s(Re)}$ = EC caused by residual ions in the irrigation water in dS m^{-1}
$EC_{d(Re)}$ = EC caused by residual ions in the drainage water in dS m^{-1}

For a given ion concentration in the irrigation water and uptake concentration of the crop, the concentration in the drainage water can be calculated as follows:

$$c_d = [c_s - (1 - LF)\ c_u\ ] / LF \qquad (7.25)$$

in which:

c_d = concentration of an ion in the drainage water in mmol l^{-1}
c_s = concentration of that ion in the irrigation water in mmol l^{-1}
c_u = uptake concentration of that ion in mmol l^{-1}
LF = leaching fraction

The corresponding contribution to the EC for a given ion of a given concentration can be calculated by formula (7.15) when the calculation is made for a mixture of ions, while for specific ions the formulae of McNeal et al. (1979) should be used. For NaCl up to 50 mmol l^{-1} following formula is derived from McNeal et al. (1979) and Sonneveld et al. (1966).

$$EC_{(NaCl)} = 0.115\ c_{(NaCl)} \qquad (7.26)$$

in which:

$EC_{(NaCl)}$ = contribution to EC in dS m^{-1} caused by NaCl at concentration c_{NaCl} in the solution
$c_{(NaCl)}$ = NaCl concentration in the solution in mmol l^{-1}

The residual space in the solution in the root environment ($EC_{ss(Re)}$) depends on crop, growing conditions, required fertilization level, growing system and leaching fraction. Calculations should be made for every individual situation. In Figure 7.3 the relationships between the NaCl concentration in the irrigation water and its contribution to the total EC in the root environment for a tomato and a rose crop are shown, both with a leaching fraction of 0.25. For tomato the recommended EC in practice is chosen, being a value of 3.7 dS m^{-1} for nutrients (De Kreij et al., 1997a) plus the usual small space of 0.3 for residual ions. For rose the salinity threshold value 2.1 dS m^{-1} given in Table 3.9 is selected as an example. When a nutrient level ($EC_{ss(Nu)}$) of 1.5 dS m^{-1} will be maintained, the residual space $EC_{ss(Re)}$ is 2.5 and 0.6 respectively. The absorption of NaCl by the crop is fixed equal to that of $c_{u(Na)}$, being the element with the lowest uptake of both Na and Cl.

Figure 7.3 The relationship between the NaCl concentration in the irrigation water ($c_{s(NaCl)}$) And the EC originated by the nutrients in the irrigation water ($EC_{s)Nu)}$ and in the drainage water ($EC_{d(Nu)}$) and the EC originated by NaCl in the irrigation water ($EC_{s(NaCl)}$) and in the drainage water ($EC_{d(NaCl)}$) for a tomato and a rose crop. The leaching fraction, average EC of the substrate solution and the EC of the nutrient uptake for tomato was 0.25 and 4.0 dS m^{-1} and 1.5 dS m^{-1}, respectively, and those for rose 0.25, 2.1 dS m^{-1} and 0.6 dS m^{-1}, respectively.

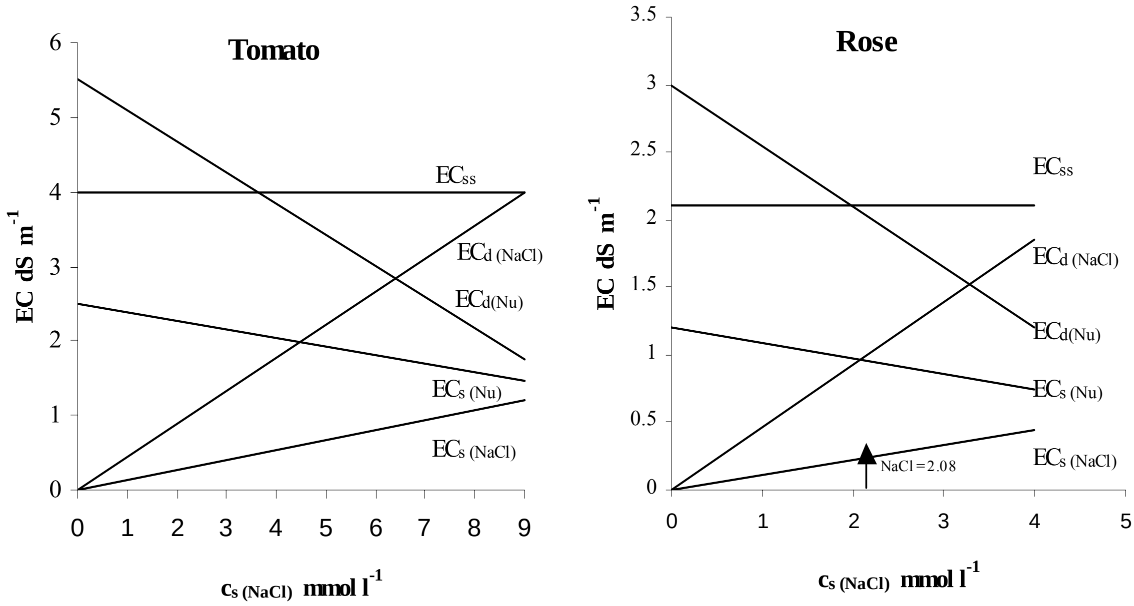

Figure 7.3 clearly shows that for tomato a NaCl concentration in the irrigation water of 9.5 mmol l^{-1} is acceptable, while for rose only 2.1 mmol l^{-1} is acceptable to keep the nutrient level sufficiently high and the EC_{ss} values within the limits set. The threshold value of 2.1 dS m^{-1} for rose, however, may be considered as acceptable in that part of the root environment where the concentrations are lowest i.e. the irrigation water, in this way giving the plant a sufficient osmotic escape. The corresponding values in the root environment are given in Table 7.10. Under these

conditions a NaCl concentration in the water supplied of 9.9 mmol l^{-1} should be acceptable, while in the drainage water a NaCl concentration of 39.7 mmol l^{-1} and an EC of 6.6 dS m^{-1} prevail. These values seem acceptable for tomato, but were too high for cucumber. For rose, however, no experimental data are available. Effects of unequal distribution should firstly be studied with this crop.

Table 7.10. Calculated EC values in the root environment for a rose crop on basis that an EC value of 2.1 dS m^{-1} in the irrigation water is accepted. The leaching fraction is maintained at 0.25 and the uptake concentration at 0.6 dS m^{-1}.

EC values calculated	Abbreviation	dS m^{-1}	Equivalent NaCl mmol l^{-1}
EC water supplied	EC_s	2.10	
EC drainage water	EC_d	6.60	
EC nutrients in the irrigation water	$EC_{s(Nu)}$	0.96	
EC nutrients in the drainage water	$EC_{d(Nu)}$	2.04	
EC residual ions in the irrigation water	$EC_{s(Re)}$	1.14	9.9
EC residual ions in the drainage water	$EC_{d(Re)}$	4.56	39.7

It should be considered that, at high salinity, residual ions may hinder the uptake of nutrients or may cause toxic adsorptions by the crop. Then adjustment of the nutrient supply will be necessary. Such an effect has been shown to occur in the bouvardia experiments described in chapter 3, where the crop was less negatively affected by Na combined with a high rather than with a low nutrient level. More frequently a reduced uptake of Ca and Mg occurs at high salinity levels. For crops sensitive to this phenomenon, an increase of the Ca or Mg concentration is desirable at high salinity. In addition to an extra supply of these elements, a change of the K/Ca or Mg/Ca ratios without EC increase could be considered, which can be very effective. However, this may easily result in too low K supply, when the residual space of the EC is occupied by Na. When the residual space is filled solely with nutrients a change of the ratios is preferable, because of the sufficiently high K concentrations.
With pot plants a completely different pattern of ion distribution occurs. These plants are mostly grown in peaty substrates and irrigated by flooded bench systems. The movement of water and ions is characterized by ion accumulation in a small volume and movement from bottom to top by evaporation of the top layer of the substrate. Thus, high ion concentrations in the top layer of the containers frequently occur, as described in section 1.5 and shown by the data in Table 7.8, with nearly no possibility to control them. Rough calculations show that with rather low NaCl concentrations in the irrigation water a very high EC will occur in the top layers of pot plants if NaCl, not absorbed by the crop, accumulates in the one third top layer of the substrate used. Results of such calculations for an imaginable crop are shown in Table 7.11. The parameters used for the calculations are based on data of Otten (1994) and Van Gemert (1994). It is clear that relatively low NaCl concentrations in the irrigation water can be responsible for a very high EC in the top layers of the substrate of pot plants. EC-values of over 20 dS m^{-1} are not exceptional, and under practical conditions, such high values have been found after addition of too high concentrations of fertilizers in the irrigation water.

Table 7.11. Calculation of NaCl accumulation during one year in the substrate system with pot plants in a flooded bench irrigation system. The water use is 450 l m^{-2}, the evaporation fraction 0.3, the quantity of substrate used 60 l m^{-2}, and the water fraction of the substrate under field

conditions 0.6. The accumulation is supposed to occur in the upper one third of the substrate containers. The uptake concentrations of Na are fixed at an average, estimated from values found with other horticultural crops in this study.

$c_{s(NaCl)}$ *	Na added**	$c_{u(Na)}$*	Na absorbed**	$c_{ss(NaCl)}$*	EC_{ss}***
0.3	135	0.2	63	6	0.7
2.0	900	0.4	126	64	7.4
4.0	1400	0.6	189	101	11.6
6.0	2700	0.8	252	204	23.5

*mmol l^{-1}; **mmol m^{-2}; ***dS m^{-1}

Up till now, the effects of the very high concentrations in the top layers of pot plant containers have been insufficiently studied and, therefore, not fully understood. In our study with tomato and cucumber (chapters 4 and 5) such high concentrations in part of the root environment reduce growth. The bottom-up distribution in the pot plant containers, however, cannot unconditionally be compared with the distribution in the tomato and cucumber experiments. Therefore, for pot plants a further study is necessary. Besides, effects during the growing period, attention should be paid to shelf life effects. Consumers often change the water supply from bottom-up to top-down, leaching the high ion concentration from top down in the root zone. First experiments showed slightly negative effects of such a treatment on the shelf life of pot chrysanthemums (Bulle et al., 1996).

Incidentally high accumulations of nutrients in the top-layer can be controlled by reduced fertilizer applications, because plants are able to absorb nutrients from highly concentrated spots. However, high residual ion accumulations in top layers cannot be controlled at all, as the absorption of such ions by crops is low. It should be clear that in the root environment of substrate systems with no possibility for leaching, space for accumulation of residual ions is very restricted. Addition of nutrients should be carried out in close relation to the demand of the crop and concentrations of residual ions in the irrigation water should not significantly exceed the uptake concentration.

7.11 Environmental consequences

The strategy of irrigation and drain off in a substrate system strongly affects the environmental consequences. This strategy is complex and depends on the crop involved, the water quality, the acceptable or required concentrations of nutrients and residual ions, and the distribution of these in the root environment. Guidelines for the choice of the different parameters were discussed in foregoing sections. The ultimate decision will be made by the grower in relation to the growing conditions, the demand on the market, the economic consequences and the environmental regulations of the Government. In the present section, environmental consequences of such decisions are shown by some obvious examples. With these examples the efficiency of N and K are calculated for a number of situations, with tomato and rose as test crops. These crops have been chosen as an example, because they greatly differ in Na and Cl uptake, nutrient uptake concentrations and required and acceptable concentrations in the root environment. The calculations are carried out for a free drainage system and for recirculation of the drainage water, and for NaCl concentrations in the irrigation water of 0.3, 2, 4, and 6 mmol l^{-1}. The 0.3 mmol l^{-1} level represents the NaCl concentration of rain water in the Western part of The Netherlands. Furthermore, the recommended EC in the substrate solution (EC_{ss}) for tomato of 4.0 dS m^{-1}

(Table 1.2) is adopted as a required value, while for rose the salinity threshold value of 2.1 dS m^{-1} (Table 3.9) has been taken as an acceptable value for EC_{ss} and also as an acceptable value for the water supplied. The last situation is linked with the finding that plants react mainly to spots with the lowest concentration in the root environment (chapters 4 and 5) in this case the spot where the water is supplied. In all situations a leaching fraction (LF) of 0.25 is maintained. In case of a recirculation system this value is used as the recirculation rate (RR), being the ratio between the water supplied and the water absorbed by the crop. Thus LF = 0.25 is equivalent with RR = 1.3. The real LF in this system is the drain off determined by the NaCl accumulation. The water uptake for both crops is fixed on 750 l m^{-2} $year^{-1}$ and the uptake concentrations of nutrients are derived from Table 7.2, and those for Na and Cl from Tables 2.5 and 3.10. In the calculations the chosen parameters are considered as fixed values, though they will fluctuate in practice by decisions of the grower on the basis of items as mentioned before. The parameters used are average values and will closely reflect reality. The parameters used are summarized in Table 7.12. Calculations leading to unrealistic results are ignored. The results of the calculations are shown in the Tables 7.13 - 7.18.

Table 7.12. Parameters used for calculations of environmental consequences of substrate systems.

Crops	Tomato	Rose
System	Free drainage Recirculation	Free drainage Recirculation
Irrigation water quality	0.3, 2, 4, 6 mmol l^{-1} NaCl	0.3, 2, 4, 6 mmol l^{-1} NaCl
EC root environment	4.0 dS m^{-1} required as average	2.1 dS m^{-1} acceptable as average 2.1 dS m^{-1} in irrigation water

In the discussion about the calculations carried out use is made of the terms "required" and "acceptable" nutrient concentrations or values of the EC. A "required" nutrient concentration (c_n in Figure 1.2B) means that they are required for an optimum production, yield as well as quality. An "acceptable" concentration is not necessary in relation to an optimum production, but has no adverse effects on it and is equal on the salinity threshold value (c_t in Figure 1.2B).

Tomato with free drainage (Table 7.13)

The EC_{ss} is a required value and thus maintained, independently of the NaCl content in the irrigation water. This means that $EC_{ss(Nu)}$ and by this the N and K concentrations decrease with increasing NaCl. These decreases are calculated relatively from the standard solution given by Sonneveld and Straver (1994). The efficiency of the nutrients (E) being the ratio between the quantity absorbed by the crop and the quantity supplied is calculated as follows:

$$E = W_u c_u / W_s c_s \qquad (7.27)$$

in which E is the efficiency of any nutrient and the other parameters as defined in section 7.3.

Table 7.13. Nutrient efficiency of N (E_N) and K (E_K) as calculated for tomato grown in a free

drainage system, during one year.

Given values :	LF 0.25; W_u = 750 l m^{-2}; EC_{ss} = 4.0 (required); EC_u = 1.5; $EC_{ss(Nu)}$ = 1.5 (required); $c_{u(N)}$ = 9.6; $c_{u(K)}$ = 6.1				
Calculated values:	W_s = 1000 l m^{-2}; EC_s = 2.5; EC_d = 5.5; $EC_{s(Nu)}$ (min.) = 1.5; $EC_{d(Nu)}$ (min.) = 1.5; $c_{s(NaCl)}$ (max.) = 9; $c_{d(NaCl)}$ (max.) = 34				
$c_{s(NaCl)}$	$EC_{s(Nu)}$	$c_{s(N)}$	$c_{s(K)}$	E_N	E_K
0.3	2.5	16.5	9.1	0.44	0.50
2.0	2.3	15.2	8.4	0.47	0.55
4.0	2.1	13.9	7.7	0.52	0.59
6.0	1.8	11.9	6.6	0.61	0.69

Tomato with recirculation of drainage water (Table 7.14)

The EC_{ss} is a required value and thus the NaCl is accumulated in the recirculated solution up to maximum acceptable concentrations until the solution is drained off. The quantity of solution drained off is calculated and the N and K concentrations in the drainage water are derived from De Kreij et al. (1997a). The efficiency as defined in equation 7.27 of N and K is then calculated as follows:

$$E = W_u c_u / (W_u c_u + W_d c_d) \qquad (7.28)$$

The parameters are as defined in section 7.3

Rose with free drainage (Table 7.15)

The EC_{ss} is not a required value and, consequently, by increasing NaCl concentration there is no reduction of the nutrient supply, because $EC_{ss(Nu)}$ of 1.5 dS m^{-1} is a required value . The maximum acceptable EC_{ss} of 2.1 provides a restricted space for NaCl in the substrate solution. The efficiency is calculated on the basis of equation (7.27).

Rose with recirculation of the drainage water (Table 7.16)

The EC_{ss} is an acceptable value, but the $EC_{ss(Nu)}$ is a required one. N and K concentrations in the drainage water are calculated on the basis of data of De Kreij et al. (1997b). The quantity of water drained off is calculated and the nutrient efficiency is calculated according to equation (7.28).

Table 7.14. Nutrient efficiency of N (E_N) and K (E_K) as calculated for tomato grown in a system with recirculation of drainage water during one year.

Given values :	RR = 1.3; W_u = 750 l m^{-2}; EC_{ss} = 4.0 (required); EC_u = 1.5; $EC_{ss(Nu)}$ = 1.5 (required); $c_{u(N)}$ = 9.6; $c_{u(K)}$ = 6.1			
Calculated values:	EC_{rs} = 2.5; EC_d = 5.5; $EC_{s(Nu)}$ (min.) = 1.5; $EC_{d(Nu)}$ (min.) = 1.5; $c_{d(N)}$ = 10; $c_{d(K)}$ = 4; $c_{rs(NaCl)}$ (max.) = 9; $c_{d(NaCl)}$ (max.) = 34; $c_{u(Na)}$ = 1.2			
$c_{s(Na)}$	LF	W_{do}*	E_N	E_K
0.3	0	0	1.00	1.00
2.0	0.02	15	0.98	0.99
4.0	0.08	65	0.92	0.95
6.0	0.14	122	0.86	0.90

* Water drained off in l m^{-2}

Table 7.15. Nutrient efficiency of N (E_N) and K (E_K) as calculated for rose grown in a free drainage system during one year.

Given values :	LF 0.25; W_u = 750 l m^{-2}; EC_{ss} = 2.1 (acceptable); EC_u = 0.6; $EC_{ss(Nu)}$ = 1.5 (required); $c_{u(N)}$ = 5.2; $c_{u(K)}$ = 1.9;				
Calculated values:	W_s = 1000 l m^{-2}; EC_s = 1.2 (acceptable); EC_d = 3.0 (acceptable); $EC_{s(Nu)}$ (min.) = 0.96; $EC_{d(Nu)}$ (min.) = 2.04; $c_{s(NaCl)}$ (max.) = 2.1; $c_{d(NaCl)}$ (max.) = 8.1; $c_{u(NaCl)}$ = 0.0				
$c_{s(Na)}$	E C_s	$c_{s(N)}$	$c_{s(K)}$	E_N	E_K
0.3	0.96	7.5	2.7	0.52	0.53
2.0	1.19	7.5	2.7	0.52	0.53

Table 7.16. Nutrient efficiency of N (E_N) and K (E_K) as calculated for rose grown in a system with recirculation of drainage water during one year.

Given values :	RR = 1.3; W_u = 750 l m^{-2}; EC_{ss} = 2.1 (acceptable); EC_u = 0.6; $EC_{ss(Nu)}$ = 1.5 (required); $c_{u(N)}$ = 5.2; $c_{u(K)}$ = 1.9			
Calculated values:	EC_{rs} = 1.2; EC_d = 3.0; $EC_{rs(Nu)}$ (min.) = 0.96; $EC_{d(Nu)}$ (min.) = 2.04; $c_{d(N)}$= 16; $c_{d(K)}$ = 6; $c_{rs(NaCl)}$ (max.) = 2.1; $c_{d(NaCl)}$ (max.) = 8.3; $c_{u(Na)}$ = 0.0			
$c_{s(Na)}$	LF	W_{do}*	E_N	E_K
0.3	0.04	31	0.89	0.88
2.0	0.24	236	0.51	0.50

* Water drained off in l m^{-2}

Rose in a free drainage system with EC_s = 2.1 dS m^{-1} as an accepted value (Table 7.17)

The EC_s is not a required value, thus increasing NaCl has no effect on the nutrient supply. The nutrient efficiency is calculated with equation (7.27).

Table 7.17. Nutrient efficiency of N (E_N) and K (E_K) as calculated during one year for rose grown in a free drainage system in which an EC_s is accepted of 2.1 dS m^{-1}.

Given values :	LF 0.25; $W_u = 750\ l\ m^{-2}$; $EC_s = 2.1$ (acceptable); $EC_u = 0.6$; $EC_{ss(Nu)} = 1.5$ (required); $c_{u(N)} = 5.2$; $c_{u(K)} = 1.9$;				
Calculated values:	$W_s = 1000\ l\ m^{-2}$; $EC_d = 6.6$ (acceptable); $EC_{s(Nu)}$ (min.) = 0.96; $EC_{d(Nu)}$ (min.) = 2.04; $EC_{s(Re)} = 1.14$; $EC_{d(Re)} = 4.56$; $c_{s(NaCl)}$ (max.) = 9.9; $c_{d(NaCl)}$ (max.) = 39.6; $c_{u(Na)} = 0.0$				
$c_{s(Na)}$	$E\ C_s$	$c_{s(N)}$	$c_{s(K)}$	E_N	E_K
0.3	0.96	7.5	2.7	0.52	0.53
2.0	1.19	7.5	2.7	0.52	0.53
4.0	1.42	7.5	2.7	0.52	0.53
6.0	1.65	7.5	2.7	0.52	0.53

Rose in a system with recirculation of the drainage water and an EC in the re-supplied water (EC_{rs}) of 2.1 dS m^{-1} as an accepted value (Table 7.18)

The leaching fraction as well as the nutrient efficiency are calculated on the basis of equation (7.28).

Table 7.18. Nutrient efficiency of N and K as calculated during one year for rose grown in a system with recirculation of drainage water and an accepted EC_{rs} =2.1 dS m^{-1}.

Given values : =1.5	RR = 1.3; $W_u = 750\ l\ m^{-2}$; $EC_{rs} = 2.1$ (acceptable); $EC_u = 0.6$; $EC_{ss(Nu)}$ (required); $c_{u(N)} = 5.2$; $c_{u(K)} = 1.9$			
Calculated values:	$EC_d = 6.6$; $EC_{rs(Nu)}$ (min.) = 0.96; $EC_{d(Nu)}$ (min.) = 2.04; $c_{d(N)}$ =16; $c_{d(K)} = 6$ $c_{rs(NaCl)}$ (max.) = 9.9; $c_{d(NaCl)}$ (max.) = 39.7; $c_{u(Na)} = 0.0$			
$c_{s(Na)}$	LF	W_{do}*	E_N	E_K
0.3	0.01	8	0.97	0.97
2.0	0.05	39	0.86	0.86
4.0	0.10	83	0.74	0.74
6.0	0.15	132	0.64	0.65

* Water drained off in l m^{-2}

Conclusions

The results of tomato given in Table 7.13 show an increasing nutrient efficiency for N and K with increasing NaCl in the irrigation water. This is understandable because of the reduced supply of nutrients with increased NaCl. In case of recirculation (Table 7.14) the reverse effect occurs; the drain-off in this system is determined by the NaCl concentration of the irrigation water and increases when the concentration in the irrigation water exceeds the uptake concentration of Na. The nutrient efficiency is high, even at NaCl concentrations of 6 mmol l^{-1} in the irrigation water. For rose in a free drainage system with EC_{ss} = 2.1 dS m^{-1} as a maximum acceptable limit the residual space of the irrigation water ($EC_{s(Re)}$) is only 0.24 and thus $c_{s(NaCl)} < 2.1$ (Table 7.15). The nutrient efficiency is not affected by the NaCl concentration, because the EC_{ss} of 2.1 dS m^{-1}

is an acceptable value and not a required one. The nutrient efficiency can be increased strongly with recirculation of the drainage water starting from good quality irrigation water (Table 7.16). The use of the salinity threshold value of 2.1 dS m^{-1} as a maximum value for the irrigation water or the reused water allows the use of a wider range of NaCl concentrations in the irrigation water, but does not increase the nutrient efficiency (Table 7.17), because this maximum value is acceptable but not required; the nutrient efficiency is much improved under conditions with recirculation (Table 7.18).
From above calculations it is clear that the effect of the use of saline irrigation water on the nutrient efficiency is very diverse and depends on crop and growing conditions. When the required EC_{ss} exceeds the EC necessary for nutrition ($EC_{ss(Nu)}$) considerably, in a free drainage system the efficiency of nutrients is improved by the use of water with residual ions, because these residual ions are drained off instead of nutrients (Table 7.13). These ions are already abundantly available in natural waters and are less detrimental to the environment than most nutrients. In a recirculation system, on the contrary, an increased concentration of residual ions decreased the efficiency of nutrients (Table 7.14), but the efficiency will stay higher as long as the NaCl concentration in the primary water ($c_{s(NaCl)}$) is below those of the concentration calculated as maximum acceptable for re-supply ($c_{rs(NaCl)}$) being 9.9 mmol l^{-1}. Thus, a fine tuning between fertilization and salinity may reduce the quantity of nutrients drained off considerably, but mostly cannot prevent nutrient drain-off completely.

7.12 Dealing with salinity

Historically, greenhouse industry in North-West Europe was an agricultural activity with the aim to supply people in the area with fresh fruit and vegetable products early in the season and with products not suitable for outdoor growing later on in the season. In that period greenhouse growing was operative as a supply market, just like other agricultural branches. However, with the present improved transport facilities any horticultural product can be transfered from anywhere to all parts of the world and strictly there are now no longer arguments, that legitimize agricultural production in greenhouses. However, the greenhouse industry still exists and is even a strongly growing business all over the world. The drive for greenhouse production in North-West Europe is no longer focussed on supplying what is not available, but on producing better and cheaper products than elsewhere. In this way greenhouse production is not longer focussed on a supply but on a consumer market. In addition, many greenhouse products can be considered as luxurious products; this is especially the case for flower production in greenhouses. The demand for luxurious products is strongly related to living standards. Such a market is characterized by diversity, quality and immediate answers to demands. In this respect, produce quality will not only include taste and appearance, but also the production methods with respect to their environmental consequences. So, for the greenhouse industry it is important to search for sustainable growing methods.
In the greenhouse industry substrate growing meets the conditions mentioned, although its use has been criticized as “unnatural” or “industrial”. However, it is just the “industrial” character that supplies excellent opportunities for further improvements, such as reduction of environmental pollution by nutrients. Crops can be grown year-round in substrate systems in greenhouses without
any loss of nutrients. For that purpose water with a very low residual ion content is a necessity, but this is not always available in The Netherlands. Sometimes irrigation water must be used with too high concentrations of ions to prevent any drain-off, and with this any drain-off of nutrients.

The present study is a contribution to optimum management of salinity and fertilization with regard to quantity and quality of production, focussed on minimum environmental pollution.
Salinity in the greenhouse industry is not just a handicap, connected with yield reduction, leaching of nutrients and environmental pollution. Mild salinity may be a tool to control produce quality and crop development. Until now, salinity management as such has been insufficiently developed. The osmotic potential in the root environment should be tuned in more detail to the growing conditions to facilitate a better growth control and a higher fertilizer use efficiency. Important parameters for managing salinity in substrates are the salinity threshold values, the required levels of nutrients and the ion distribution within the root environment. In this study a start has been made in quantifying these parameters. They are strongly different among crops and therefore further studies are required focussing on specific crops and their growing conditions. It is valuable to know to what extent the salt sensitivity of a specific crop will change in relation to various growing conditions and which salinity parameter(s) will be affected, either the threshold value (c_t) or the salinity yield decrease value (SYD) or both parameters. Until now insufficient information is available about it and such information can only can be obtained by very costly experiments.
In the present study mainly the direction of various factors interacting with salinity could be traced (Figure 7.1). A quantitative estimation of the value of all vectors (factors) shown in this figure is impossible, for they depend on crop, growing system and will interact mutually. Therefore, to my opinion a study on the effects of different factors shown in Figure 7.1 should be carried out in the context of a specific crop and growing system developed for it. For a given growing system, relevant parameters can be controlled to a different extent. Some are more or less fixed for the whole growing period: the crop and cultivar grown, the type of substrate, the irrigation system and the volume and the shape of the root environment. Some other factors can only be managed to a certain extent: the climatic conditions and the water quality. The more flexible factors are suitable for full management during crop cultivation: the rate of water supply and fertilizer application.
When optimizing a growing system, first of all the strategical and tactical decisions should be optimized of crop and growing system. Obviously these decisions should be in line with the expected management at operational level. For example if the primary water source is of dubious quality, the irrigation system, and the shape and volume of the substrate should be focussed on the use of such water. In such cases, a plan should be made about the acceptable accumulation of residual ions, their distribution in the root environment, about an adjusted fertilization programme and about the limits for reuse and drain-off of drainage water. This all in relation to the crop grown, and the ambient climatic conditions. It is obvious that adjustment to climatic conditions requires seasonal rather than an ad-hoc regulation. The strongly changing weather conditions in North-West Europe mostly furnish no opportunities for ad-hoc adjustments. Substrate systems with a low circulation rate are not easily adjustable to the quickly changing weather conditions, because it often takes days to change the EC in the root environment substantially. Adjustment on basis of the daily changing weather is therefore not realistic. Seasonal adjustments, however, surely do make sense. Also, a good planning about fertilization and accumulation of residual ions in relation to water quality is very important with respect to environmental pollution. This is shown in section 7.11. The more or less dubious quality of primary water of 2 mmol NaCl l^{-1} leads to the following average fertilizer use efficiencies for N and K:

Tomato:	free drainage	0.51
	recirculation	0.98
Rose	free drainage	0.52
	recirculation	0.50
	free drainage, EC_s (acceptable) 2.1 dS m^{-1}	0.52
	recirculation, EC_{rs} (acceptable) 2.1 dS m^{-1}	0.86

This means that the environmental pollution for tomatoes can be reduced with a factor of about 25 by choice of the growing system, and for rose with a factor 3.5 by choice of the right parameter for recirculation rate and reuse and drain-off of the drainage water. It should be emphasized that the set limits should be justified for crop and growing system, under the prevailing climatic conditions.

Growers and researchers should not hesitate to choose new approaches in developing growing systems with improved potentials for salt accumulation and fertilizer utilization. The development of systems should no longer be based on a casual idea, as has happened so often in the past. Experiences of growers and scientists have made great progress. Therefore, a well planned design is certainly possible before systems are tested in expensive and time consuming experiments.

The study with unequal distribution of ions in the root environment (Chapters 4 and 5) provide an outlook to the development of new systems. In the framework of this study it seems important to develop growing systems in which the supply of plant nutrients and the process of accumulation of residual ions in the root environment can be separated. Water and nutrient uptake by plants should be considered as basically independent processes. Then the growing system furnishes optimum conditions for leaching of residual salts with a minimum of nutrients. Plants can be grown, for example, in a double root system. In such a system highly concentrated nutrients should be supplied in one root part and water with less concentrated residual ions in the other root part. Drain-off of accumulated residual ions is only necessary from the lower concentrated “water” part, containing no nutrients. So, the loss of nutrients can then be prevented almost completely. Such a system would function properly under conditions where the osmotic potential in the “water” part is maintained above that in the “nutrient” part and does not exceed values that would hinder optimum crop production. This study does not provide suggestions about size and shape of such separated root volumes, because such parameters were not incorporated. A fine tuning of water and nutrient supply in relation to the development of the plant root system is important to provide the plant with a stable situation in the root environment. In such cases the opportunity to develop sufficient roots is offered at places suitable for optimum absorption of water and nutrients.

Application of such a futuristic system needs a solution for a number of practical problems. However, when crop and growing systems do not provide opportunities for such an extreme separation of water and nutrient uptake, the traditional “single root” systems offer possibilities for reduced environmental pollution. In these systems a good separation between nutrients and residual ions in the root environment will offer considerably contributions in this direction. A system in which the nutrient solution is depleted as much as possible from nutrients on its way from irrigation to drain-off and where as much as acceptable the residual ions are accumulated is effective with respect to this pollution. Until now the development of growing systems has been insufficiently directed to this item.

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Summary

Since the mid 1970s substrate growing has become popular for the production of vegetables as well as ornamentals in the greenhouse industry in The Netherlands. Because of the small rooting volumes that are used in substrate growing, such systems require a more accurate fertilization than growing in soil, but they offer possibilities for an easier control of the conditions in the root environment. The latter is important for greenhouse crop production, because the osmotic potential of the substrate solution in the root environment is often used for improvement of the quality of the produce. A fine tuning of the osmotic potential is necessary to utilize the favourable effects of a low osmotic potential in the root environment and to prevent the negative aspects as much as possible. Furthermore, the problems arising from leaching of salts and nutrients can be minimized. This requires a fertilization programme in which the fertilizer application is carefully tuned to minimum quantities required for optimal production. This can be realised best in closed growing systems, but primary water of sufficient quality is then required. Too high salt concentrations in the primary water easily lead to accumulation of salts in the root environment, which necessitates leaching in order to remove these salts.
For an adequate management of the osmotic potential of the substrate solution different parameters should be controlled to achieve greenhouse crops of a quality in accord with the demand of the market and with a minimum environmental pollution. Firstly, information about the absorption of water and ions by the crop is essential. The quantities and mutual ratios of ions absorbed are dependent on crop, growing stage and growing conditions. Secondly, the effect of the osmotic potential and the interaction of it with the climatic conditions in the greenhouse on crop development must be known. Thirdly, information on the spatial distribution of water and nutrients in the root environment should be available, because this may strongly affect salinity effects on plants.
In studies on effects of low osmotic potentials on crops, both osmotic and specific ion effects should be distinguished. The osmotic effects predominate for most crops and growing conditions. Mostly such effects are described according to the model developed by Maas and Hoffman. This model is characterized by two parameters, the salinity threshold value and the salinity yield decrease value. In this model the EC caused by plant nutrients is ignored, though nutrients have a significant effect on the EC of the substrate solution in greenhouse cultivation. So the model needs adjustment for the contribution of nutrients to the EC. Furthermore, effects of EC variations in time and space have been described. The objective of the study was to fill up gaps in the knowledge in order to reach better management of salinity and fertilization in substrate systems. In Chapter 1 research lines were developed with emphasis on the growing conditions in the greenhouse industry in North-West Europe.
In Chapters 2 and 3 fruit vegetables and cut flowers were used as test crops in experiments with different EC values in the root environment. Comparisons were made between EC effects caused by NaCl and by nutrients. Yield of tomato, cucumber, and sweet pepper were reduced at increasing EC. Most fruit quality characteristics were favourably affected. Blossom-end rot, however, increased with increasing EC. For sweet pepper this was especially the case after NaCl addition. Apart from blossom-end rot, only slight specific NaCl effects were noticed. Salinity threshold values for the vegetable crops vary between 2.3 and 3.5 dS m^{-1} and relative salinity yield decrease values between 2.3 and 7.6 % per dS m^{-1}. In the experiments with cut flowers gerbera, carnation, rose, aster, bouvardia and lily were grown. The flower weigths were negatively affected by the addition of NaCl. Salinity threshold values ranged from 1.1 to 4.3 dS m^{-1} and salinity yield decrease values varied between 2.1 and 16.8% per dS m^{-1}. For aster such parameters could not be obtained, because the highest EC of 4.2 dS m^{-1} in this experiment

did not affect the production. However, the regrowth of this crop after the first harvest, however, was specifically strongly hindered by NaCl. This was also the case with the flower production of the bouvardia crop. These crops exhibited a specific sensitivity to NaCl. For the bouvardia crop this effect was studied in more detail to obtain information about which ion, either Na or Cl, was responsible for this effect. The results showed that bouvardia was specifically sensitive to Na. It could not be assessed whether the increased absorption of Na or the decreased absorption of nutrients was responsible for the drastic yield reduction, because both processes were strongly affected by Na addition to the root environment.

The absorption of Na and Cl differed strongly among crops and increased at increasing addition of NaCl. The rose crop, however, hardly absorbed Na irrespective of the concentration in the root environment. Mostly a linear relationship was found between the Na and Cl concentrations in the root environment and in the crop. For Cl sometimes a curvilinear relationship was observed.

In the Chapters 4 and 5 the response of tomato and cucumber to an unequal distribution of nutrients and NaCl in the root environment was studied. Plants were grown in a split-root system, consisting of two separate rock wool cubes or strips subsequently irrigated with solutions with equal or different concentrations of nutrients or NaCl. Beside optimal values for nutrients, also too high and too low concentrations for maximal production were included. Tomato yield was determined by the EC value considered optimal for production if present in one of the rock wool cubes, despite the fact that the EC in the other cube was up to 10 dS m^{-1}. With tomato water was preferably taken up from the root part with the lowest EC and nutrients from the root part with the highest EC. With cucumber when the EC was varied from low to standard by nutrients the nutrient uptake was highest in root parts with the highest concentration. In root parts with concentrations of nutrients > 4 dS m^{-1} the uptake decreased strongly with concentration. Nutrient uptake from one root part with high NaCl was also reduced when the NaCl concentration in the other root part was low. When both root parts had high NaCl concentrations the plant was able to take up adequate amounts of nutrients. Also cucumber absorbed water preferably from the root part with the lowest EC. In case no nutrients were supplied in one root part, the water uptake from that root part was reduced. There was no specific reduction of the water uptake caused by a high NaCl concentration. Cucumber was more sensitive than tomato to local high EC in the root environment.

In Chapter 6 interactions between salinity effects and climatic conditions and effects of varying salinities in time were studied with tomato as the test crop. High EC under low light conditions did not affect yields. In spring and summer yield reductions between 5 and 7 % per dS m^{-1} were found. In one experiment at very high humidity the yield reduction was about 10 % per dS m^{-1}. This was in contradiction with other experiments and with the nature of the interaction between salinity and climate in other studies. Obviously the calcium status of the plant had played a dominant role in this experiment. From the experiments with temporal variation of EC it could be concluded that for estimation of the yield reduction with EC variation in time not only the lengths of the EC-intervals and the EC-level during the interval but also the light intensity during the interval has to be taken into account.

Finally in Chapter 7 the management of salinity in relation to nutrient supply was discussed. The nutrient absorptions of greenhouse crops were studied by determining the total nutrient uptake and the nutrient uptake in relation to the water absorption; the so-called uptake concentrations. The published very low external concentrations to achieve optimal yields, are not realistic because of the high flow rate necessary to adequately supply crops with nutrients under such conditions. External nutrient concentrations corresponding with 1.5 dS m^{-1} are required for sufficient nutrient supply to greenhouse crops. However, theoretically there may be possibilities to reach maximum yields with lower external nutrient concentrations. The reason why such low concentrations easily lead to insufficient nutrient absorption is still unclear and needs further study.

Required and acceptable external concentrations were defined considering following items. Required external concentrations are concentrations necessary for sufficient supply of nutrients in order to attain maximum growth or yield. However, greenhouse crops often show a lush growth connected with poor produce quality. Therefore, growers frequently make use of the positive side effects of low osmotic potentials in the substrate solution to ensure optimal produce quality. So required concentrations in the substrate solution should not exclusively be related to maximum yield, but also to quality demands of the market. Acceptable concentrations can be considered with respect to maximum accumulation of residual ions to a level that does not affect crop production and quality negatively. In this way leaching and thus environmental pollution is minimized.

In the assessment of required and acceptable concentrations osmotic and specific ion effects should clearly be distinguished. When no specific ion effects occurred, the concentration "space" between the required nutrient concentration and the required concentration with respect to the produce quality or the acceptable concentration with respect to maximum salt accumulation can be filled up with any ion available in the system. This concept, however, can be frustrated by sensitivities of crops to a specific ion. Then the accumulation of an ion is restricted by the level not toxic to the crop or not harmful with respect to disturbance of uptake of nutrients.

Required and acceptable concentrations of ions strongly depend on crop and growing conditions. Under cool and humid growing conditions, use of drip irrigation, and CO_2 supply, EC-values in the substrate solution between 3 and 6 dS m^{-1} seem to be realistic. Such conditions can be realised in greenhouses in North-West Europe from autumn until early spring. For summer conditions the EC-values found in this study are more realistic. In the interpretation of EC-values more credit should be given to the consequences of spatial distribution of ions in the substrate. The stable equilibrium established between low and high concentrated spots in the systems used, offers excellent possibilities for an osmotic escape by plants. Consequently an adjusted interpretation of higher acceptable and required external EC-values is then necessary. The discussion is concluded with some calculations of environmental pollution as a consequence of different management strategies of irrigation and drain-off.

Samenvatting

Sinds het midden van de jaren zeventig is telen in substraat populair geworden in de Nederlandse glastuinbouw, voor zowel de produktie van groenten als siergewassen. Het kleine wortelvolume dat bij deze wijze van telen wordt gebruikt, vereist enerzijds een veel nauwkeuriger regeling van het watergeven en bemesten dan bij teelten in grond, maar schept anderzijds veel betere mogelijkheden de omstandigheden in het wortelmileu te beheersen. Dit laatste is belangrijk, omdat de regeling van de osmotische potentiaal in het wortelmileu vaak gebruikt wordt voor verbetering van de kwaliteit van het produkt dat geteeld wordt. Een nauwkeurige afstemming van de osmotische potentiaal is nodig om de gunstige effecten van een lage waarde goed te kunnen benutten en negatieve neveneffecten daarvan zo veel mogelijk te vermijden. Ook kunnen de milieu problemen die door het uitspoelen van zouten ontstaan zoveel als mogelijk worden teruggebracht. Dit vereist een bemestingsprogramma waarbij de toediening van nutriënten nauwkeurig is afgestemd op de minimale hoeveelheden die nodig zijn om een optimale produktie te verkrijgen. Dit kan het best worden gerealiseerd in gesloten teeltsystemen. Het telen in dergelijke systemen stelt echter hoge eisen aan de kwaliteit van het water dat gebruikt wordt. Te hoge concentraties aan bepaalde ionen leidt gemakkelijk tot ongewenste accumulatie van deze ionen in het wortelmileu, hetgeen doorspoeling nodig maakt.
Voor een goede regeling van de osmotische potentiaal van de oplossing in het substraat moeten verschillende parameters goed worden beheerst om produkten af te kunnen leveren van een kwaliteit die goed is afgestemd op de vraag van de markt, met een minimum aan milieubelasting. In de eerste plaats dient nauwkeurige informatie beschikbaar te zijn over de opname van water en diverse ionen. De hoeveelheden en de onderlinge verhoudingen van de ionen die worden opgenomen zijn afhankelijk van het gewas, het groeistadium van het gewas en teeltomstandigheden. Vervolgens dienen de effecten van de osmotische potentiaal in relatie tot de teeltomstandigheden bekend te zijn. Tenslotte is informatie nodig over de effecten van de ruimtelijke verdeling van water en ionen in het wortelmileu.
In studies naar de effecten van een lage osmotische potentiaal in het wortelmileu dient goed onderscheid te worden gemaakt tussen osmotische en specifieke ion effecten. De osmotische effecten overheersen voor de meeste gewassen. Dergelijke effecten worden veelal beschreven met het model van Maas en Hoffman. Dit model wordt gekenmerkt door twee parameters, de drempelwaarde en de opbrengstdaling onder invloed van een toenemende osmotische potentiaal boven de drempelwaarde. In het model wordt de osmotische potentiaal veroorzaakt door de aanwezigheid van nutriënten verwaarloosd. Bij kasteelten nemen de nutriënten in het wortelmileu echter een belangrijk stuk van de osmotische potentiaal voor hun rekening. Het genoemde model behoeft dus aanpassing op dit gebied. Ook zijn modellen ontwikkeld voor effecten op de opbrengst van verdeling van de osmotische potentiaal in ruimte en tijd. Het doel van de gepresenteerde studie was het opvullen van leemten in kennis op dit gebied bij teelten in substraat, om op deze wijze te komen tot een betere beheersing van de bemesting en zoutaccumulatie. In hoofdstuk 1 zijn de onderzoeklijnen uitgezet met het oog op de globale teeltomstandigheden in Noord-West Europa.
In de hoofdstukken 2 en 3 worden proeven beschreven die zijn uitgevoerd bij verschillende EC-waarden in het wortelmileu met zowel vruchtgroenten als snijbloemen als proefgewassen. In deze proeven is de EC verhoogd met natriumchloride of met nutriënten. In de proeven met vruchtgroenten daalde de opbrengst van tomaat, paprika en komkommer bij toenemende EC. Meestal werd de kwaliteit van de vruchten gunstig beïnvloed, maar het optreden van neusrot in de vruchten nam juist toe door verhoging van de EC. Bij paprika was dit vooral het geval na het toedienen van natriumchloride. Afgezien van het optreden van neusrot, traden bij vruchtgroenten

weinig specifieke ion effecten op. De drempelwaarden die werden gevonden lagen tussen 2.3 en 3.5 dS m^{-1} en de relatieve opbrengstdaling boven de drempelwaarde tussen 2.3 en 7.6% per dS m^{-1}. In de proeven met snijbloemen werden gerbera, anjer, roos, aster, bouvardia en lelie onderzocht. De bloemgewichten werden negatief beïnvloed door het verhogen van de EC door het toedienen van natriumchloride. De drempelwaarden die gevonden werden voor deze gewassen lagen tussen 1.1 en 4.3 dS m^{-1} en de relatieve opbrengstdaling varieerde tussen 2.1 en 16.8% per dS m^{-1}. Voor aster kon geen drempelwaarde worden berekend, omdat de hoogste EC van 4.2 dS m^{-1} in de betreffende proef de opbrengst niet negatief beïnvloedde. Bij de meeste bloemgewassen traden geen specifieke effecten op door natriumchloride toediening. De hergroei van aster na de eerste snede werd echter wel specifiek beïnvloed door de toediening van natriumchloride. Bij bouvardia werd de ontwikkeling van de bloemtakken specifiek nadelig beïnvloed door de toediening van natriumchloride. Voor dit gewas werd een nader onderzoek uitgevoerd om na te gaan welk ion hiervoor verantwoordelijk was, natrium of chloride. De resultaten toonden aan dat dit het natriumion was. Uit de resultaten kon niet worden afgeleid of de sterke groeireduktie bij dit gewas werd veroorzaakt door een te grote opname van natrium of door een vermindering in de opname van nutriënten. Beide effecten traden namelijk gelijktijdig op.

De opname van natrium en chloride verschilde sterk van gewas tot gewas en nam toe met verhoogde toediening van natriumchloride. Voor roos werd echter geen noemenswaardige opname van natrium gevonden en werd ook geen toename als gevolg van verhoogde toediening geconstateerd. Meestal nam de opname van natrium en chloride lineair toe met het toedieningsniveau. Voor chloride werd soms een kromlijnig verband tussen toediening en opname gevonden.

In de hoofdstukken 4 en 5 is de reactie van tomaat en komkommer op een ongelijke verdeling van nutriënten en natriumchloride in het wortelmilieu bekeken. In de proeven werden planten geteeld in zogenaamde “split-root” systemen. Deze systemen bestonden uit twee gescheiden steenwolblokken of strippen waaraan achtereenvolgens oplossingen van nutriënten of natriun-chloride van gelijke of verschillende concentraties konden worden toegediend. Naast optimale concentraties aan nutriënten werden te hoge en te lage waarden voor optimale producties in het onderzoek betrokken. Voor tomaten werd de opbrengst bepaald door de EC waarde die optimaal geacht kon worden voor de produktie indien deze waarde aanwezig was in één van de steenwolblokken; dit ondanks het feit dat de EC in het andere blok een waarde bereikte van 10 dS m^{-1}. Water werd door tomaten bij voorkeur opgenomen vanuit het gedeelte met de laagste EC en nutriënten daarentegen vanuit het gedeelte met de hoogste EC. In de proeven met komkommer waren de resultaten vanaf lage tot standaardwaarden van de EC gelijk aan die bij tomaat. In gedeelten boven 4 dS m^{-1} nam de opname van nutriënten echter sterk af. De opname van nutriënten vanuit een gedeelte met een hoge concentratie natriumchloride werd sterk geremd, wanneer het andere gedeelte weinig natriumchloride bevatte. Wanneer beide wortelgedeelten een hoge concentratie natriumchloride hadden, bleek de komkommer toch in staat voldoende nutriënten op te nemen. Water werd door komkommer bij voorkeur opgenomen van het gedeelte met de laagste EC. Als geen nutriënten werden toegediend aan een wortelgedeelte, werd de wateropname daaruit geremd. Een specifieke remming van een hoge concentratie natriumchloride op de wateropname door werd niet gevonden. Uit de resultaten kon worden geconcludeerd dat komkommer meer gevoelig was voor een plaatselijk hoge EC in het wortelmilieu dan tomaat.

In hoofdstuk 6 zijn resultaten van proeven opgenomen waarin interacties werden bestudeerd tussen zouteffecten en klimaatsomstandigheden en effecten van variatie van de EC in het wortelmilieu in de tijd, met tomaat als proefgewas. Hoge EC waarden onder lichtarme omstandigheden hadden meestal geen enkel effect op de opbrengst. In voorjaar en zomer werden

relatieve opbrengstreducties gevonden tussen 5 en 7% per dS m^{-1}. In een proef bij een erg hoge luchtvochtigheid werd een opbrengstreduktie gevonden van 10%. Dit was niet in overeenstemming met de resultaten in de andere proeven en met resultaten van elders. Het lag voor de hand dat in deze proef het nutriënt calcium een belangrijke rol speelde. De reeds geringe calcium opname bij de zeer hoge luchtvochtigheid werd nog verder geremd door de hoge EC, hetgeen aanleiding gaf tot ernstig calcium gebrek in het gewas. De resultaten van de proeven met variërende EC in de tijd hebben geleid tot aanpassing in de bestaande opbrengstmodellen hiervoor. Niet alleen de lengte van een periode en de hoogte van de EC moesten in rekening worden gebracht, maar ook de instraling tijdens een periode.
In hoofdstuk 7 is de beheersing van verzouting in het wortelmilieu in relatie tot het toedienen van nutriënten bediscussieerd. De opname aan nutriënten werd vastgelegd in relaties tussen opbrengst en kwantitatieve opname van nutriënten en in opnameconcentraties. De lage externe concentraties die zijn gepubliceerd voor het verkrijgen van optimale opbrengsten zijn niet realistische voor praktische toepassingen, gezien de hoge doorstromingssnelheid van de nutriëntenoplossing die in zulke gevallen nodig is om voldoende nutriënten bij de wortel te krijgen. Op basis van recente gegevens blijkt dat veelal een externe concentratie is overeenkomende met een EC van 1.5 dS m^{-1} vereist is om de plant optimaal van de benodigde nutriënten te voorzien. Berekeningen op basis van nutriëntenopname leerde dat het mogelijk zou moeten zijn met lagere concentraties maximum opbrengsten te realiseren. De reden waarom dit toch vaak in de praktijk niet lukt, is nog niet duidelijk en vraagt nadere studie.
Vereiste en aanvaardbare externe concentraties worden in hoofdstuk 7 gedefinieerd. Vereiste concentraties zijn die welke nodig zijn voor het verkrijgen van maximum groei en opbrengst. Gezien de vaak snelle groei van gewassen in kassen worden vaak hogere waarden aangehouden dan direct voor een maximale groei van het gewas nodig is. Een te snelle groei leidt veelal tot een week gewas en een slechte kwaliteit van het produkt. Vereiste externe concentraties moeten daarom niet uitsluitend worden afgestemd op een maximale opbrengst, maar ook op de marktvraag naar kwaliteitsprodukten. Over aanvaardbare concentraties wordt vooral gesproken in relatie tot accumulatie van restzouten in het wortelmileu. Hoe hoger het niveau waarop deze zouten mogen accumuleren in het wortelmilieu zonder negatieve gevolgen voor een optimale opbrengst, hoe minder behoeft te worden uitgespoeld. Op deze wijze wordt belasting van het milieu zoveel mogelijk beperkt.
Bij het vaststellen van zowel vereiste als aanvaardbare concentraties dienen osmotische en specifieke ioneffecten scherp in het oog te worden gehouden. Als geen specifieke ioneffecten aanwezig zijn, mag de ruimte in de EC tussen de vereiste of aanvaardbare EC en de EC nodig voor optimale nutriënten voorziening worden ingenomen door elk willekeurig zout. Door specifieke ioneffecten kan dit echter worden doorkruist. De accumulatie van zouten wordt dan niet bepaald door de totale osmotische potentiaal, maar door de concentratie van een bepaald ion dat toxisch is voor het gewas of de concentratie van een bepaald ion dat de nutriëntenopname teveel verstoort.

De vereiste en aanvaardbare concentraties hangen sterk af van de teeltomstandigheden. Koele en vochtige weersomstandigheden, het gebruik van druppelbevloeiïng en CO_2 toediening verhogen de toelaatbare of vereiste EC. Onder dergelijke condities zijn waarden tussen 3 en 6 dS m^{-1} realistisch. Vanaf de herfst tot in het vroege voorjaar zijn dergelijke waarden dan ook acceptabel en soms vereist in kassen in Noord-West Europa. Voor omstandigheden in de zomer zijn de EC waarden gevonden in deze studie meer realistisch. Bij de interpretatie moet echter terdege rekening worden gehouden met de verdeling van de EC in het wortelmilieu. Het stabiele evenwicht dat vaak ontstaat tussen hoge en lage waarden in substraat bij gebruik van druppelbevloeiïng geeft de plant een goede mogelijkheid aan de effecten van plaatselijk hoge EC-waarden in het wortelmilieu te ontsnappen. Een aangepaste interpretatie is dan noodzakelijk. De discussie wordt besloten met enkele berekeningen van de milieubelasting in relatie tot het volgen van verschillende strategieën in het beheer van het toedienen en uitdraineren van de nutriëntensoplossing.

List of symbols

Symbol	Description	Unit
A	ion absorption rate by the crop	mmol m^{-2} d^{-1}
C^+	sum of valences of total cations in a solution	mmol (p^+) l^{-1}
c	ion concentration in a solution	mmol l^{-1}
c_d	ion concentration in the drainage water of a system	mmol l^{-1}
c_f	ion concentration in a solution from fertilizer supply	mmol l^{-1}
c_h	highest total ion concentration in a substrate solution	dS m^{-1}
c_l	lowest total ion concentration in a substrate solution	dS m^{-1}
c_n	minimum total nutrient concentration necessary for optimum production	dS m^{-1}
c_{rs}	total ion concentration in the re-supplied water (mixture of drainage water and fresh solution)	dS m^{-1}
c_s	ion concentration in the solution supplied to a system	mmol l^{-1}
c_{ss}	ion concentration in the substrate solution	mmol l^{-1}
c_{ss} (max)	maximum acceptable ion concentration in a substrate solution	mmol l^{-1}
c_t	salinity threshold value (maximum total ion concentration in the substrate solution without yield reduction)	dS m^{-1}
c_{th}	c_t value for the compartment with the highest total ion concentration in root environment	dS m^{-1}
c_{tl}	c_t value for the compartment with the lowest total ion concentration in the root environment	dS m^{-1}
c (tox)	toxic concentration of an ion	mmol l^{-1}
c_u	uptake concentration (ratio between the uptake of an ion and the water uptake)	mmol l^{-1}
c_w	ion concentration in the primary water	mmol l^{-1}
c_z	total ion concentration in the substrate solution beyond which the yield is zero	dS m^{-1}
D	the of drainage rate of water	l m^{-2} d^{-1}
E	nutrient uptake efficiency (the ratio between the amounts absorbed and supplied)	
EC	electrical conductivity at 25 °C	dS m^{-1}
$EC_{1:5}$	EC of a 1: 5 substrate/water v/v extract	dS m^{-1}
EC_d	EC of drainage water	dS m^{-1}
EC_{di}	EC in root environment on day i	dS m^{-1}
$EC_{d(Nu)}$	EC required for total nutrients in drainage water	dS m^{-1}
$EC_{d(Re)}$	EC available for accumulation of residual ions in drainage water	dS m^{-1}
EC_e	EC of the saturation extract	dS m^{-1}
EC_{ess}	EC estimated for substrate solution from data from a diluted extract	dS m^{-1}
EC_{ew}	EC of a water extract of a substrate	dS m^{-1}
EC_i	EC in root compartment i	dS m^{-1}
EC_{mt}	EC in substrate solution over a period of i days	dS m^{-1}
EC_{rs}	EC of the re-supplied solution (mixture of drainage water and fresh solution)	dS m^{-1}

EC_R	apparent EC estimated on basis of radiation	dS m^{-1}
EC_s	EC of the solution supplied	dS m^{-1}
$EC_{s(Nu)}$	EC required for nutrients in the solution supplied	dS m^{-1}
$EC_{s(Re)}$	EC available for residual ions in the solution supplied	dS m^{-1}
EC_{ss}	EC in substrate solution	dS m^{-1}
$EC_{ss(Nu)}$	EC in substrate solution required for nutrients	dS m^{-1}
$EC_{ss(Re)}$	EC in substrate solution available for accumulation of residual ions	dS m^{-1}
$EC_{ss(Ro)}$	apparent EC estimated on basis of the presence of roots in root compartments with different EC	dS m^{-1}
$EC_{ss(W)}$	apparent EC estimated on basis of water uptake in root compartments with different EC	dS m^{-1}
EC_u	EC of the uptake concentration	dS m^{-1}
EC_t	apparent EC in the root environment calculated on basis of time interval	dS m^{-1}
LF	leaching fraction	
n	number of observations	
Ro_i	root length or weight in root compartment i	length or weight per volume
R_i	daily radiation	J cm^{-2} d^{-1}
RR	water recirculation rate (ratio between the water supplied and the water absorbed)	
RWV	relative water content of a substrate under field conditions	
S	rate of water supply	l m^{-2} d^{-1}
SYD	salinity yield decrease	% per dS m^{-1}
SYD_h	salinity yield decrease value for the compartment with the highest EC in the substrate solution	% per dS m^{-1}
SYD_l	salinity yield decrease value for the compartment with the lowest EC in the substrate solution	% per dS m^{-1}
t	time	d
U	rate of water absorption by the crop	l m^{-2} d^{-1}
W_d	water drained out	l m^{-2}
W_i	water uptake from root compartment i	l m^{-2}
W_s	water supplied	l m^{-2}
W_u	water absorbed by the crop	l m^{-1}
Y_m	maximum possible yield without salinity	weight per area
Y_r	relative yield in relation to the yield under non saline conditions	
Y_x	yield at EC x	dS m^{-1}

Curriculum vitae

De schrijver van dit proefschrift werd op 7 september 1934 te Pijnacker geboren. Na de lagere school was hij werkzaam op het ouderlijke tuinbouwbedrijf en volgde tevens de Lagere Tuinbouwschool in zijn geboortedorp met aansluitend het Tuinbouwvakonderwijs in Naaldwijk. In 1953 werd hij op het Proefstation voor Tuinbouw onder Glas te Naaldwijk aangesteld als assistent bij de bemestingsadvisering. In de jaren 1954 - 1956 vervulde hij zijn militaire dienstplicht en keerde daarna terug in zijn eerdere functie, aanvankelijk met dezelfde werkopdracht. Na enkele jaren schakelde hij over naar het onderzoekswerk op hetzelfde Proefstation. Naast zijn werk volgde hij verschillende dag/avondstudies en behaalde hij diverse diploma's, waarvan als belangrijkste kunnen worden genoemd Chemisch Analist (1958), Statistisch Analist Algemeen Toepassingsgebied (1960) en Technologisch Toepassingsgebied (1962). In 1973 werd hij cum laude ingeschreven in het Ing-register.
Bij zijn onderzoek op het Proefstation te Naaldwijk heeft hij vooral werk verricht op het gebied van plantenvoeding, verzouting en watervoorziening bij kasteelten. Belangrijke onderwerpen bij zijn onderzoek waren: ontwikkeling van analysemethoden voor chemisch onderzoek van kasgronden en substraten, de nauwkeurigheid van analyseresultaten bij chemisch grondonderzoek, effecten van zout gietwater bij kasteelten, chemische en biologische effecten van grondstomen op de ontwikkeling van kasteelten, fertigatie bij kasteelten en het ontwikkelen van bemestingssytemen voor substraatteelten.
Bij zijn onderzoek gaf hij vele jaren leiding aan de research groep Bemesting en Watervoorziening van de afdeling Grond, Water en Bemesting van voormelde Proefstation. In 1986 werd hij hoofd van deze afdeling die inmiddels was omgevormd tot de afdeling Plantenvoeding en Substraten. Na de fusie tussen het Proefstation te Naaldwijk en het Proefstation voor de Bloementeelt te Aalsmeer werd hij in 1995 benoemd tot hoofd van de afdeling Teelt en Bedrijfsvoering. In 1997 maakte hij op eigen verzoek gebruik van de VUT regeling.
Tijdens zijn loopbaan heeft hij veel buitenlandse dienstreizen gemaakt. Het betroffen oriëntatiebezoeken als onderzoeker, bezoeken aan congressen en verzoeken voor lezingen en advisering betreffende zijn vakgebied. Hierbij werden naast de Europese landen ook landen op vrijwel alle continenten bezocht. Over zijn onderzoek heeft hij veel gepubliceerd in internationale wetenschappelijke tijdschriften, terwijl hij via de vakpers talrijke publicaties heeft geschreven om tuinders over de resultaten van het onderzoek te informeren.