

# Chapter 3

## Soil Solution

### 3.1 Introduction

The characteristics of the soil solution in the root environment in the greenhouse industry differ much from those for field grown crops. This is caused firstly by the growing conditions in the greenhouse, which strongly differ from those in the field and secondly the function attributed to the soil solution with respect to plant development. One of the most striking differences between growing in the greenhouse and in the field is the exclusion of the natural precipitation in greenhouses, which offers opportunities for a full control of the water supply. Another difference is the heavy fertilizer application, related to the high nutrient uptake. In addition these application fertilizers are for the greater part added by fertigation. Furthermore, the irrigation and fertilizer addition not only has a function with respect to supply the plant with sufficient nutrients and water, but in greenhouses these actions are also a tool to control plant growth and produce quality. Sometimes, low osmotic potentials in the soil solution are maintained to prevent a lush growth or to improve fruit quality. Such effects on plant development, especially makes sense in substrate growing, where plants are grown in small rooting volumes and thus the composition of the soil (substrate) solution easily can be adjusted, for example on the demand of the crop under changing growing conditions. Thus, in principle it seems possible to supply plants under greenhouse conditions at the right time with the right quantity of water and nutrients, and losses of water and nutrients to the environment can be minimized. However, this is often frustrated by a heterogeneous water supply of irrigation systems, a heterogeneous water uptake by plants and accumulation of salts in the root environment from the irrigation water used. Thus, a precise matching on the demand by the water supply is hindered by an overdose of irrigation water to equalize the differences between wet and dry spots and to prevent too high accumulations of residual salts.

In the greenhouse industry an adequate management of water and nutrient supply is important. On the one hand to maintain optimal conditions for the plant in the soil solution with respect to plant nutrient uptake and to the requirements for the osmotic potential and on the other hand with respect to prevent leaching of nutrients and by this prevention of environmental pollution. Especially the high concentrations of nutrients in the soil solution contribute strongly to a high environmental pollution

per area. This does not mean that the leaching of nutrients is high in relation to the total uptake. However, this item will be discussed further on in Chapter 6.

In the present chapter the osmotic potential of the soil solution will be discussed in relation to the prevailing moisture conditions during cultivation. Hereby, the connection will be discussed between the definition of the soil solution of soils in situ and those of substrates, because in the greenhouse industry substrate growing is important and will expand further on. Following the definition for soil solution the term “substrate” solution will be defined, being the solution extracted from substrates at moisture contents maintained during crop cultivation. Besides the osmotic potential, being a measure for the total of the different concentrations of mineral constituents, an impression will be given of the specific composition of the mineral constituents in the soil solution. Finally some guidelines about the role of the composition of the soil solution in relation to the mineral uptake of crops are presented.

## 3.2 Osmotic Potentials of Soil Solutions

In Table 3.1 the composition of soil solutions from field soils is given in comparison with those from greenhouse industry. In the comparison soil solutions as well as substrate solutions are taken into account. The most striking difference between the solutions derived from field soils and those from greenhouses soils are the overall much higher nutrient concentrations in solutions from greenhouse. This especially holds for greenhouse soils where the EC in the solution is highest. Furthermore, it is obvious that in greenhouse cultivation nutrients contribute substantially to the total salt concentrations of soil and substrate solutions and thus to the osmotic potential.

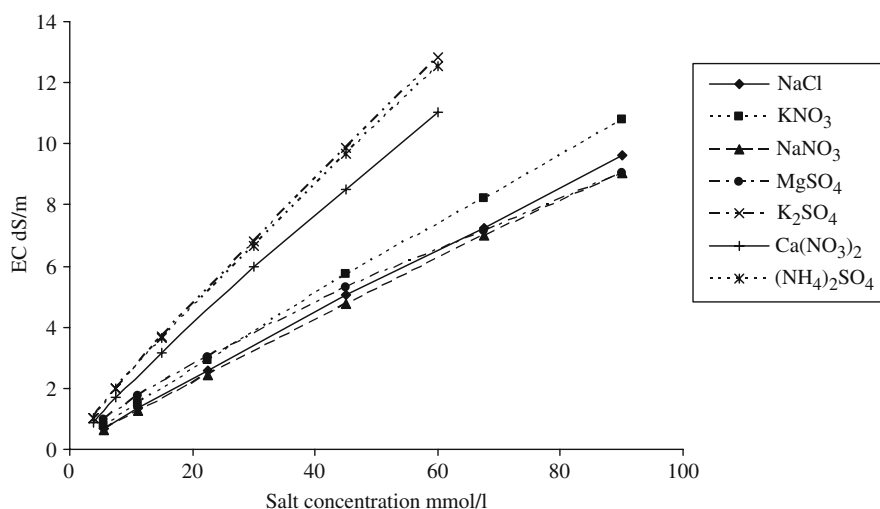
**Table 3.1** Ionic compositions of soil solutions. Ions expressed as mmol l<sup>-1</sup> and EC as dS m<sup>-1</sup>. The no's 1–5 are from field soils and the no's 6–9 from greenhouses

No <sup>1</sup>	K	Na	NH <sub>4</sub>	Ca	Mg	NO <sub>3</sub>	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	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	–	0.32	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

<sup>1</sup>Composition derived from: 1 – means of a historical series from 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 after top dressing with N, respectively; 6 – means of greenhouse soils by Van den Ende (1989) and Sonneveld et al. (1990); 7 – means peaty substrates of Sonneveld and Van Elderen (1994); 8 and 9 – recommended values for rock wool grown tomato and rose, respectively (Sonneveld, 1995).

This especially is the case in substrate systems where low saline primary water is used, and the osmotic potential is thus more or less solely brought about by nutrients. However, when water is used with a higher salinity level, and low osmotic potentials are desired in substrate cultivation, as indicated in Table 3.1 for tomato, the nutrient levels will be reduced to the required optimum for plant nutrition, while the osmotic potential will be lowered further by accumulation of the residual salts from the saline water (Sonneveld, 1995). In the Chapters 7, 13 and 16 this item will be discussed in detail.

The most important characteristic of the soil solution for greenhouse cultivation is the determination of the EC, because the results of this determination in soil solutions is within the operational range for greenhouse cultivation closely linearly correlated with the osmotic potential of the soil solutions. Such a close relationship will be found, when the osmotic potential is solely build up by ions and ionic pairs of mineral salts. The relationship between the EC and the salt concentration is linear, over a relatively wide range. True enough, each ion has its own specific contribution to the EC (McNeal, et al., 1979; Sonneveld et al., 1966). In Fig. 3.1 an impression is given of the relationships between the concentrations of different salts and the EC of a number of single salt solutions as found by Sonneveld et al. (1966). The contribution of a specific salt to the EC depends on factors like the valence of the ions, the dissociation constant, the activity of the ions and the ion pair formation and furthermore the temperature of the solution. In Fig. 3.1 the linear relationships between the salt concentrations and EC values of different single salt solutions are shown over a range up to 60 and 90 mmol l<sup>-1</sup> for tertiary and binary salts, respectively. The



**Fig. 3.1** The relationship between the concentrations of different salts and the EC, after Sonneveld et al. (1966) (Relationships calculated: NaCl,  $EC = 0.106c + 0.17$ ; KNO<sub>3</sub>,  $EC = 0.119c + 0.24$ ; NaNO<sub>3</sub>,  $EC = 0.100c + 0.18$ ; MgSO<sub>4</sub>,  $EC = 0.094c + 0.73$ ; Ca(NO<sub>3</sub>)<sub>2</sub>,  $EC = 0.180c + 0.39$ ; K<sub>2</sub>SO<sub>4</sub>,  $EC = 0.208c + 0.45$ ; (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>,  $EC = 0.204c + 0.44$ )

relationships between salts differ strongly. With increasing solution temperature the EC of salt solutions increases also. Therefore, the EC is expressed at a standardised temperature, mostly 25°C. When the EC is measured at a different temperature, the value at the standard temperature can be approached by the temperature coefficient, which is the relative increase or decrease of the EC by an increase or decrease of 1°C, respectively. This coefficient is somewhat different for the temperature interval, the relation temperature and the salt composition of the solution. However, at a relation temperature of 25°C and no bigger deviations than 10°C a temperature coefficient of 2% is proved to be very suitable (Campbell et al., 1948; Sonneveld et al., 1966). Modern apparatus compensate the effect of the temperature deviation automatically.

For mixed salt solutions McNeal, et al. (1979) showed a linear segment method with which the contribution of various concentrations of different salts to the EC can be calculated. The method is suitable for concentrations up to 50 mmol l<sup>-1</sup> for mono-valence and up to 25 mmol l<sup>-1</sup> for bi-valence ions. The low intercepts given with these linear relationships point out that they are suitable for calculations until rather low concentrations.

For rough estimations the formula given by Sonneveld et al. (1999) can be used for mixed salt solutions.

$$EC \approx 0.1C^+ \quad (3.1)$$

In which

EC = electrical conductivity of the solution in dS m<sup>-1</sup>  
 C<sup>+</sup> = the sum of valences of the cations in mmol l<sup>-1</sup>

However, for a precise calculation of the EC from the ion composition the already mentioned method presented by McNeal et al. (1979) will be recommended.

For soil solutions, but also for various other mixed salt solutions like soil extracts, and natural waters a close relationship has been found between the osmotic potential and the EC, as shown with the data in Fig. 3.2. The relationships found for different solutions show strong similarity and a general formulation can be established as given in Eq. (3.2).

$$OP \approx -33.3EC \quad (3.2)$$

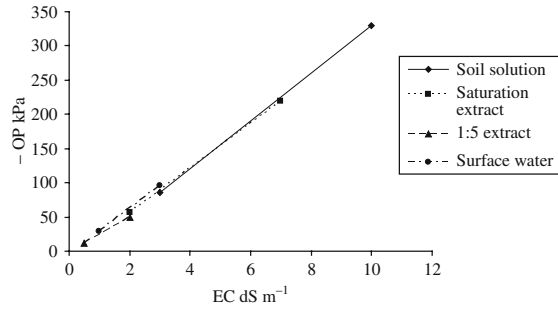
In which

OP = osmotic potential of the solution in kPa at 0°C  
 EC = electrical conductivity of the solution in dS m<sup>-1</sup> at 25°C

For strongly diluted extracts like the 1:5 by weight soil extract, a somewhat different relationship has been found. The data agree very well with the results presented by Campbell et al. (1948).

The osmotic potential of the solution in the root environment in greenhouse cultivation appeared to be an important factor for growth regulation of crops. This was

**Fig. 3.2** The relationship between the EC and the osmotic potential (OP) of different solutions, after Van den Ende (1968) and Sonneveld and Van den Ende (1967). The dots show the interval of the data (Regression equations: Soil solution OP =  $-34.9 \text{ EC} - 19$ ; Saturation extract OP =  $-32.6 \text{ EC} - 8$ ; 1:5 extract OP =  $-24.5 \text{ EC} - 0$ ; surface water OP =  $-33.3 \text{ EC} - 4$ )



not recognised from the beginning. In history, low osmotic potentials (high EC) in greenhouse soils were exclusively connected with the negative aspects of high salinity, like growth reduction and nutrient disorders (Riemens, 1951; Van den Ende, 1952). However, in greenhouses where crops easily show a lush growth often connected with a poor quality, also positive effects of a low osmotic potential in the soil solution were observed (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 for example 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 cultivation in substrate as developed for various greenhouse crops especially enhanced the availability of water in the root environment by the usually low matrix potential in the substrates of such growing systems, which accentuate the need for the use of the osmotic potential as a tool for growth regulation. Substrate growing, as mentioned before, offers excellent perspectives for such a regulation, because of the controllability of the usually small rooting volumes.

In greenhouse crops disorders of a high osmotic potential (low EC) in the root environment are well known in vegetables as well as in flowers and covers a great variation of plant characteristics. Examples are: irregular colouring of tomato fruits (Sonneveld and Voogt, 1990), glassiness in lettuce (Maaswinkel and Welles, 1986) and aggravation of the occurrence of soft rot in *Hippeastrum* bulbs (Van den Bos, 1996). Guide values for required and acceptable concentrations of nutrients and residual ions in the root environment will be discussed in Chapter 7.

### 3.3 Moisture Contents

A drawback with the determinations in soil and substrate solutions is the lack of a good definition of the moisture status of soils and substrates for preparation of the solution. The moisture content of a soil fluctuates with the evaporation and the water uptake of the crops grown and the precipitation, irrigation and capillary rise.

This especially occurs for field crops grown without artificial irrigation or with low frequency irrigation schedules. In such cases, the moisture withdraw from the root zone between irrigations can be considerable, which for example directly will be reflected by a decrease of the osmotic potential of the soil solution. The fluctuations in greenhouse soils are restricted, because of the high frequency irrigation schedules maintained. This especially is the case in substrate systems, where the irrigation frequency under high transpiration conditions increases up to several times per hour.

### 3.3.1 Greenhouse Soils In Situ

For a wide range of soil types Van den Ende (1988a) found a close linear relationship between the water content of greenhouse soils cultivated with tomatoes and the water content at a pressure head of  $-6.3$  kPa, as shown with formula (3.3).

$$w_f = 1.047w_{-6.3} - 0.012 \quad r = 0.987 \quad (3.3)$$

In which:

$w_f$  = mass ratio water/solid phase of field moist soil

$w_{-6.3}$  = mass ratio water/solid phase of soil at a pressure head of  $-6.3$  kPa

Thus, the water contents of the greenhouse soils grown with tomato were more or less equal to that at a pressure head of  $-6.3$  kPa.

Furthermore Van den Ende (1988b) found that the water content of the field moist soil was closely related to the loss on ignition, as given in following formula.

$$w_f = 2.617f_i - 0.118 \quad r = 0.985 \quad (3.4)$$

In which:

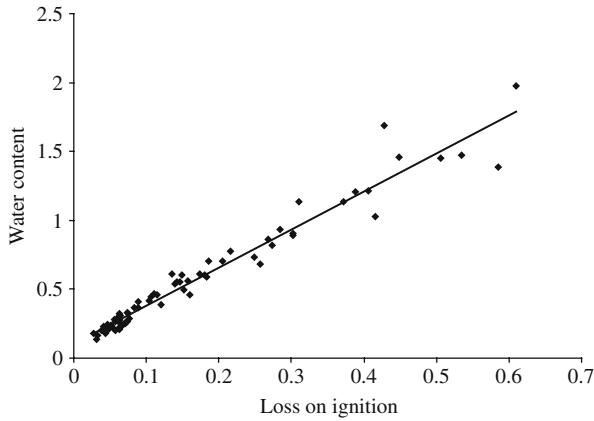
$w_f$  = mass ratio water/solid phase of field moist soil

$f_i$  = mass fraction loss-on-ignition of oven dry soil

Sonneveld et al. (1990) also determined the relationship between the loss on ignition and the water content under growing conditions and found a comparable relationship for a series of 75 greenhouse soil samples. These samples were gathered from greenhouses with different crops, merely during the cultivation period. The mass fraction organic matter and clay of the soils varied from 0.03–0.61 and 0.03–0.40, respectively. The relationship is shown in Fig. 3.3, and the equation found is given in formula (3.5).

$$w_f = 2.821f_i - 0.100 \quad r = 0.982 \quad (3.5)$$

Both formulae resulted in comparable values over a wide range of soil types. Thus, on basis of these formulae the field moist condition for greenhouse soils can be defined.



**Fig. 3.3** The relationship between the loss on ignition (m/m) of greenhouse soils and the water content (g/g) at field moist conditions. After Sonneveld et. al. (1990). Regression equation:  $y = 2.821x + 0.100$ ,  $r = 0.982$

With the given formulae also the water volume can be calculated because the bulk density is also closely related with the loss-on-ignition fraction (Sonneveld, 1990), like already given in formula (2.10).

Combination of the formula (3.5) and (2.10) gives an equation for the water volume in greenhouse soils, as shown in Eq. (3.6).

$$wv_f = \frac{2.821 f_l + 0.100}{4.67 f_l + 0.69} \tag{3.6}$$

In which

- $wv_f$  = volume fraction of water of field moist soil
- $f_l$  = mass fraction loss-on-ignition of oven dry soil

This formula can be used to calculate roughly the current moisture condition of greenhouse soils under growing conditions and will be used as a standard when reference is made to the soil solution of greenhouse soils. This definition is true with a reasonable frequent irrigation and thus, the relation between loss on ignition and water content are in agreement with the formula presented as (3.5).

### 3.3.2 Substrates

For substrates no reasonable relationship between organic matter and water holding capacity will be expected, due to the great variation of materials used as a substrate or used as a substrate constituent and utmost the great variation of the quality within these materials. For example, a lot of substrates do not contain noteworthy organic matter, while they have a high water holding capacity. But even when substrates con-

tain considerable quantities organic matter, like peaty substrates, the characteristics of the organic matter differ strongly and show a great variation in water holding capacity. In an investigation with peaty substrates (Sonneveld et al., 1974) a correlation coefficient of 0.809 was found between the mass fraction loss-on-ignition and the ratio moisture/solid phase at a pressure head of  $-3.2$  kPa, which is considerably lower than the correlation coefficient found with greenhouse soils. Since then the variation in materials used to produce substrates is strongly increased. The pressure head of  $-3.2$  kPa was chosen as being approximately the moisture content under growing conditions in that period. Later on, the moisture contents of substrates during cultivation became higher.

The growing conditions are another hindrance for a precise estimation of the water holding capacity. The moisture in most substrates is quite loosely bound and thus, the thickness of the substrate layer applied in the growing system will affect strongly the water holding capacity. Another factor is the irrigation method that plays an important role. When the water is supplied on the top, the water distribution in the substrate will differ strongly from the situation with water supply from the bottom. Thus, the definition of the water content at field capacity of a substrate not only depends on the characteristics of the substrate, but also on the growing conditions.

Wever (1995) compared the bulk densities and the water contents of a series of peaty growing media as found in practice for potted plants with the same characteristics measured at the laboratory following the CEN standard methods (CEN, 2006). The water content in the samples prepared at the laboratory following this method was measured at a pressure head of  $-1$  kPa. The correlation coefficient between the bulk density as found in the field and measured at the laboratory was rather low ( $r = 0.83$ ), but the average values had an acceptable agreement. The correlation coefficient for the water content found under field conditions and the content determined at  $-1$  kPa at the laboratory was also rather low ( $r = 0.83$ ), but on average the contents determined at the laboratory approached the field condition reasonably. Results of some calculations are listed in Table 3.2. The data in this table show that for a wide range of peaty substrates with a bulk density in the range from 50 to 300 kg m<sup>3</sup>, that there is on average an acceptable agreement between the water contents of the growing media under field conditions and those found at the laboratory at  $-1$  kPa. Thus, under growing conditions the water contents of the peaty growing

**Table 3.2** Bulk density and water content of peaty substrates as determined at the laboratory at  $-1$  kPa and comparable values of the bulk density and water content under field conditions, estimated by the regression equations found by Wever (1995)

Bulk density kg m <sup>-3</sup>		Water content g g <sup>-1</sup>	
Determined	Value estimated for practice	Determined	Value estimated for practice
50	54	10	9.6
300	261	3	3.9



media approaches on average reasonably the water contents at a pressure head of  $-1$  kPa. The low correlation coefficient found for the relationships can be explained easily by the strong differences realised under growing conditions, as there are the different potting techniques, irrigation methods and frequencies, differences in time between latest watering and sampling errors and so on.

For some substrates other than peat, the water content at a pressure head of  $-1$  kPa is not a good estimation of the water content under growing conditions. These substrates have lost already important parts of the water at such a relatively low suction. It seems that for these substrates the water content at free drainage after saturation is a better estimation for the water content under growing condition than at a pressure head of  $-1$  kPa. For bulk material this free drainage situation can be compared with the determination of the water content at  $-0.3$  kPa at the laboratory, being half of the height of the rings used for the standard method of CEN (2006). For pre-shaped material half of the height of the slabs or blocks should be considered as the pressure head of the free drainage condition. In Table 3.3 the water contents of a number of substrates is given at free drainage (leak out) condition and at  $-1$  kPa, following Kipp et al. (2000). In mostly cases there is a considerable difference between both water contents. For pre-shaped materials like slabs and blocks of PU-foam and rock wool it should be concluded that the water content under growing conditions will be approached mostly better by the “leak out” condition than at  $-1$  kPa, because at this pressure head an important part of the water is lost and the “leak out” condition approaches the situation in the field. The water content of expanded clay granules is already low at the “leak out” situation. Under growing conditions this substrate is usually placed in a water layer, which layer plays an important role in the uptake of water and nutrients. For the bulk materials the thickness of the substrate layer especially determines the water content at field capacity and thus at what pressure head the determination on the laboratory should be carried out.

**Table 3.3** Relative water contents by volume of a series of substrates at a pressure head of  $-0.3$  (leak out) and  $-1$  kPa

Type of substrate	Pressure head	
	$-0.3$ kPa <sup>1</sup>	$-1$ kPa
Wood fibre	0.72	0.32
Expanded clay granules	0.19	0.13
Coco peaces	0.40	0.33
Coco dust	0.91	0.67
Perlite	0.44	0.31
PU foam slabs	0.60	0.06
PU foam pieces	0.58	0.07
Pumice	0.58	0.40
Rock wool slabs	0.94	0.42
Peat	Nd	0.79

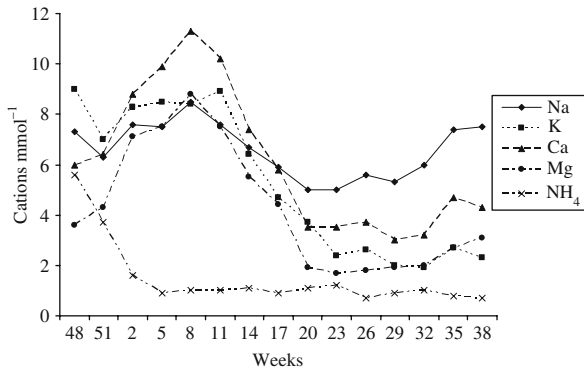
<sup>1</sup>For bulk substrates, for pre-shaped substrates the pressure head will be half the height of the slabs. After Kipp et al. (2000).

So with respect to a definition for “soil solution” following general conclusions are possible:

- For substrates retaining their water at a pressure head of  $-1$  kPa or higher, the water content at  $-1$  kPa should be considered as being the field capacity
- For substrates that have lost an important part of their water at  $-1$  kPa, the water content at free drainage after saturation should be considered as being field capacity, because such substrates will be used in thin layers
- For very coarse substrates with a low water holding capacity placed in a water layer, this water layer at the bottom should be considered as being the “soil solution”.
- For growing systems with a very restricted substrate volume and a high speed of the nutrient solution, like NFT and deep water culture, the circulating water can be considered as the “soil solution”.
- For strongly different growing systems and growing conditions strongly different from the formulations described, specific definitions are required and should be formulated.

### 3.4 Changes in the Chemical Composition

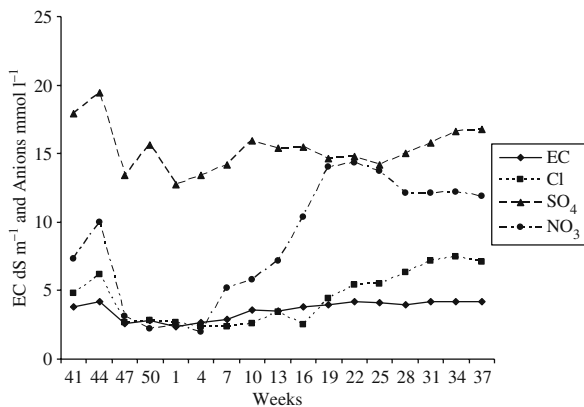
The chemical composition of soil solutions will change strongly, mainly by factors like nutrient uptake by crops, leaching of nutrients by irrigation and supply of nutrients by fertilization. The grower often switches the concentrations of specific ions as well as the total ion concentration (EC) deliberating the requirements of the crop. For some crops the EC is increased strongly like at the start of fruit vegetable crops to promote an early fruit setting and to prevent a lush growth, as mentioned in Section 3.2. Such an increase is realised by use of accumulated residual salts in the soil left from the former crop cultivation, by the addition of extra nutrients, or by a combination of both factors. Later on in the growing cycle of such crops, when lower EC levels are required, the grower let them gradually decrease by means of over irrigation and by the nutrient uptake of the crop. When necessary, growers start the fertigation to prevent that the nutrient concentrations will be decreased until too low values, which negatively can affect fruit quality. In Fig. 3.4 the course of the cation composition of the soil solution is shown for the described situation, with a soil grown tomato cropping as an example. The cations were determined in the saturation extract, the concentrations of which are closely correlated to those in the soil solution. The  $\text{NH}_4$  concentration is high at start, because of the steam sterilisation carried out just before the first sampling (see Chapter 10). The concentration gradually decreases with increasing microbiological activity in the soil. The concentrations of K, Ca and Mg were brought on the required high levels for tomato by base dressing. During the first months the concentrations of these cations gradually increase further on, by evaporation and action of capillary rise from the saturated zone, as long as there was no irrigation. When the irrigation started around



**Fig. 3.4** The course of the cation contents as determined in the saturation extract in a greenhouse during a tomato cropping. The soil type was a sandy soil with 5% organic matter

week 8, the concentrations gradually decreased and the top dressing by fertigation started around week 14. Until the end of the cropping period at week 32, by fertigation 300 kg K and 35 kg Mg per ha was supplied. In the greenhouse concerned, water and fertilizers were supplied by sprinkler irrigation and the soil was sampled over a depth of 25 cm. The Na concentration is relatively high during the whole growing period, as a result of the high concentration of this ion in the irrigation water used.

A total different course of the analytical data in the soil solution can be expected for flower crops that does not require a low osmotic potential in the soil solution at start. Such crops often are started at a low fertilization level in the soil. An example of such a situation is given for a gerbera crop in Fig. 3.5, where the course of the anion concentrations together with the EC in the saturation extract is shown. After flooding of the soil in week 45, the salt contents were decreased. The base dressing



**Fig. 3.5** The course of the EC and the anion concentrations of the saturation extract in a greenhouse during a gerbera cropping. The soil type was loam soil with 4% organic matter

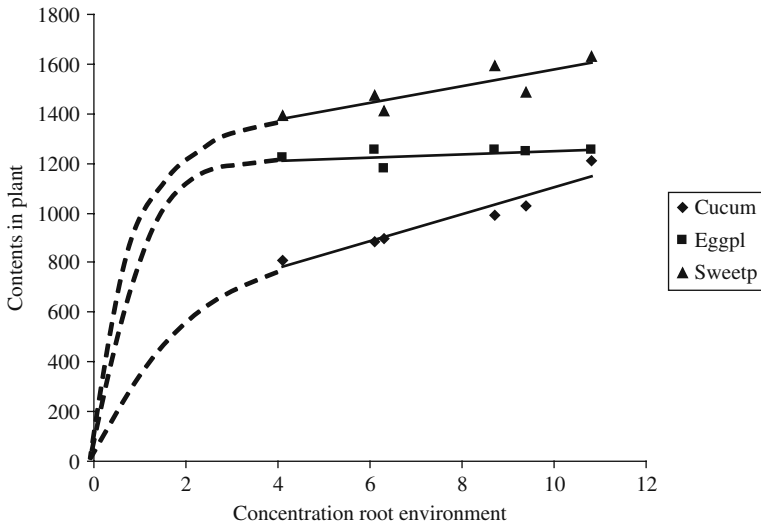
with nitrogen in week 6 strongly increases the N concentration. After planting in the same week the irrigation during the cropping period scarcely covered the transpiration of the crop, so there was no leaching of minerals from the root zone. Top dressings were not given during the cropping period. From the irrigation water Cl and SO<sub>4</sub> accumulated in the second part of the growing period. The strong accumulation of NO<sub>3</sub> should be explained by mineralization or from capillary water ascended from soil layers below the root zone.

Both examples show that in greenhouses with soil grown crops by fertilization the osmotic potential (EC) of the root zone surely can be affected and by this the development of crops. However, the often high nutrient concentrations in the soil solution can involve heavily losses of minerals by leaching, which in turn strongly will pollute the deep ground water or surrounding surface water.

In substrate cultivation the control of salt and nutrient concentrations in the root environment has special effects in comparison with the control of these parameters in the soil solution. On the one hand the concentration can be adjusted much easier, because of the small rooting volume. On the other hand for the same reason, mistakes by errors and mismanagement are also more obvious. This directly follows from the quantity of water available in the rooting volume. For soil grown crops a quantity of 75–150 l m<sup>-2</sup> can be calculated, while for substrate grown crop quantities between 4 and 12 l m<sup>-2</sup> are calculated (Sonneveld, 1981a; Sonneveld, 2000). Thus, salt accumulations in the root environment in substrate growing are about 5–40 times more effective than in soil growing. Therefore, for substrate growing a precise control on the supply of fertilizers and the realized concentration in the root environment is very important. This especially is the case in closed growing systems, where the drainage water is re-used and mistakes are not washed out in the drainage water discharged.

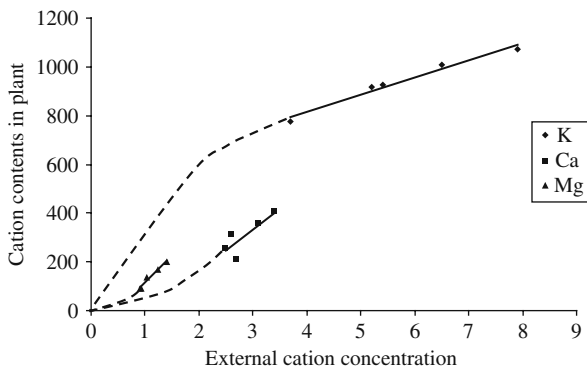
### 3.5 Soil Solution and Uptake of Major Nutrients

Marschner (1997) showed an interesting general model for the uptake of macro nutrients in relation to the external concentration. K, P, NO<sub>3</sub> and SO<sub>4</sub> are supposed to be adsorbed at relative high quantities at low external concentrations and the uptake of Na, Mg and Ca are much more dependent of the external concentration. Comparable relationships has been found for substrate grown crops like for K and Mg with sweet pepper, eggplant and cucumber grown in rock wool (Sonneveld and Voogt, 1985), K and Ca with tomato grown in nutrient solution (Voogt, 1988), for P with cucumber grown in rock wool (Sonneveld, 1991) and for Ca with carnation grown in rock wool (Sonneveld and Voogt, 1986). The relationship differs for crops as is clear from Fig. 3.6, where the relationship is shown between the external and internal K concentration for different crops. In the low range of the external concentration the curve is very steep for sweet pepper and eggplant, while for cucumber the slope in this range is lower, but in the higher range a considerable concentration effect is noticed for the latter crop. Differences among the uptake of cations are clearly shown by the data in Fig. 3.7. The slopes are steep for Ca and Mg, while the



**Fig. 3.6** The relationship between the K concentration in the root environment (mmol l<sup>-1</sup>) and the K concentration (mmol kg<sup>-1</sup> dry matter) in young leaves of rock wool grown cucumber, eggplant and sweet pepper. After Sonneveld and Voogt (1985). *Modified by permission of Marcel Dekker*

slope for the relationship for K is lower. In the lower range the relationship for K will become curvilinear, including a very steep slope to the point 0.0. With the supposition that in Fig. 3.7 all relationships end in the point 0.0, for K a convex model will occur, while for Ca and Mg a concave model will occur, like suggested in this figure. This is in full agreement with earlier supposed models (Sonneveld, 1991). This means that in a nutrient solution sufficient K will be adsorbed at relatively low concentrations in the root environment, while Ca and Mg are more dependent from a sufficient high concentration. Thus, in relation to the uptake the concentrations of



**Fig. 3.7** Relationship between the external concentration of cations (mmol l<sup>-1</sup>) and the cation concentration of young leaves (mmol kg<sup>-1</sup> dry matter) of a carnation crop grown in rock wool. After Sonneveld and Voogt (1986)

Ca and Mg should be relatively much higher than the K concentration (Voogt and Sonneveld, 1997).

For soil grown crops comparable relationships will be expected for the relationship between external and internal concentrations as has been found for substrate growing. This has been demonstrated by Voogt (2002) for K with tomato. In the soil solutions of greenhouses the concentrations of nutrients are of the same magnitude as the solutions in the root environment of substrates, as already shown in Table 3.1. However, P is an exception, because of the relatively low concentrations found in soil solutions when compared with substrate solutions. Therefore, for most nutrients can be expected that the nutrient concentrations in substrate grown crops are reasonably in agreement with those found in soil grown crops. Such data have been found in a study with which the mineral composition of tomato and cucumber grown in soil or grown in rock wool were compared (Sonneveld, 1980). Results of this study are listed in Table 3.4. In soil grown crops often the Ca concentration is mostly somewhat higher than in substrate grown crops, because of the often higher Ca concentrations found in soil solutions. The K concentrations are mostly somewhat higher in substrate grown crops, which can be explained as a compensation for the lower Ca uptake. Because of the generally very high P availability in substrate solutions the P concentrations in the plant tissues are mostly highest for crops grown in substrate. The differences shown with Na and Cl will be explained by the quality of the irrigation water used. The Na and Cl concentrations in the irrigation water used for soil growing were mostly higher than those in the water used for substrate growing.

**Table 3.4** Average mineral nutrient contents as has been found in young cucumber and young tomato leaves from greenhouse crops grown in rock wool or in soil. The crops on the holdings were sampled 3 till 5 times during the season. In the study for cucumber 9 and 3 and for tomato 3 and 5 holdings were incorporated with crops grown in rock wool and soil respectively. The contents are expressed as mmol kg<sup>-1</sup> dry matter

Elements	Cucumber		Tomato	
	Rock wool	Soil	Rock wool	Soil
Na	48	52	57	87
K	683	552	1064	841
Ca	1177	1192	611	843
Mg	263	321	173	169
NO <sub>3</sub>	286	221	257	250
N	4086	3750	3607	3343
Cl	90	293	130	231
P	210	161	174	145
SO <sub>4</sub>	75	72	344	362
Mn	2.5	0.9	3.9	0.8
Fe	1.9	1.6	1.5	1.6
Zn	0.7	0.8	0.7	0.4
B	5.4	5.4	5.6	4.2

Data of Sonneveld (1980).

It is striking, that under conditions of sufficient and over-sufficient nutrient availability of macro nutrients in the root environment, great differences in external concentrations result in only small differences in the internal concentrations. This effect points to the strong control of plants on the uptake of major nutrients. Every plant type and even every plant part preferentially realises certain specific optimum concentrations. Such concentrations differ much between plants, which is clear from the differences between the mineral compositions of cucumber and tomato in Table 3.4. Both crops in this study were grown under more or less comparable conditions, but differ seriously for plant concentrations. Internal optimum concentrations are realised by the plant at a relative high absorption at low external concentrations and a relative reduced uptake at relative high external concentrations, like shown for K in Fig. 3.6. Thus, despite a specific high external concentration of a major element, many plants are able to survive at a relative strong restriction of the uptake of such an element under these conditions. This is clearly shown in a study where different crops were grown under addition of specific salts to the root environment (Sonneveld and Van den Ende, 1975). In the experiments of this study beside the standard application of major nutrients to the irrigation water, chlorides of Na, K, Ca and Mg were added in two concentrations. The binary salts (NaCl and KCl) in concentration of  $12\frac{1}{2}$  and  $25 \text{ mmol l}^{-1}$  and the tertiary salts  $\text{CaCl}_2$  and  $\text{MgCl}_2$  of  $8\frac{1}{3}$  and  $16\frac{2}{3} \text{ mmol l}^{-1}$ , aiming at comparable osmotic potentials in the irrigation water with these additions. By these treatments the Na, Ca and Mg concentrations in the soil solution were increased with a factor 3 till 5 in comparison with the concentration in the standard treatment and for K with a factor 5–10. The effects on the cation uptake and on the yield of tomato and chrysanthemum are shown in Table 3.5 (Sonneveld and Van Beusekom, 1973; Sonneveld 1981b).

**Table 3.5** Effects of the addition of specific salts to the root environment on the uptake of cations of soil grown tomato and chrysanthemum. The salts were added to the irrigation water at concentrations of  $12\frac{1}{2}$  and  $25 \text{ mmol l}^{-1}$  for the binary salts and  $8\frac{1}{3}$  and  $16\frac{2}{3} \text{ mmol l}^{-1}$  for tertiary salts. For a further description of the experiment see text. The element contents are determined in young fully grown leaves and expressed as  $\text{mmol kg}^{-1}$  dry matter and yields in % of the standard

Salts added	Tomato					Chrysanthemum				
	Na	K	Ca	Mg	Yield <sup>1</sup> %	Na	K	Ca	Mg	Yield <sup>1</sup> %
Standard	261	939	1182	342	100	17	1606	456	276	100
NaCl $12\frac{1}{2}$	670	749	1257	370	83	17	1529	454	280	66
NaCl 25	748	693	1322	358	66	39	1514	426	272	50
KCl $12\frac{1}{2}$	187	1212	1137	313	80	13	2118	312	181	70
KCl 25	165	1714	1005	296	62	9	2338	244	136	58
$\text{CaCl}_2 8\frac{1}{3}$	117	900	1496	263	82	17	1394	723	169	67
$\text{CaCl}_2 16\frac{2}{3}$	122	949	1521	296	64	22	1240	823	148	54
$\text{MgCl}_2 8\frac{1}{3}$	152	818	1157	580	82	17	1396	284	601	66
$\text{MgCl}_2 16\frac{2}{3}$	135	719	1007	951	71	9	1176	212	819	45

<sup>1</sup>For tomato fruit weight and for chrysanthemum plant weight.

Data of Sonneveld and Van Beusekom (1973); Sonneveld (1981b).

The strong increases in the external concentrations are only partly reflected in the internal concentrations. The internal concentration increases in comparison with the standard with a factor between 1.3 and 3.0. The increased uptake of a specific cation reduces the uptake of other cations. Na was not absorbed by chrysanthemum and did not affect the level of other cations of this crop. Tomato absorbed significant quantities of Na, which reduces the K uptake. High K, Ca or Mg increases the uptake of these elements, and reduces the cations other than supplied in the overdose. It is remarkable that the sum cations ( $C^+$ ) absorbed by the crops in this way remains more or less constant; showing an average of 4550 and 3123 for tomato and chrysanthemum, respectively, with no more deviation from the average than about 5%. Despite the great changes in cation uptake the yield of the crops was not strongly specifically affected, except the yield of chrysanthemum at the highest  $MgCl_2$  concentration. The yield of tomato was only negatively affected by the decreased osmotic potential with 18 and 32% for the lowest and highest salt applications, respectively, and the yield of chrysanthemum with 33 and 46% respectively. However, at the highest  $MgCl_2$  concentration the yield reduction was 55%. These results show that with the high nutrient concentrations in the soil solution many crops survive well with relatively great differences in the uptake of major elements. The composition of the soil solution reflects the uptake of nutrient elements quite well, but the relationships between external and internal concentrations are not linear.

### 3.6 Soil Solution and Uptake of Micro Nutrients

The quantities of micro nutrients in soil solutions are small in comparison with those found for major nutrients. In Table 3.6 average concentrations of micro nutrients are shown as has been found in greenhouse soil solutions (Sonneveld and De Bes, 1986) and in substrate solutions of rock wool (Sonneveld and Van Voorthuizen, 1988). The concentrations in the different growing media are of the same order of magnitude. Greatest difference has been found for Fe, which will be explained by the use of chelates in solutions used with rock wool substrates. Such complexes are used to

**Table 3.6** Micronutrient concentrations as has been found in soil solutions of greenhouses (Sonneveld and De Bes, 1986) and in substrate solutions of rock wool (Sonneveld and Voorthuizen, 1988). Average values of 75 and 90 Dutch sites respectively. Concentrations given as  $\mu\text{mol l}^{-1}$

Elements	Soil	Rock wool substrate
Fe	4.0	22.6
Mn	15.1	8.1
Zn	5.9	11.5
B	62.0	55.3
Cu	2.2	1.1
Mo	0.5	–

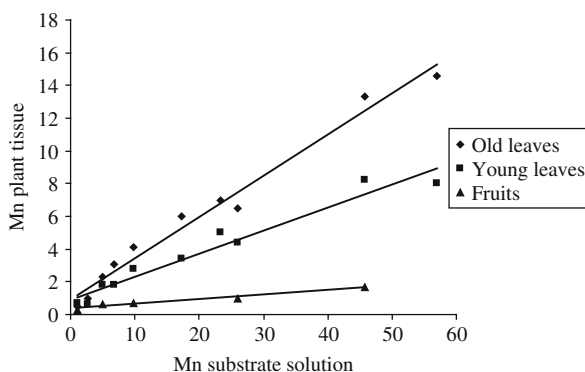


keep Fe available to plants in substrate cultures, while such compounds in soils are only scarcely used.

The micronutrient concentrations in soil and substrate solutions are not always a good measure for the uptake of the crop. Apparently many factors affect the relationship between external and internal concentrations of micronutrients. The pH in the root environment and in the rhizosphere and organic compounds in the root environment are likely important factors. The great variation in these conditions in the root environment are probably responsible for the poor correlations often found between external and internal concentrations for micro nutrients under practical conditions (Marschner et al., 1987).

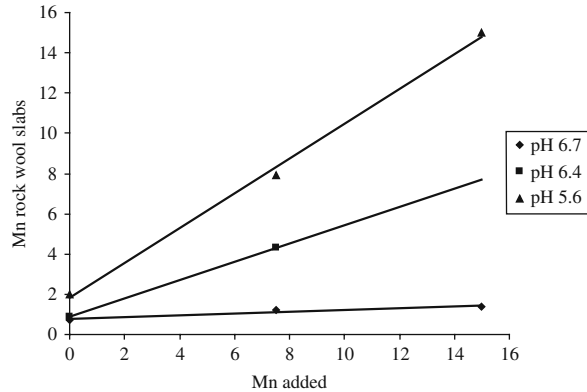
However, when micronutrients are applied to a more or less inert growing medium like rock wool, close correlations will be found between the concentrations in the nutrient solution supplied, the quantities in the substrate solution and the concentrations in the plant tissues (Sonneveld and De Bes, 1984). In Fig. 3.8 an example for such conditions is given for Mn with rock wool grown cucumber. However, even in more or less inert media like rock wool the availability in the root environment can be affected by the growing conditions, like shown for a gerbera crop in Fig. 3.9. The pH maintained in the root environment strongly affects the availability of the Mn supplied with the irrigation water (Sonneveld and Voogt, 1997).

The relationship between micronutrient concentrations in soil or substrate solution and in plants can be disturbed by soluble organic compounds. Such has been found for example for Cu and Zn. These elements can be bound at higher pH values on artificially produced organic (chelate) complexes that strongly, that plants are not able to absorb the Cu and Zn. Nevertheless, these elements are determined as soluble in soil or substrate solutions (Sonneveld and Voogt, 2001; Voogt and Sonneveld, 2009). Comparable complex formations also will be expected with natural organic compounds, which for example has been found for Cu with peat based organic complexes (Verloo, 1980). Then, the Cu bound on the soluble organic matter in soil or



**Fig. 3.8** The relationships between the Mn concentrations in the substrate solution ( $\mu\text{mol l}^{-1}$ ) and in plant tissues ( $\text{mmol kg}^{-1}$ ) of rock wool grown cucumber. After Sonneveld and De Bes (1984). Modified by permission of Marcel Dekker

**Fig. 3.9** The relationship between the Mn concentration added with the irrigation water ( $\mu\text{mol l}^{-1}$ ) and the Mn concentration in the substrate solution of the rock wool slabs ( $\mu\text{mol l}^{-1}$ ). Results of an experiment with rock wool grown gerbera, after Sonneveld and Voogt (1997)



substrate solutions is traced with the analysis, but not or only partly available to plants.

In view of the chemical and biological processes in the rhizosphere due to the activity of micro-organism or plant roots, simple relationships between external and internal micronutrient concentrations will not be expected (Marschner, 1997). An important reason for this lack on correlation is also the great difference that exists between the availability of micro nutrients in the rhizosphere and the bulk soil represented in soil or substrate samples gathered for laboratory analysis. When in experiments close relationships are found between internal and external concentrations of micro nutrients mostly such results are only operative for the specific experimental conditions. More about the uptake of micro nutrients will be discussed in the Chapters 13 and 16 about nutrient management in substrate and soil grown crops, respectively.

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