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Osmotic pressure of the soil solution: Determination and effects on some glasshouse crops*

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Summary

In a factorial experiment, calcium sulphate, sodium chloride and potassium nitrate were added to the soil in various quantities. The experiment was carried out in an unheated glasshouse and several test crops were grown.

The salt status of the soil was determined with the aid of different methods of aqueous extraction. The results were correlated with the osmotic pressure of the soil solution. A very close correlation was obtained with the conductivity of the saturation extract. Crop yields were correlated with the conductivity of the saturation extract and with the osmotic pressure of the plant sap. The correlation with the conductivity of the saturation extract was generally highest. With tomatoes, a very clear relationship was found between the conductivity and the incidence of blotch on the fruits. In lettuce, there was a clear relationship between conductivity and the occurrence of tipburn.

The yield reduction of some crops was significantly greater after the application of sodium chloride than after potassium nitrate had been applied. Apparently, this was caused by specific ion effects.

The desirable salt level, the salt distribution in the soil and the determination of the osmotic pressure of the soil solution for routine soil-testing purposes are discussed. The curvilinear relationship between the salt level of the soil and the incidence of tipburn may be explained by the calcium uptake of the crop.

Introduction

The osmotic pressure of the soil solution may have an important effect on plant growth. Both high and low osmotic pressures are harmful. In glasshouses it is often possible to regulate the osmotic pressure of the soil solution by maintaining close control of fertilization and irrigation. For this purpose the osmotic pressure should be checked regularly.

A low osmotic pressure of the soil solution tends to promote lush growth. In fruiting crops this may lead to excessive vegetative growth and proportionally insufficient generative growth. The risk is particularly high in poor light conditions. The quality of the produce may also be affected by lush growth.

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The harmful effect of a high osmotic pressure is usually the result of an impediment of the water uptake by the crop. The consequence is that yield is reduced. Besides this so-called osmotic effect, damage to the crop may also occur through specific ion effects. However, in most crops the damage is caused mainly by the osmotic effect.

The harmful effects of a low osmotic pressure of the soil solution may be observed for instance in new glasshouses in which the salt level of the soil often is very low. Lush growth of tomatoes may result in poor fruit quality. The same symptoms may be found on soils with a high capillary capacity. Irrigation on these soils is often reduced as the plants tend to obtain a large part of their water requirements from the water rising from the sub-soil through capillary action. The sub-soil water has a low salt content.

However, in the main glasshouse areas in the west of the Netherlands, there is more trouble from high than from low osmotic pressures. In these areas the osmotic pressure of the soil solution is increased mainly by the irrigation water. Practically all the water used here is surface water which contains an average of more than 1000 mg salt per litre. The osmotic pressure may also reach high levels as a result of too liberal use of fertilizers.

At the Naaldwijk research station a great deal of research has been conducted on osmotic pressures in recent years. Some of the results obtained are discussed in this publication.

Methods

Experimental design

The results were obtained in a factorial experiment in which calcium sulphate, sodium chloride and potassium nitrate were added in various quantities to the soil. Two levels of sodium chloride and potassium nitrate were used, 0 and 2½ gmol per m^2, and four levels of calcium sulphate, 0, 2½, 5 and 7½ gmol per m^2. Further applications of these salts were made as soon as the salt levels in the soil were reduced through leaching or through salt uptake by the crop. Sodium chloride and potassium nitrate had to be replenished more often than calcium sulphate, probably because the latter did not leach very easily. Sodium chloride and potassium nitrate were always added in quantities of the same equivalence.

The conductivity of the saturation extract of the soil with the different treatments ranged generally between 3 and 10 mmho[1]/cm (25 °C).

The experiment was conducted in an unheated glasshouse block. The soil was a loamy sand with an organic matter content of 5 %, a calcium carbonate content of 2.5 % and a pH of 7.2. Soil moisture was virtually maintained at field capacity through frequent watering with spray lines.

Soil samples were obtained from a depth of 0 to 30 cm.

Soil extraction methods

Press extracts were prepared from field-moist soil with the aid of a hydraulic press.

[1] 1 mmho = 1 $m\Omega^{-1}$ = 1 mS (millisiemens, the S1 unit).

Saturation extracts were prepared from air-dried soil (Richards, 1954), as were the 1 :1, 1 : 2 and 1 : 5 extracts.

Extraction of plant sap
Leaf samples were obtained from young, full-grown leaves and fruit samples from harvestable fruits. The plant tissue was killed by exposing it to temperatures of —35 to —40 °C immediately after collection. The samples were stored at this temperature for a fortnight, after which they were thawed out and pressed as quickly as possible.

Analytical methods
The osmotic pressure of soil extracts and plant sap was determined by measuring the freezing point (van den Ende & Koornneef, 1961). The osmotic pressure is expressed in atm. (0 °C). The electrical conductivity was measured with a direct reading conductivity meter and expressed in mmho/cm (25 °C).

Results

Osmotic pressure of the soil solution
The osmotic pressure of the soil solution may be determined by measuring the freezing point of the press extract or of field-moist soil (van den Ende, 1968). However, the preparation of the press extracts and the measuring of freezing points are rather laborious. This is why the osmotic pressure of the soil solution is generally estimated from the conductivity of an aqueous soil extract. Accurate estimates may be obtained if the soil solution is not diluted too much in the course of aqueous extraction. At a high rate of dilution, slightly soluble salts like calcium sulphate will dissolve in relatively large quantities.

The results of the factorial experiment confirm that high dilution rates are undesirable. During the first few years, the osmotic pressure of the press extract was compared with the conductivity of various aqueous extracts. The correlation coefficients are shown in Table 1. The table shows a high correlation of the conductivity of the saturation extract and the osmotic pressure of the press extract. With an increasing proportion of water to soil the correlation coefficients drop rapidly. In view of the results in Table 1, the conductivity of the saturation extract may be

Table 1. Correlation coefficients for the relationship between the osmotic pressure of the press extract and the electrical conductivity of various extracts.

Extracts	First year		Second year	
	tomatoes	lettuce	tomatoes	lettuce
Press extract	1.00	0.99	0.98	0.99
Saturation extract	0.92	0.99	0.99	0.98
1 : 1 extract	0.86	0.89	0.82	0.73
1 : 2 extract	0.40	0.46	0.48	0.43
1 : 5 extract	0.24	0.25	0.35	0.25

Table 2. Correlation coefficients for the relationship between the osmotic pressure (OP) and the electrical conductivity (EC) of various extracts, on the one hand, and the yield of tomatoes and lettuce on the other hand.

Extracts	Tomatoes, first year		Lettuce, first year		Tomatoes, second year	
	OP	EC	OP	EC	OP	EC
Press extract	—0.58	—0.57	—0.95	—0.95	—0.91	—0.87
Saturation extract	—0.59	—0.56	—0.94	—0.96	—0.92	—0.92
1 : 1 extract	—0.58	—0.58	—0.87	—0.81	—0.74	—0.70
1 : 2 extract	—0.47	—0.34	—0.54	—0.31	—0.29	—0.29
1 : 5 extract	—0.24	—0.34	—0.34	—0.14	—0.42	—0.17

used as a measure of the osmotic pressure of the press extract. The conductivity of the saturation extract was on average 2.1 times as great as the osmotic pressure of the press extract. The usefulness of the conductivity of the saturation extract as a measure of the osmotic pressure of the press extract is confirmed by the correlations between the crop yields on the one hand, and the osmotic pressure and conductivity of various extracts on the other (Table 2). The correlation coefficients for the yield and the conductivity of the saturation extract are practically the same as those for the yield and the osmotic pressure of the press extract. At increasing proportions of water to soil the correlation coefficients decrease rapidly.

Osmotic pressure of plant sap

Table 3 shows the regression equations for the relationship between the conductivity of the saturation extract and the osmotic pressure of the plant sap of a number of crops grown in the experiment. As the regression coefficients show, there was a great deal of variation in the effect that the osmotic pressure of the soil solution had on the osmotic pressure of the plant sap of different crops. The regression

Table 3. Relationships between the electrical conductivity of the saturation extract (x) and the osmotic pressure of plant sap (y).

Crops	Regression equation	Correlation coefficient
Tomatoes (fruits)	$y = 0.435x + 5.51$	0.911
Tomatoes (leaves)	$y = 0.125x + 7.06$	0.533
Lettuce (leaves)	$y = 0.396x + 4.99$	0.978
Sweet pepper (fruits)	$y = 0.127x + 5.59$	0.649
Sweet pepper (leaves)	$y = 0.177x + 9.26$	0.488
Endive (leaves)	$y = 0.328x + 4.80$	0.946
Cauliflower (leaves)	$y = 0.207x + 6.56$	0.718
Beans (pods)	$y = 0.047x + 7.76$	0.392
Beans (leaves)	$y = 0.193x + 7.60$	0.669
Spinach (leaves)	$y = 0.474x + 5.02$	0.955

Table 4. Relationships between the electrical conductivity of the saturation extract (x), on the one hand, and the yield as a percentage of the control, together with the percentage of the yield affected by physiogenic disorders (y), on the other hand.

Crops	Regression equation	Correlation coefficient
Tomatoes (yield)	$y = -8.11x + 144.2$	—0.913
Tomatoes (uneven ripened)	$y = -0.83x + 12.5$	—0.832
Lettuce (yield)	$y = -6.84x + 136.7$	—0.956
Lettuce (tipburn)	$y = -4.78x^2 + 76.80x - 239.9$	0.948
Sweet pepper (yield)	$y = -10.00x + 151.6$	—0.870
Endive (yield)	$y = -5.17x + 114.2$	—0.912
Cauliflower (yield)	$y = -1.22x + 103.4$	—0.279
Beans (yield)	$y = -4.92x + 118.6$	—0.733
Spinach (yield)	$y = -4.12x + 124.9$	—0.745

coefficients vary from 0.474 in the case of spinach leaves to 0.047 in bean pods. There were also large differences between the different parts of the same crop plants. With tomatoes the salt content of the soil had a greater effect on the osmotic pressure of the fruit juice than on the osmotic pressure of the leaf sap. The reverse was true for beans and with peppers the differences between the regression coefficients of the fruits and the foliage were relatively small.

Yield in relation to osmotic pressure

In tables 4 and 5, the regression equations are given for the relationship between the yield on the one hand, and the conductivity of the saturation extract and the osmotic pressure of the leaf sap on the other. The yields are given in percentages of the yields in the treatment which had no salts added to the soil (control). In the case of tomatoes the relationships with the percentage blotchy fruits are given too, and for lettuce the relationships with the percentage tipburn-affected heads are shown.

Table 4 shows generally high correlation coefficients for the relationship between the conductivity of the saturation extract and the yield. The correlation coefficient for cauliflower is an exception. Apparently, cauliflower is not very salt sensitive where the curd formation is concerned. However, this crop is much more salt sensitive in respect of leaf formation. The correlation coefficient for the relationship between the conductivity of the saturation extract and the total weight of curd and leaf together is —0.753, substantially higher than the correlation coefficient given in Table 4. For lettuce a quadratic equation has been calculated, Fig. 1, for the relationship of the percentage tipburn affected heads.

The salt sensitivity of the crops shows a wide variation. A 1 mmho/cm rise in the conductivity of the saturation extract caused a yield reduction of about 1 % in cauliflower and 10 % in peppers.

The data in Table 5 show that there is also a close correlation between the yields of a number of crops and the osmotic pressure of the leaf sap. However, for toma-

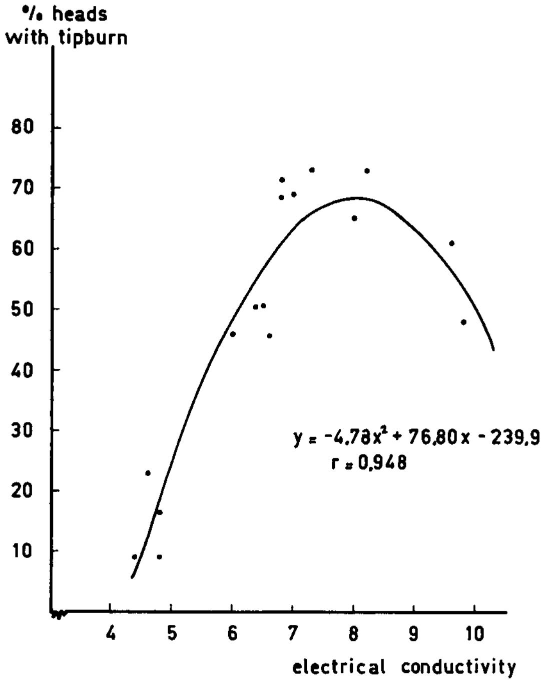

Fig. 1. The relationship between the electrical conductivity of the saturation extract and the percentage lettuce heads with tipburn.

toes, peppers and cauliflowers, the correlation coefficients are substantially lower than those obtained with the conductivity of the saturation extract. A rise of 1 atm in the osmotic pressure of the leaf sap caused yield reductions which ranged from about 1 % in cauliflowers to 20 % in tomatoes.

Table 5. Relationships between the osmotic pressure of leaf sap, (x), on the one hand, and the yield as a percentage of the control together with the percentage of the yield affected by physiogenic disorders (y), on the other hand.

Crops	Regression equation	Correlation coefficient
Tomatoes (yield)	$y = -20.2x + 248$	—0.535
Tomatoes (uneven ripened)	$y = -1.8x + 21$	—0.414
Lettuce (yield)	$y = -16.3x + 216$	—0.925
Lettuce (tipburn)	$y = -29.2x^2 + 475.5x - 1869$	0.931
Sweet pepper (yield)	$y = -13.2x + 225$	—0.417
Endive (yield)	$y = -15.5x + 188$	—0.948
Cauliflower (yield)	$y = -1.3x + 106$	—0.089
Beans (yield)	$y = -17.9x + 242$	—0.767
Spinach (yield)	$y = -7.5x + 159$	—0.678

Table 6. Relative yields and the electrical conductivity of saturation extracts (EC).

Crops	Without NaCl and KNO_3		NaCl application		KNO_3 application	
	yield	EC	yield	EC	yield	EC
Tomatoes	100	5.0	82	7.4	89	7.1
Lettuce	100	4.6	86	7.0	89	6.4
Sweet pepper	100	5.4	85	6.3	89	6.6
Endive	100	3.2	85	5.3	90	5.3
Cauliflower	100	4.3	98	7.2	100	6.9
Beans	100	5.3	71	8.8	90	8.4
Spinach	100	3.6	89	7.2	103	6.4

Specific effects of NaCl and KNO_3

As sodium chloride and potassium nitrate were added to the soil in equivalent quantities, a comparison of the yields of the different crops gives an impression of their specific salt sensitivity. In Table 6 the yields are given as percentages of the yields obtained from the treatments which did not have sodium chloride or potassium nitrate added. The conductivity of the saturation extract is also shown.

The application of sodium chloride gave a greater yield reduction in all crops than potassium nitrate. The differences were greatest in beans and spinach. Sodium chloride generally caused a greater increase in the conductivity of the saturation extract than potassium nitrate. A possible explanation is that the uptake of potassium and nitrate by the crops was greater than the uptake of sodium and chloride. Denitrification of the nitrate possibly also played a part in this.

The differences in conductivity were not large enough to be able to say that the variations in yield reductions caused by the different salts were osmotic effects. Apparently most crops have a specific sensitivity to sodium chloride. Beans in particular are sensitive to sodium chloride. The large difference in the yield reductions in spinach was caused mainly by the relatively high yields obtained after the application of potassium nitrate. Although the nitrogen and potassium levels in the soil were quite satisfactory, in the case of spinach there was a bonus effect of the addition of potassium nitrate. This effect may probably be explained by the shallow rooting of the crop which would have depleted the nutrients in the surface layers of the soil. This theory is supported by the fact that the beneficial effect of the potassium nitrate applications only started to show up towards the end of the cropping period.

Sodium chloride caused a greater incidence of tipburn in lettuce than potassium nitrate. The percentages of heads affected were 70 % and 48 %, respectively. With regard to the percentages of blotchy tomatoes, no great differences were found between the effects of the two salts. With sodium chloride the percentage blotchy fruit was 6.8 % and with potassium nitrate 6.0 %.

Effects of calcium sulphate

In tomatoes, peppers and cauliflowers, no clear effects were found by the application of calcium sulphate to the soil. Lettuce, endive, beans and spinach on the other hand showed clear effects. Some of the results have already been published in a previous report (van den Ende and Sonneveld, 1968).

Discussion

A low osmotic pressure of the soil solution appears to be beneficial for most of the crops tested. Growth and yield increase the lower the osmotic pressure. However, there must be a limit. The soil must contain sufficient nutrients which means that the osmotic pressure of the soil solution should not fall below a certain value. However, in the case of tomatoes a higher osmotic pressure than is necessary for the nutrition of the plant is often desirable. This experiment has shown again that with the tomato crop a low osmotic pressure may affect the quality of the fruits. The level to which the osmotic pressure should be raised is determined to a large extent by the environmental conditions of the crop (van den Ende, 1962).

Tipburn in lettuce may also be prevented by raising the osmotic pressure of the soil solution. However, in this case the osmotic pressure would have to be raised to such high levels that the result would be a very slow growing crop and coarse produce. It is therefore better to combat tipburn in lettuce by keeping the osmotic pressure of the soil solution at a low level. The effect of the osmotic pressure on tipburn may probably be explained by the calcium uptake of the crop. Several research workers have found a relationship between tipburn and calcium deficiency (Ashkar & Ries, 1971; Kruger, 1966; Thibodeau & Minotti, 1969). The incidence of the disorder on saline soils is probably also the result of low calcium uptake. The decrease in the disorder at very high salt concentrations is probably the result of a relatively better calcium supply of the young leaf as a result of the slower rate of growth (Geraldson, 1957). Increasing the osmotic pressure by the application of sodium chloride resulted in more tipburn than with the use of potassium nitrate. This is confirmed by other research work in which it was found that the sodium ion promotes tipburn more than the potassium ion (Sonneveld & van den Ende, 1975).

On the whole, the osmotic pressure of the soil solution was a better indicator of the crop development than the osmotic pressure of the leaf sap. A possible explanation for this is that the osmotic pressure of the leaf sap is only partly determined by the salts contained in the sap.

A good assessment of the osmotic pressure of the soil solution may be obtained by determining the conductivity of the saturation extract. We, as well as other research workers, have used this extract for many years (Arnold Bik, 1970; Massey & Winsor, 1968; Winsor et al., 1963). The preparation of the saturation extract is very laborious for routine soil-testing purposes, which is why a method was developed at our research station which is less laborious and in which the analytical results are closely correlated with those obtained with the saturation extract (Sonneveld & van den Ende, 1971).

With the determination of the osmotic pressure of the soil solution, divergent values may be obtained as a result of the salt distribution in the soil and the method of sampling. Particularly in the glasshouse soils large differences may occur in the distribution of salts in the horizontal as well as the vertical plane. Vertical differences for example occur if little water is applied and the salts accumulate in the top few inches of the soil. Horizontal differences are often the result of the use of irrigation systems, such as trickle irrigation and strip irrigation which apply water to certain areas of the soil only (van den Ende & De Graaf, 1974).

Mentioned variations in the osmotic pressure of the soil solution have an effect on the relationship found between the yield and the conductivity of the saturation extract. The result of this is that varying data may be obtained in experiments. In our experiment, beans were shown to be not particularly salt-sensitive, whilst the crop is described as salt-sensitive by most research workers (Hayward & Bernstein, 1958). In our case the beans received little water which caused the salts to accumulate in the top soil. The response of the crop will have been mainly to the lower soil layers which contained lower salt levels. As the top layer was sampled for the determination of the conductivity of the saturation extract, it is likely that the assessment of the osmotic pressure of the soil solution was too high.

Besides the osmotic effect of the salts on beans, an important specific effect of sodium chloride was found. The high salt sensitivity of beans appears to be based to a large extent on specific ion effects.

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