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Crop salt tolerance

under controlled field conditions in The Netherlands, based on trials conducted by Salt Farm Texel

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Summary

Between 2012 and 2015 field trials were performed at the open-air laboratory of Salt Farm Texel in The Netherlands. Through its unique design, reliable field trials can be conducted under highly controlled conditions, irrigating crops with seven different salt concentrations, each replicated eight times. In this way it is possible to evaluate the crop salt tolerance of many different species and varieties. In this report the results of five potato varieties, seven carrot varieties, four onion varieties, three lettuce varieties, two cabbage varieties and one barley variety are presented. Root zone salinity levels were sufficiently constant within the season and seasonal average salinities were close to targeted values across all years. These findings are based on actual measurements of the root zone salinity, and a simple mass-balance model to provide insight in the inter-sample behavior. Plant yields show considerable variation at similar salinity levels but due to the high number of repetitions the salt tolerance can be charted in a reliable way. Results show that for some of the tested crop species, varieties exist with a larger salt tolerance than was assumed up until now. This implies that, at least on sandy soils using drip irrigation, these varieties can be cultivated under moderate saline conditions without loss in yield. It also opens perspectives for cultivation on moderately saline soils anywhere in the world.

Preface

Since 2006 different field trials regarding crop salt tolerance have been performed on the island of Texel, the Netherlands. Details of this work can be found in De Vos (2011), among others. Although the trials focused on obtaining practical results for breeders and farmers, the set up of the various trials was scientifically solid, demonstrated by the publication of Bruning *et al*., in 2015. In 2016 the Dutch Ministry of Economic Affairs and Wageningen Environmental Research (Alterra) commissioned Salt Farm Texel to publish the data on crop salt tolerance that had been collected between 2012 and 2015 at the open-air laboratory of Salt Farm Texel (The Netherlands), which has resulted in this report. At the research facility of Salt Farm Texel, controlled field trials can be conducted at seven different salinity levels. In the period 2012-2015 trials have been conducted with potato, carrot, barley, lettuce, cabbage and onion. This report describes the results of these trials. To be able to compare these results with the standard crop salt tolerance data currently in use in the international literature, salt tolerance is expressed in terms of a yield reduction curve at various salinity levels.

Besides the authors of this report, this report has been reviewed by several other key persons: Dr. I.M. van der Meer (Wageningen Plant Research), Prof. Dr. K.R. Timmermans (NIOZ-University of Groningen), Dr. Ir. L.C.P.M. Stuyt (Wageningen Environmental Research) and Prof. Dr. Ir P. Vellinga (Wadden Academy). During a meeting on Texel all results were discussed comprehensively and feedback on the report was given and processed.

Background

Salinization is one of the major threats to agriculture worldwide, and is a major escalating problem. Globally, 1 billion hectares of land is negatively affected by salinity and of all irrigated arable land about 20% or 63 million ha is salt affected (Ghassemi *et al*., 1995, Qadir *et al*., 2014). This number increases with 2000 ha every day and crop damage in the irrigated areas is estimated at US$ 27.3 billion every year (Qadir *et al*., 2014). In the Netherlands it is expected that the salinization of arable land will increase up to 125.000 hectares (De Kempenaer *et al*., 2007). In general, crops produce lower yields at higher salinity levels and in the worst case farmers have to abandon their fields and clear new land that adds to the pressure on natural ecosystems and the associated biodiversity. Moreover, salinity is expected to increase even further under current climate change predictions. Thus, with a growing human world population and climatic changes on a global scale, salinity is an issue that will only grow in importance and urgently requires a solution (Qadir *et al*., 2014). In 2008, Rozema and Flowers published an article in Science that emphasizes the potential of cultivating salt tolerant crops since it can help address the threats of irreversible global salinization of freshwater and soils.

Classification of salinity

Table 1 shows a general classification of saline water, based on the electrical conductivity (EC, in dS/m) and the chloride concentration (specifically used as salinity standard in water management in The Netherlands). In this table EC is converted to equivalent chloride concentration with the established correlation presented in this report (figure 10). According to this table, water containing less than 150 mg Cl^-/l or an EC lower than 0.7 dS/m is considered as non-saline or fresh water. The maximum salt concentration for water that is also suitable for irrigation is, according to table 1, considered to be 2 dS/m or 480 mg Cl^-/l. In different areas in The Netherlands the general guideline of 200-250 mg Cl^-/l is used as the desirable upper limit for the maximum salt concentration of surface water.

Table 1. *Classification of saline water (Rhoades et al., 1992) based on EC (in dS/m) and equivalent chloride concentration of water (calculated from figure 10).*

Water class	EC (in dS/m)	in mg Cl^-/l	
Non-saline	< 0.7	< 150	Drinking and irrigation water
Slightly saline	0.7 - 2	150 - 480	Irrigation water
Moderately saline	2 - 10	480 - 2940	
Highly saline	10 - 25	2940 - 8250	
Very highly saline	25 - 45	8250 - 15970	
Brine	> 45	> 15970	Seawater=55 dS/m or 19,000 mg Cl^-/l

The salts in irrigation water can affect plant growth in several ways. When sprinkler irrigation is used, the irrigation water can cause leaf burn or extra salt uptake by the leaves. In the case of drip irrigation, which is used at the research facility of Salt Farm Texel, no direct contact between the irrigation water and the leaves takes place and only root uptake of salts is considered. So results described in this report are based on drip irrigation, but when sprinkler irrigation is used the outcome of the crop salt tolerance may differ from the results described in this report. Another disclaimer is that the soil type at the facility of Salt Farm Texel is sand.

It is well known that salts can influence the soil structure of clay soils to a great extend. The replacement of especially calcium, bound to the clay fraction, by sodium may cause poor soil structure and waterlogging. These (indirect) effects of salinity on crop growth in salt affected clay soils are not present in the trials described in this report but should be considered under actual field conditions. A well-known soil salinity classification that is often used as a general guideline in relation to crop growth is presented in table 2. According to table 2 yields of many crops are likely to be restricted under these “moderate saline” conditions.

Table 2. *Soil salinity classes and crop growth (Abrol et al., 1988). Soil salinity is based on the electrical conductivity of the extract of a soil saturated paste (EC_e, in dS/m).*

Soil salinity class	EC (in dS/m)	Effect on crop plants
Non-saline	0 - 2	Salinity effects negligible
Slightly saline	2 - 4	Yields of sensitive crops may be restricted
Moderately saline	4 - 8	Yields of many crops are restricted
Strongly saline	8 - 16	Only tolerant crops yield satisfactorily
Very strongly saline	> 16	Only a few very tolerant crops yield satisfactorily

Salinity and crop growth

Elevated salinity levels in the soil pore water affect plants in several ways. First, it lowers the osmotic potential of the soil pore water. This makes water uptake more difficult for plants since the plant has to lower the osmotic potential of the roots to levels lower than the osmotic potential of the soil moisture (water will move to the component with the lowest osmotic potential). Secondly, the NaCl molecules that enter the plant with the water can cause physiological damage. Na^+ ions especially can quickly reach toxic levels within the plant. Finally, because of the high concentrations of Na^+ in the soil pore water, increased competition with potassium (K^+) ions –essential to plant growth- for use of the same ion channels occurs and plants may have difficulties absorbing sufficient K^+.

Not withstanding the generally adverse effects of salinity, plants differ in their sensitivity to salinity. There is large variation in salt tolerance between species, from the extremely sensitive (some cultivars of chickpea (Cicer arietinum) die at 25 mM NaCl; Flowers *et al*., 2010) to many species that survive and reproduce at seawater salinity (~500 mM NaCl) or even higher. Different varieties or cultivars within one species can also differ in their tolerance to salinity (Khrais, 1996).

Most commonly, a species' salt tolerance is described by the renowned Maas-Hoffman model (Maas and Hoffman 1977, see Figure 1). According to Maas and Hoffman the salt tolerance of a crop can be best described by plotting its relative yield as a continuous function of soil salinity. For most crops, this response function follows a sigmoidal relationship. Maas and Hoffman proposed that this response curve could be approximated by two line segments: one, a tolerance plateau with a zero slope, and the other, a concentration-dependent line whose slope indicates the yield reduction per unit increase in salinity. The point at which the two lines intersect designates the "threshold", i.e. the maximum soil salinity that does not reduce yield below that obtained under non-saline conditions. This two-piece linear response function provides a reasonably good fit for commercially acceptable yields plotted against the electrical conductivity of the soil saturated paste (EC_e). The threshold and slope concept has its greatest value in providing general salt tolerance guidelines for crop management decisions. Based on the threshold and slope, a division in sensitive, moderately sensitive, moderately tolerant and tolerant crops can be made (see figure 1).

The crop salt tolerance data of Maas and Hoffman (1977) and the FAO (Tanji and Kielen, 2002) have been used as a reference to predict the effect of increasing salinity on crop growth in The Netherlands previously (Roest *et al*., 2003; Van Dam *et al*., 2007).

Farmers need to know the soil salinity levels at which yields start to decline and how much yield will be reduced at levels above the threshold. However, Maas and Hoffman already indicated that more precise plant response functions would be advantageous for crop simulation modelling. Van Genuchten and Hoffman (1984) have described several non-linear models that more accurately describe the sigmoidal growth response of plants to salinity.

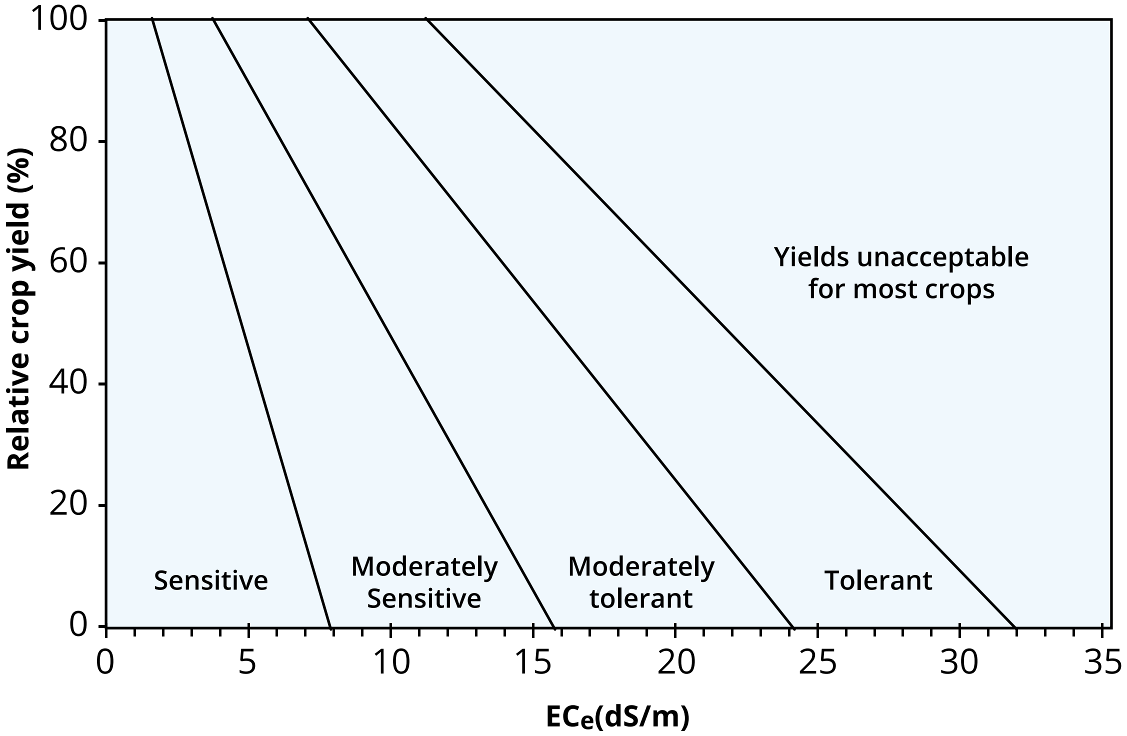


Figure 1. *Division for classifying crop tolerance to salinity (Maas and Hoffman, 1977).*

As described, plant species and cultivars within species differ in their tolerance to salinity. Most data that is presented by Maas and Hoffman (1977) and the FAO (Tanji & Kielen, 2002 using the same model) is based on a single variety of a specific crop and most trials were performed in a different climate zone than the climate zone of The Netherlands (temperate). Moreover, in many trails, salt and drought and/or heat stress appear to coincide, while in The Netherlands drought and heat stress is much less of an issue. This makes the trails performed at Salt Farm Texel highly important for the Dutch situation. At Salt Farm Texel, various varieties of multiple crops have been tested under controlled field conditions in the Dutch climate zone. For most crops no heat stress occurs during the growth cycle in The Netherlands and the frequent irrigation ensured that no drought stress occurred. On clay soils different interaction between the salts and the clay fraction can occur that can also influence crop performance. At the test facility on Texel the soil is mainly sand which makes it possible to assess the crop performance based only on the salts that are present in the pore water, in contrast to clay soils where more complex interaction can influence crop performance. Because of this, plants are only faced with the challenges of water uptake and salt uptake and not with any potential secondary effects that may take place in salt affected clay soils. So the trials described in this report really focus on crop salt tolerance alone rather than a potential combination of stresses.

The goal of this report is to present an overview of the recent trials performed by Salt Farm Texel, focussing on the crop salt tolerance, and to assess whether these results imply that salt tolerant crops may be cultivated under elevated salinity levels. Is it possible to use irrigation water with a salt concentration of 2 dS/m or higher? Is it possible to grow conventional crops on salt affected land in the range of 4-8 dS/m without major restrictions? The results presented in this report are especially applicable for sandy soils using drip irrigation.

Open-air laboratory of Salt Farm Texel

Experimental setup

Salt Farm Texel has set up a large research facility under field conditions in The Netherlands and this high tech location resembles an open-air laboratory. In 2011, the top 30 cm of the soil was removed and mixed to obtain a uniform topsoil. Drainage pipes were placed every five meters at 60 cm depth to obtain optimal drainage. The soil consists of sand (about 93% sand, 3% loam, 2% clay and 2% organic matter), with soil particle density around 2.5 Mgm-3, bulk soil density at saturation is about 1.5Mgm^{-3}, and field capacity around pF 2. Despite homogenization, there are known differences between various corners of the test site regarding porosity (between 0.39 and 0.42) and water holding capacity (between 0.24 and 0.27 kg(water) kg^{-1}(dry soil). A high irrigation intensity was maintained during all years (13.7 mm m^{-2} day^{-1} in 2012, 13.2 mm in 2013 up to 17 June and after this date this was reduced to 12.0 for the rest of the season, and 10.7 mm in 2014 and 2015) to keep the soil moisture content permanently close to the field capacity. Leaching of the irrigated water at the drain level takes place every day, so that the soil is flushed through, and soil salinity is kept as constant as possible. At the research station, fresh water and seawater can be mixed into any desired salt concentration by means of a proportional-integral-derivate (PID) controller with frequency-regulated pumps. In total seven different salt concentrations have been used, targeted at 1.7, 4, 8, 12, 16, 20 and 35 dS/m, at a minimum of 0.5 dS/m accuracy. Irrigation takes place by means of drip irrigation. Not all crops were grown at the 35 dS/m treatment especially when it was known that crops could not survive at this high level. Each salinity treatment is replicated eight times on plots of eight by 20 meters that are randomly distributed over the field. In this way, 56 (eight replicas x seven salt concentrations) individual plots of 160 m^2 each are irrigated (Figure 2; total research location is one hectare). Within each plot, different crops can be tested simultaneously. After planting, crops were allowed to germinate under fresh water conditions before the salt treatment started. Similar to most greenhouse experiments reported in the literature, the salt treatment started when crops reached the second or third true leaf stage. The dates of the start of the salt treatment were 29th of May, 27th of May, 30th of May and 8th of June for 2012, 2013, 2014 and 2015, respectively.

Climatic conditions are monitored by a Davis Vantage Pro2 line weather station that records precipitation and evapotranspiration, among others.

Figure 2. *An aerial impression of the open-air laboratory of Salt Farm Texel where the trials were performed. In total 56 plots of 160 m^2 are irrigated with seven different salt concentrations, with each salt concentration consisting of eight randomly divided repetitions.*

Root zone salinity

Root zone salinity is carefully monitored using three different methods. First, soil salinity is measured according to the international standard of extracting water from a saturated paste soil sample (EC_e, in dS/m). This has been done for a limited number of samples each year (n=81 for all four years combined). Secondly, from all the plots and at least two times per year, soil samples (each composed of ten subsamples collected within a 2 m radius of the pore water samplers, sample depth is 30 cm) are measured according to the commonly used 1:2 method ($EC_{1:2}$). For this, one part soil (dried and sieved (2 mm)) is diluted with two parts demineralized water (method 1:2 volume:volume). The conductivity of this solution is determined and the correlation between EC_e and $EC_{1:2}$ is determined (see Figure 3). To save labour time, the number of saturated paste measurements was reduced in favour of more $EC_{1:2}$ measurements after the observation was made that the correlation between these two methods was highly significant ($EC_e=EC_{1:2}*5{,}3$, with $r^2=0{,}95$: see Figure 3) and highly constant throughout the years. Thirdly, pore water samplers (rhizon sampler) consisting of a ceramic element put under vacuum, which extracts soil moisture, were placed in half of the replicate plots in 2012 and 2013 and in all plots in 2014 and 2015 at three different depths (0-10, 20-30 cm and 50-60 cm, with 10 cm length of the suction). The 50-60 cm depth was only used to determine the salinity of the leaching fraction. For crop growth analysis the average of the 0-10 and 20-30 cm depth was used. With no visible roots present below 30 cm in the field, the average of the top two suction cups represents the average root zone for at least 90% of the roots. Correlations between the conductivity of these extractions (EC_{pore}) and EC_e were also highly significant ($EC_e=EC_{pore}*0{,}69$, with $r^2=0{,}84$, n= 711: see Figure 3). For this calibration all three depths of the suction cups were used and plotted against the soil salinity of the individual plots with EC_e calculated from $EC_{1:2}$ using the calibration formula from Figure 1 when no direct data of EC_e were available. Because of the strong correlations between the three methods for measuring salinity, all salinity measurements have been expressed in terms of EC_e. For measuring the electrical conductivity in the water phase a WTW Cond 3310 was used.

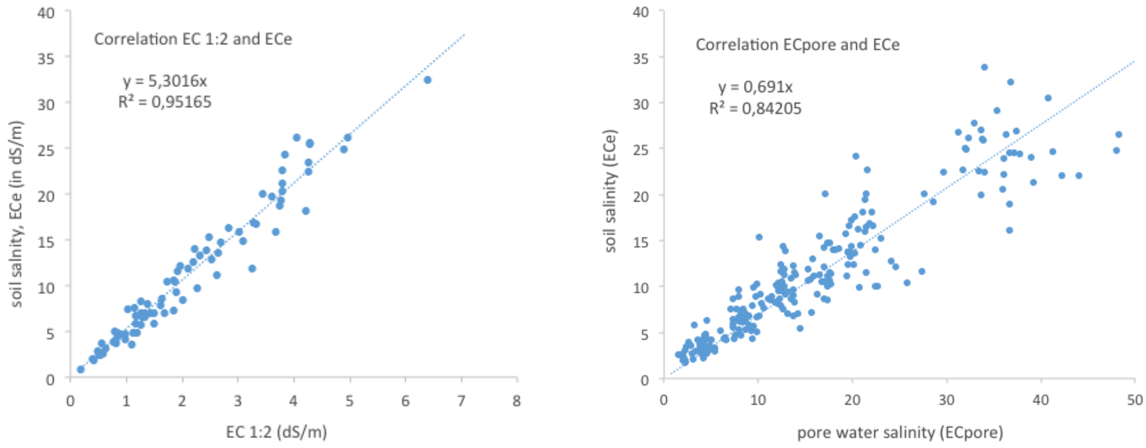


Figure 3. *Correlation between EC_e and $EC_{1:2}$ (left, with n=81) and between EC_e and EC_{pore} (right, with n=711). Data from all four years of testing have been used. The formula of the best fit line and the R^2 are shown in the top left corners of the graphs. See main text "root zone salinity" for detailed methods.*

Modelling root zone salinity

Soil and pore water samples were collected a number of times during the season. In order to have an idea about the inter-sample behaviour, the soil salinity at Salt Farm Texel was simulated (modeled) using water and salt balances as described by J.W. van Hoorn and J.G. van Alphen (1994). This model can predict the root zone salinity, to provide insight in the inter-sample behavior. More details about this model can be found in Appendix 1.

Crop data

Various varieties have been tested for most crops, and some varieties have been tested for multiple years (details in Table 3). Some crops have been planted in blocks (potato, cabbage, lettuce), whereas others have been planted in rows (onion, carrots). Details about the different crops are presented below. A contiguous area covered by one variety within a 8 x 20 m^2 field is called a plot. Within such a plot either a row or a block on a certain amount of plants were used to analyse the yield.

Potato

Eight potato plants per plot were planted (four plants per ridge, two adjacent ridges, total of eight plants per plot which equals 1.8 m^2 (ridges spaced 75 cm and tubers spaced at 30 cm) and different varieties were separated by planting two extra plants with a different tuber colour to make harvesting easier (Figure 4). Before planting, the initial weight of the eight tubers was determined. Potatoes were planted on 17th of April, 1st of May, 28th of April (Achilles) or 29th of April (Miss Mignonne) and 7th of May in 2012, 2013, 2014 and 2015 respectively. Harvest took place on 19th of July, 29th of August, 12th of August and 18th of August in the subsequent years, resulting in a 93, 120, 105-106 and 103 day growth period after planting and 51, 94, 74 and 71 days of salt treatment during that growth period, respectively. Number of replicate plots in 2012 were eight, in 2013 4 for treatments 1.7 and 8 dS/m and eight for the other treatments, and four replicas per treatment in the years 2014 and 2015. Fresh and dry weights of the tubers were determined. Herbicide use and spraying against late blight was conform standard agricultural practises.

Figure 4. *Impression of the potato trials. Tubers are hand planted and each variety consists of eight plants (two ridges with four plants) in each plot.*

Cabbage

Blocks of ten seedlings of cabbage, equalling 2.5 m^2 per plot, were planted on June 10, 2014. Seedlings with two true leaves were planted directly in the saline soils (irrigation started 11 days earlier) (Figure 5). The cabbage was harvested on August 26. Only the fresh weight of the above ground biomass (excluding the older leaves that were touching the ground) was taken into account when determining the yield, combining four plants per plot. For broccoli, the same approach as for cabbage was used, and only the edible part that is sold on the market was harvested to determine the yield. Each salt treatment was replicated eight times.

Onion

On April 29, 2014 the different onion varieties were sown. Each variety was sown in a single row, with 25 cm spacing between the variety rows. Each row was 8 m long in every plot, so that the area per variety was 2.0 m^2. Sowing was performed with a mechanical sowing machine, set at one million seeds per hectare sowing density. The salt treatment started when seedlings were about 6 cm in height. Harvest took place on September 16, 2014, after a 109 days period of salt treatment. For the harvest a length of 1.0 m per row was selected. Each salt treatment was replicated eight times.

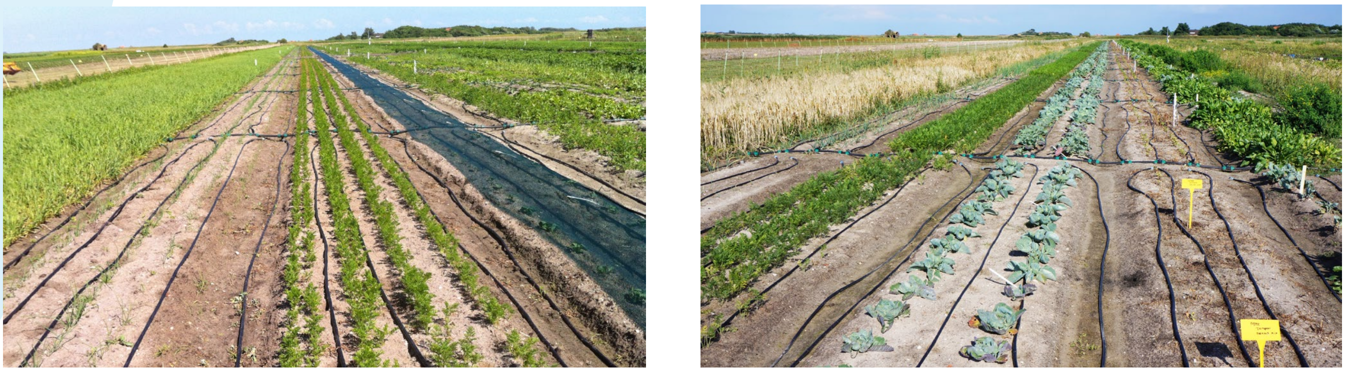


Figure 5. *Impression of onion, carrot and cabbage (under green net) 13 days after the start of the salt treatment (image left) and 67 days after the start of the salt treatment (image right).*

Carrot

On April 29, 2014 the different carrot varieties were sown. Varieties were sown in a row, with 25 cm spacing between rows. Sowing was performed with a mechanical sowing machine, set at 1.2 million seeds per hectare sowing density. Each variety consisted of a row of 8 m in every plot, which equals 2.0 m^2. The salt treatment started when seedlings were about 8 cm in height. Harvest took place on September 30, 2014, after a 113 days period of salt treatment. Fifteen plants within a 1.5 m row were collected and fresh weight of the whole plants (above and below ground biomass) was determined. Each salt treatment was replicated eight times. In 2015, the sowing date was May 19. Seedlings reached the third true leaf stage at the start of the salt treatment. Harvest took place on October 7, after a 121 days period of salt treatment. In 2015, salt treatments were only replicated four times and a 1 m row was harvested.

Table 3. *Overview of the crop growth data presented in this preliminary report*

Crop	Variety	Year tested	Harvested part	Repetitions
Potato	Miss Mignonne	2012, 2013, 2014, 2015	Tubers, fresh weight	4 - 8
	Achilles	2012, 2013, 2014, 2015		4 - 8
	Foc	2015		4
	Met	2015		4
	927	2015		4
Carrot	Cas	2014	Whole plant, fresh weight	8
	Nat	2014		8
	Ben	2014		8
	Ner	2014		8
	101	2015		4
	102	2015		4
	Pri	2015		4
Onion	Alo	2014	Aboveground biomass, fresh weight	8
	Red	2014		8
	San	2014		8
	Hyb	2014		8
Lettuce	Batavia, heading, red	2015	Aboveground biomass, fresh weight	4
	Butterhead, var. Suzan	2015		4
	Butterhead, Lob	2015		4
Cabbage	White cabbage, early variety	2014	Edible part of above ground biomass, fresh weight	8
	Broccoli	2014		8
Barley	Que	2014	Seeds, fresh weight	8
	Que	2014	Stems, fresh weight	8

Lettuce

Seedlings that had developed 3-4 true leaves were planted on June 2, 2015, six days before the salt treatment started. Of the Batavia variety, eight plants per plot were planted, whereas Butterhead varieties had three plants per plot. Planting distance was 40 cm between plants and 40 cm between rows. Each salt treatment was replicated four times. At harvest, the fresh weight of the above ground biomass was determined.

Barley

In 2014 seeds were sown on April 25, harvest took place on August 14. The whole plot (40 m^2) was harvested with a small combine. Only the salt treatments 1.7, 4, 8 and 12 dS/m were harvested, each with 8 repetitions. In 2015 seeds were sown on May 9 and harvest took place on September 10. In 2015 plots of 2 m^2 were harvested. By this time many seeds unfortunately had already fallen on the ground so yield could only be expressed as shoot biomass (excluding all seeds). The maximum salt concentration that was used was 20 dS/m (EC irrigation water) and 8 repetitions per salt treatment were used.

Statistical analysis

Our statistical model for determining crop salt tolerance, based on Maas and Hoffman (1977) has three parameters: EC_{e_thr} (the threshold EC_e in dS/m), S (the slope in units yield per dS/m) and the unaffected yield, i.e. the yield at no salinity stress, Y0. The parameters are estimated by minimizing the sum of squared differences between the model values and the observations. It has been demonstrated (for proofs, a scientific publication containing all details is in preparation) that under the conditions of Salt Farm Texel this method yields unbiased estimates, even in the presence of uncertainty in the ECe. The parameter uncertainties, and prediction error bounds, were obtained with a method based on the Jacobian matrix (i.e. the matrix of the derivatives of the residuals to the parameters) in conjunction with the Cramér-Rao bound (Draper and Smith, 1966; Lewis, 1986; Ljung, 1987; Montgomery *et al*, 2001). In the threshold model, there is the risk of local minima in the search for the minimum sum of squares. The first starting value for the maximum yield prior to the search was chosen as the mean over the lowest seven measured EC values, together with an estimate for slope and threshold, and these starting values were permutated a number of times to obtain the lowest sum of squares. To allow for comparison between crops and between years, the average yield value (in tons per hectare) at low salinity levels was taken as 100% and yields at increasing salinity levels as a percentage of this value. Besides the Maas and Hoffman approach also the Van Genuchten-Gupta (1993) approach, that assumes a more gradual S-shaped decline function of crop yield with increasing salinity, was used to analyse the crops salt tolerance data. This model, too, has three parameters. Details of the models and the estimation method are given in Appendix 2.

Results

Root zone salinity

Salinity levels in the individual plots have been regularly monitored throughout the four growing seasons (year 2012, 2013, 2014 and 2015). First of all, the salinity levels of the salt treatments (EC irrigation water) were plotted against the observed salinity levels of the pore water (EC pore) of which the results are presented in Figure 6. The seasonal average salinity levels found in the pore water correspond well to the salinity levels of the irrigation water that was used. During the first 2 years some fields with the lower salt concentrations (treatment 1.7 and 4 dS/m) were above the intended salt concentration. This was mostly due to the fine-tuning of the irrigation system in the beginning and the non-availability of fresh water. Overall, thanks to the rather strong irrigation, Salt Farm Texel succeeded very well in maintaining a target pore water EC in the root zone of the crops. The pore water EC is slightly higher than the irrigation EC, which is to be expected because during the season there is more evapotranspiration than rainfall, resulting in a concentration effect.

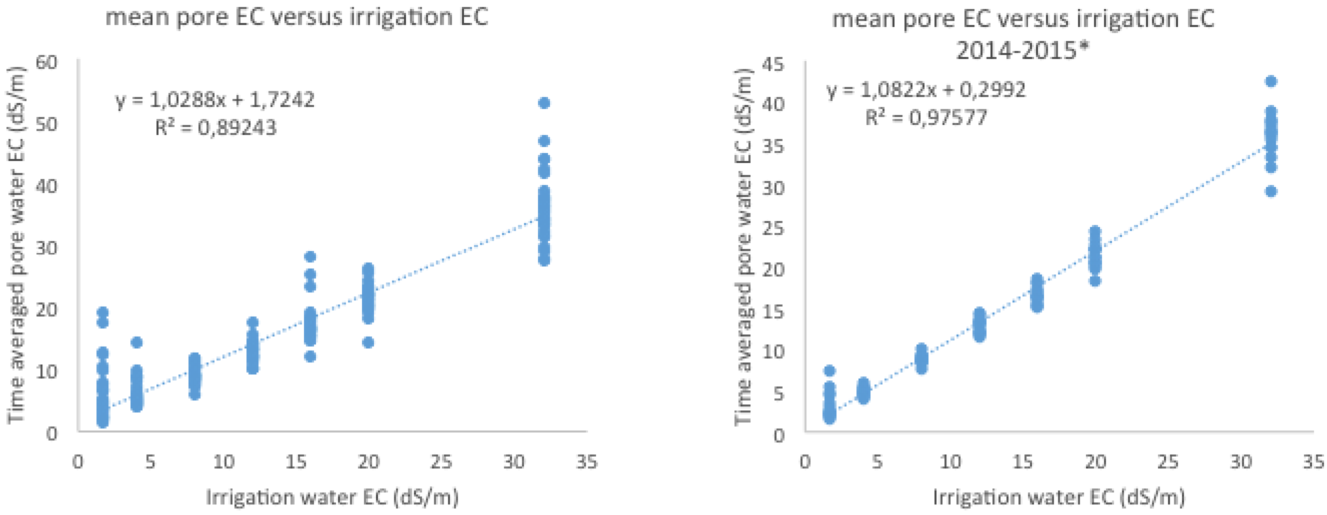


Figure 6. *The salinity level of the irrigation water (x-axis) plotted against the observed seasonal average salinity levels of the pore water (y-axis). Each individual blue dot represents one plot in one year and all 4 years (2012-2015) are used to determine the correlation between EC pore water and EC irrigation water for the image on the left side. On the right side only the years 2014 and 2015 were used. The * means that one outlier was excluded.*

In figure 7 the EC measurements of the pore water in time during the four seasons are presented (excluding the first two weeks of irrigation), which show the temporal dynamics in salt concentration. Especially 2014 and 2015 show very little variation during the season.

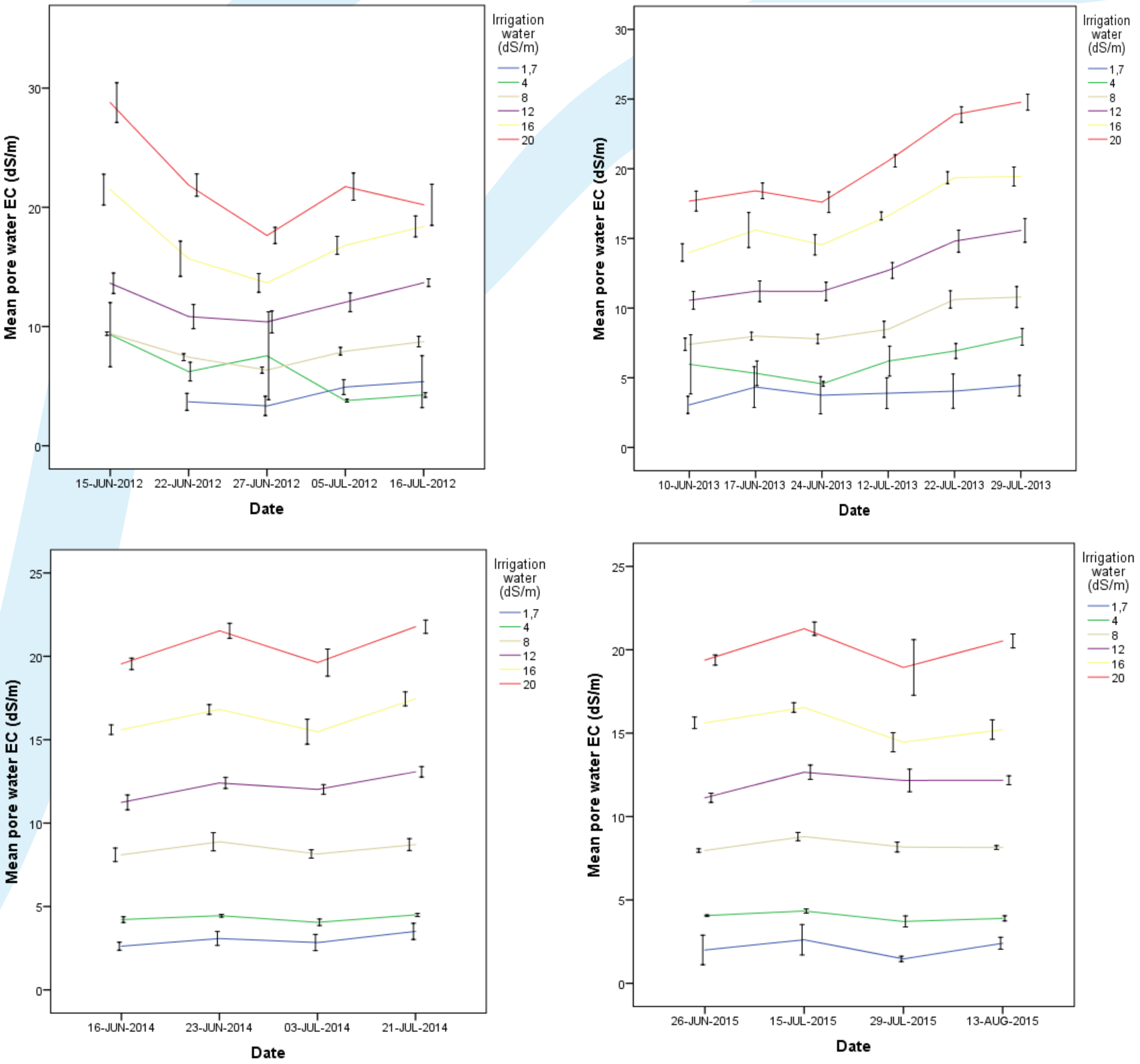


Figure 7. *Salinity measurements (based on EC pore water) during 2012 (top left), 2013 (top right), 2014 (bottom left) and 2015 (bottom right) with n=4 for 2012 and 2013 and n=8 for 2014 and 2015.*

Also the modelling of the root zone salinity shows little temporal variation. In appendix 1, two graphs are presented which show both the measured (indicated as yellow stars, average of the top two depths of measurements (0-10 and 20-30 cm depth)) and the simulated (based on Appendix 1, equation 9) salinity levels of the pore water. This simulated root zone salinity also takes evapotranspiration and rainfall into account. Results clearly show that the model predicts the root zone salinity very well and that, although that there is some variation in time, root zone salinity remains close to the intended salt concentration. In farmer's practises, irrigation often takes place when field capacity is down to about 80%, which corresponds to a

25% increase in salt concentration. Based on this "natural variation" under field conditions it was also the intention of Salt Farm Texel to maintain the root zone salinity within 25% of the intended concentration. Figure 6 shows that this variation of the average root zone salinity is indeed smaller than 25% of the salinity level of the irrigation water. Only some deviation occurred during occasional rainfall events up to 10 mm and recovery after intensive rainfall is quick.

Although the analysis of the pore water salinity of the root zone shows strong correlation with the salinity level of the irrigation water, pore water salinity is not often used in greenhouse experiments or field surveys. The international standard to express root zone salinity is based on the salinity level of the extract of a saturated paste of a soil sample (EC_e). Also, although the mean salinity levels at each point in time showed relatively small variations within each group of fields with the same treatment (see error bars in figure 7). Consequently, also the time averaged values over the growing season of each field within a treatment group show little variation. Despite this, it was decided to use the seasonal mean salinity and crop yield measurements of the individual fields of each treatment as separate data points, rather than clustering the points per treatment, to ensure the optimal comparison between crop growth and salinity level. The results from figures 6, 7 and appendix 1 justify the calculation of one average salinity level per plot per year in order to evaluate crop tolerances to salinity. In all subsequent analyses, soil pore water salinities are expressed in equivalent saturated paste electrical conductivities (EC_e), based on the correlations in Figure 2.

Summary results soil salinity at Salt Farm Texel:

Root zone salinity is sampled frequently and accurately and results, including the modelled inter-sample root zone salinity levels, show that little variation occurs during the season. In addition, pore water salinity is closely related to irrigation water salinity. Based on these results it is concluded that, at the open-air lab of Salt Farm Texel, it is possible to conduct reliable experiments regarding crop salt tolerance under actual field conditions.

Crop growth

In figures 8 and 9 examples are given of the output of the growth analysis, based on the statistical analysis as explained in the "experimental set up". Figure 8 is based on the growth of white cabbage (early variety). In this figure the solid dots represent the measured relative yields per plot (relative to the estimated absolute yield), the solid blue line represent the best fit, the dashed green line is the 95% confidence interval for the prediction with simultaneous repetition of the experiment, and the ellipse represents the approximate 95% confidence contour of the threshold value and the unaffected yield, assuming that the estimated slope is correct. Figure 9 is based on the growth of potato, variety Miss Mignonne, combining four years of data. In figure 9 the confidence contours are not shown, as these are involved in multiple year estimation, but the resulting confidence intervals on the threshold parameter are listed in table 5.

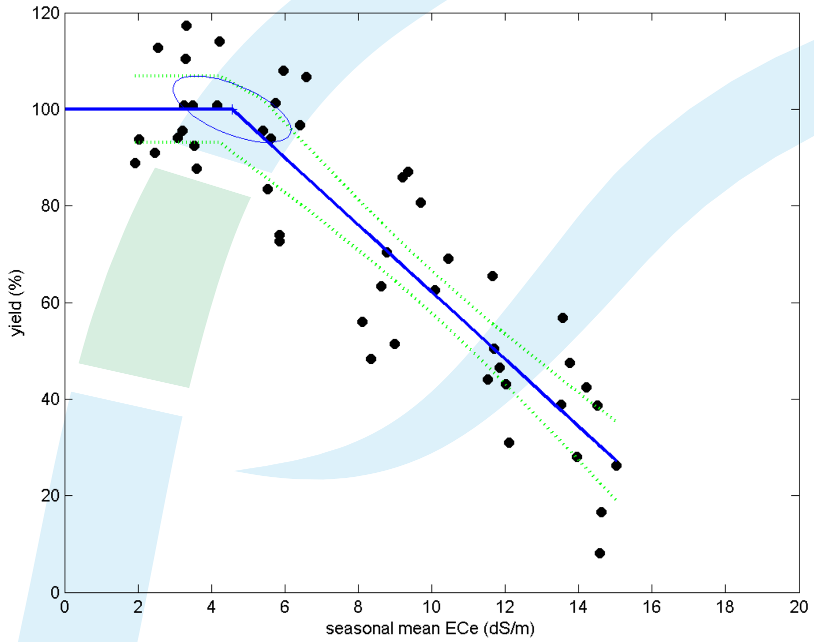


Figure 8. *Relative yield of white cabbage (early variety). The threshold 4.6 dS/m and the salinity level at which yield is reduced by 50% is 11.7 dS/m.*

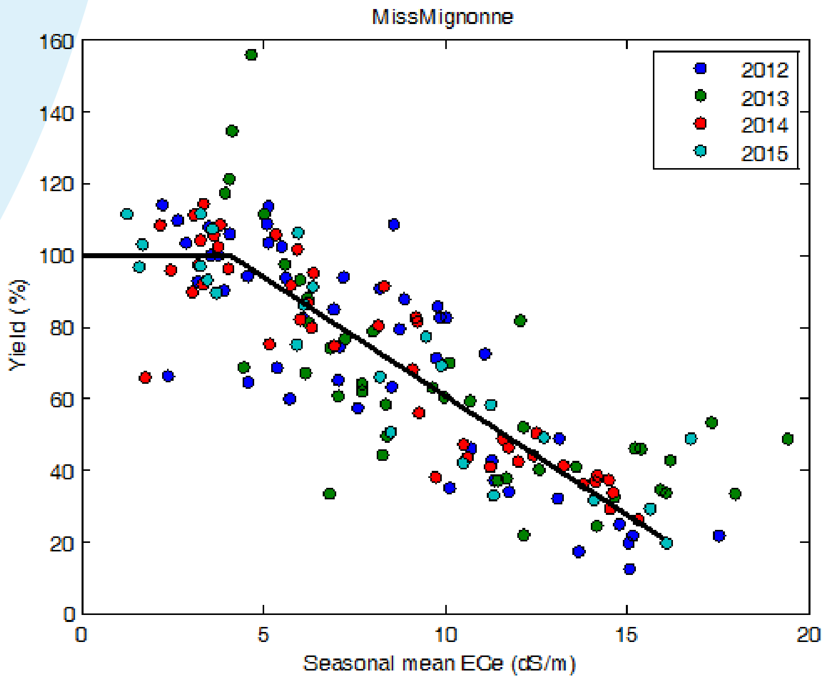


Figure 9. *Relative tuber yield of Miss Mignonne for all years combined. The threshold of Miss Mignonne of all years combined is 4.1 dS/m and the salinity level at which tuber yield is reduced by 50% is 11.6 dS/m.*

In Table 4 an overview is given of the 90% and 50% yield corresponding EC levels when the Van Genuchten-Gupta (1993) growth curve is used to interpret the results. This Van Genuchten-Gupta model does not define a threshold value and only salinity levels of the 90% and 50% yield are given in table 4. In table 5 all results are summarized, based on a similar analysis as presented in figure 8 and 9, including threshold and slope values as reported by Maas and Hofmann (1977) and the FAO (Tanji and Kielen, 2002) which is often used to indicate the crop salt tolerance. Some details of these analyses are highlighted in the "discussion" section of this report and more details will be shared in the next publication (in prep.). Additionally, also the upper and lower values of the 95% confidence interval of the threshold value and the EC_e at which 50% yield reduction occurs are given. In table 6 an overview is given of the threshold values based on the EC levels of the irrigation water. In this table a comparison is made with the recent report on crop salt tolerance by *Stuyt et al*. (2016). In both table 4 and 6 the salinity values based on EC_e (in dS/m) are also expressed as mg chloride per litre, using the correlation presented in figure 10 (based on samples taken form the irrigation water during 5 subsequent years).

Results in Table 5 and 6 show that the salt tolerance of some varieties of the tested crops indicate that salt affected soils up to a salinity level of 4-6 dS/m (EC_e) and irrigation water up to a salinity level of 5 or even 7 dS/m can be used for crop production without loss in yield, implying that moderate saline conditions may be suitable for crop production under conditions similar to the experimental set up described in this report.

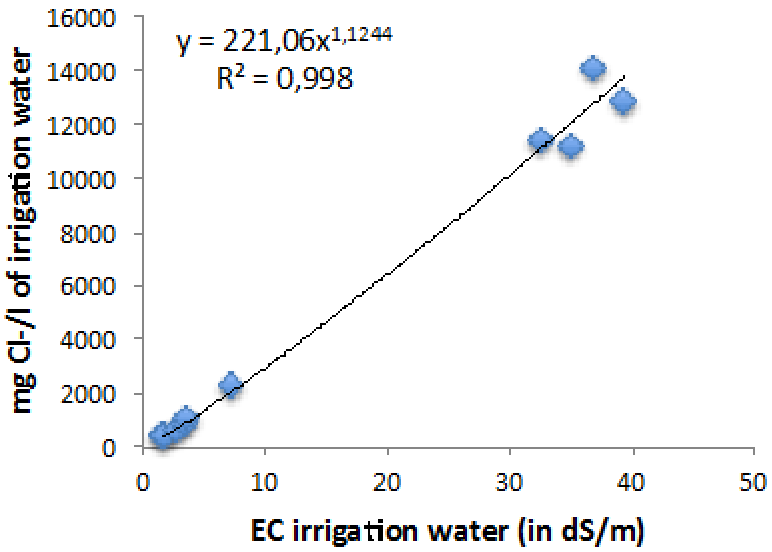


Figure 10. *The correlation between the EC of the irrigation water (in dS/m) and the chloride concentration (in mg/l) of the same irrigation water (n=10, including two samples from 2016).*

Table 4. *Soil salinity levels, based on EC_e (electrical conductivity of the extract of a saturated soil sample, the "saturated paste method") and mg Cl^-/l (based on values of EC_e), that result in a 90% yield (10% reduction) or a 50% yield. Values are based on the yield data per plot using the Van Genuchten-Gupta model to fit the data. Values of chloride were obtained by using the correlation of figure 10.*

		Soil Salinity EC_e, in dS/m		Soil salinity, in mg Cl-/l	
Crop	**Variety**	**90% yield**	**50% yield**	**90% yield**	**50% yield**
Potato	Miss Mignonne	4.6	11.0	1230	3277
	Achilles	3.9	11.4	1021	3411
	Foc	4.0	11.1	1051	3310
	Met	3.7	11.3	963	3378
	927	5.5	12.7	1505	3852
Carrot	Cas	5.7	13.2	1565	4022
	Ner	4.0	11.0	1051	3277
	Nat	n.d.	n.d.	n.d.	n.d.
	Ben	n.d.	n.d.	n.d.	n.d.
	101	3.9	7.9	1021	2258
	102	6.3	9.5	1751	2779
	Pri	4.7	7.6	1260	2162
Onion	Alo	4.7	8.6	1260	2485
	Red	6.8	9.9	1908	2911
	San	5.0	9.6	1350	2812
	Hyb	4.8	7.2	1290	2035
Lettuce	Batavia, heading, red	n.d.	n.d.	n.d.	n.d.
	Butterhead, Suzan	3.6	8.5	933	2452
	Butterhead, Lob	1.5	6.6	349	1845
Cabbage	White cabbage, early	6.0	11.5	1658	3445
	Broccoli	6.7	13.3	1877	4057
Barley	Que seed 2014	5.2	12.3	1411	3715
	Que shoot 2015	3.0	6.8	760	1908

n.d. = non-determinate species, no perceivable salt tolerance

Table 5. *Overview of the salt tolerance of the crops and varieties tested by Salt Farm Texel in the period 2012-2015. Salt tolerance is expressed as the threshold value (maximum salt concentration (as EC_e, in dS/m) without yield loss), the 95% confidence interval of the threshold value (upper and lower values of this interval are listed between brackets in the threshold column), the slope (expressed as the percentage of yield decrease per unit of salinity (1 dS/m) beyond the threshold), and the salinity level at which 50% yield reduction occurs ("50% yield", as EC_e, in dS/m). Also included are the values given by the FAO (Tanji and Kielen, 2002).*

		Values		
Crop	**Variety**	**Threshold**	**Slope (% per dS/m)**	**50% yield**
Potato	Miss Mignonne	4.1 (2.9 - 5.2)	6.6	11.6
	Achilles	2.9 (1.5 - 4.4)	5.6	11.9
	Foc	2.1 (0.3 - 3.8)	5.2	11.7
	Met	1.9 (0.2 - 3.7)	5.0	12.0
	927	3.4 (1.8 - 5.1)	5.2	13.1
	FAO reference	*1.7*	*12*	*5.9*
Carrot	Cas	4.5 (1.8 - 7.3)	5.6	13.4
	Ner	3.6 (0.5 - 6.6)	6.1	11.8
	Nat	n.d.	n.d.	n.d.
	Ben	n.d.	n.d.	n.d.
	101	3.0 (0.3 - 5.8)	9.0	8.6
	102	5.0 (1.9 - 8.1)	11.2	9.4
	Pri	2.1 (0 - 6.0)	9.0	7.6
	FAO reference	*1.0*	*14*	*4.6*
Onion	Alo	2.4 (0 - 7.6)	7.7	8.9
	Red	5.9 (2.7 - 9.2)	11.7	10.2
	San	3.2 (0 - 7.2)	7.4	10.0
	Hyb	3.4 (0 - 8.0)	11.6	7.7
	FAO reference	*1.2*	*16*	*4.3*
Lettuce	Batavia, heading, red	n.d.	n.d.	n.d.
	Butterhead, Suzan	2.3 (0 - 8.7)	6.8	9.6
	Butterhead, Lob	1.8 (0 - 10.7)	5.8	10.3
	FAO reference	*1.3*	*13*	*5.1*
Cabbage	White cabbage, early	4.6 (2.9 - 6.2)	7	11.7
	FAO reference	*1.8*	*9.7*	*7.0*
	Broccoli	5.6 (1.2 - 10.1)	6.3	13.6
	FAO reference	*2.8*	*9.2*	*8.2*
Barley	Que seed 2014	3.3 (0 - 7.3)	5.3	12.8
	Que shoot 2015	1.7 (0 - 3.6)	8.4	7.6
	FAO reference	*8.0*	*5.0*	***18.0***

n.d. = non-determinate species, no perceivable salt tolerance

Table 6. *The threshold values of the various crops, expressed as the salt concentration of the irrigation water (expressed as dS/m and mg* Cl^-*/l). To calculate values listed in this table, the initial thresholds and the 95% confidence interval of the threshold value from Table 5 were used and correlations between* EC_e *and EC pore water from Figure 3 and correlation between EC pore water and EC irrigation water from Figure 6 were used. To calculate the chloride concentration, the correlation found in figure 10 was used. The "Stuyt et al." reference is taken from the report of Stuyt et al., 2016.*

		Treshold for irrigation water, in dS/m		Treshold for irrigation water, in mg Cl^-/l	
Crop	**Variety**	**Treshold**	**Range**	**Treshold**	**Range ***
Potato	Miss Mignonne	5.2	3.6 - 6.7	1411	933 - 1877
	Achilles	3.6	1.7 - 5.6	933	401 - 1534
	Foc	2.5	0.1 - 4.8	619	17 - 1290
	Met	2.2	0.0 - 4.6	537	0 - 1230
	927	4.2	2.1 - 6.5	1110	509 - 1814
	"Stuyt et al."	*3.7*		*838*	*500 - 1200*
Carrot	Cas	5.7	2.1 - 9.5	1565	509 - 2779
	Ner	4.5	0.4 - 8.5	1200	79 - 2452
	Nat	n.d.	n.d.	n.d.	n.d.
	Ben	n.d.	n.d.	n.d.	n.d.
	101	3.7	0.1 - 7.5	963	17 - 2130
	102	6.4	2.2 - 10.5	1782	537 - 3110
	Pri	2.5	0 - 7.7	619	0 - 2194
	"Stuyt et al."	*3.8*		*868*	*800 - 950*
Onion	Alo	2.9	0 - 9.9	732	0 - 2911
	Red	7.6	3.3 - 12.0	2162	846 - 3614
	San	4.0	0 - 9.3	1051	0 - 2713
	Hyb	4.2	0 - 10.4	1110	0 - 3077
	"Stuyt et al."	*3.8*		*867*	*875 - 1050*
Lettuce	Batavia, heading, red	n.d.	-	n.d.	-
	Butterhead, Suzan	2.8	0 - 11.3	704	0 - 3378
	Butterhead, Lob	2.1	0 - 14.0	509	0 - 4298
	"Stuyt et al."	*3.7*		*848*	*425 - 1300*
Cabbage	White cabbage, early	5.9	3.6 - 8.0	1627	933 - 2291
	"Stuyt et al."	*4.5*		*1093*	1025 - 1150
	Broccoli	7.2	1.3 - 13.2	2035	297 - 4022
	"Stuyt et al."	*2.9*		*600*	-
Barley	Que seed 2014	4.1	0 - 9.5	1080	0 - 2779
	Que shoot 2015	2.0	0 - 4.5	482	0 - 1200
	"Stuyt et al."	*8.9*		*2626*	*1150 - 4100*

n.d. = non-determinate species, no perceivable salt tolerance

* Reported range for confidence intervals are 95%, for "*Stuyt et al*. (2016)" this is 40%

[1] Data for *Brassica oleracea* convar. *Capitata* var. *sabauda*

[2] Wheat and barley combined

Discussion

The different measurements of root zone salinity have shown that pore water salinity is highly determined by the salinity of irrigation water for the majority of the growing season. These pore water samples represent the root zone salinity that plant roots are actually experiencing. In this regard, pore water samples are very suitable to analyse crop growth at various salinity levels. However, in the scientific literature, pore water samples are not often used, probably partly because they can only be extracted in sandy or loamy saturated soils. So, to compare the results of Salt Farm Texel to those of other experiments done elsewhere it is necessary to use values of soil saturated paste extracts (EC_e). This conversion based on the calibration in figure 3, will result in some additional variation. The least squares method assumes that the independent variables, here the EC irrigation water, are known with large precision. However, as the observed EC_e is a time average of samples, the EC_e is, itself, an uncertain value. In principle, this so-called errors-in variables case (also known as type 2 in regression literature) may lead to biased estimates. Therefore it has been tested what the effect of random noise in EC_e on the estimates is. In order to do this, 100 sets of synthetic data were generated with the theshold model (see Appendix 2 for more details), using known realistic parameters, and by injecting random noise in the observed EC_e, as well as the observed yields (figure 11). It was established that the centre points of the 100 estimates are close to the true estimates. This means that the method, in practice, yields unbiased estimates as shown in table 7.

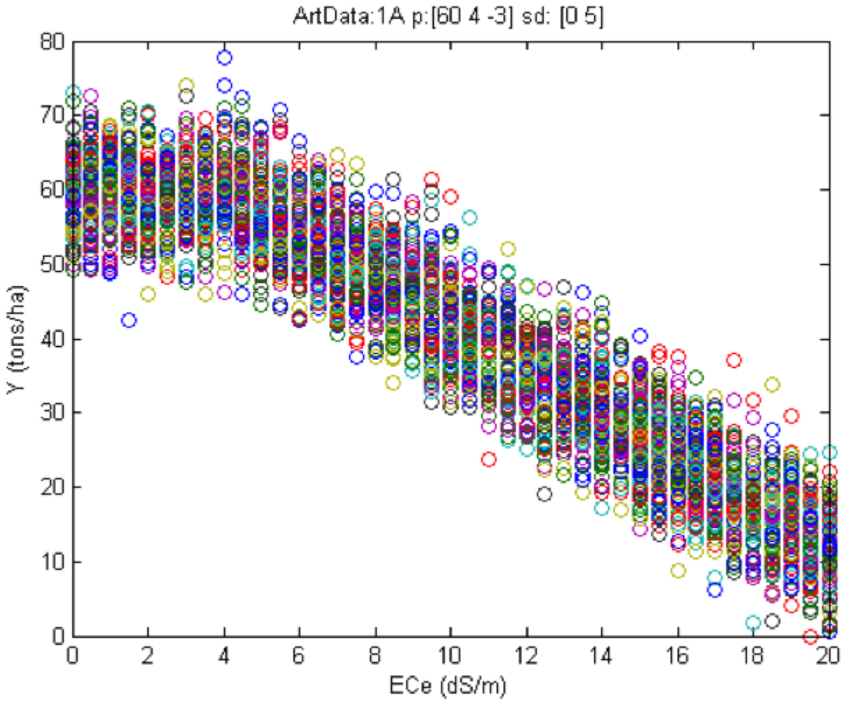


Figure 11. *Results of the 100 sets of synthetic data that were generated with the breakpoint model, using known realistic parameters, and by injecting random noise in the observed EC_e as well as the yield.*

Table 7. *Results of the centre point of the 100 estimates of Y0, EC threshold and slope (S) and the true estimates. The estimates of the "true" and "estimated" values are comparable, meaning that the method, in practice, yields unbiased estimates. Sample sd stands for standard deviation.*

	Sample mean		Sample sd		Mean estimated correlation		
	True	Estimated	True	Estimated	Y0	EC_{thr}	S
Y0	60	59.9930	1.7504	1.7079	1	-0.6950	0
EC_{thr}	4	4.1291	0.8669	0.8105	-0.6950	1	-0.6198
S	-3	-3.0365	0.1856	0.1881	0	-0.6198	1

This does not mean that for an individual data set the estimated parameters are equal to the true ones, yet on average the parameters are unbiased.

Overall the irrigation strategy results in a uniform salt concentration within replicates of one salt treatment and little variation between years. In addition, crop growth is linked with salinity levels of individual plots to obtain the most accurate analysis of crop response to increasing salinity, so some variation within the 8 repetitions of one salt treatment is of less importance. Maas and Hoffman (1977) also concluded that several studies support the hypothesis that plants respond to the mean salinity of the root zone. Hence, using the average seasonal salinity level per plot is an accurate way of linking crop response to increasing salinity under otherwise constant conditions. Therefore, at the open-air laboratory of Salt Farm Texel, it is indeed possible to conduct reliable field trials with respect to root zone salinity. Although under open field conditions more variation can be expected than in greenhouse experiments, the results from the open-air lab are more suitable for comparing the effect of salinity on crop growth under field conditions at other locations. The data was collected under specific conditions at the research location of Salt Farm Texel (sandy soil, optimal drainage, and drip irrigation, with high intensity of irrigation, leaching fraction close to 90%). Locations with a different soil type, different drainage intensity and different irrigation techniques obviously will result in different effective EC values in the root zone, and hence will lead to other responses of crop yield to irrigation salinity. However, without prove of the contrary, the yield reduction functions themselves can be assumed valid.

Despite stable root zone salinity levels, crop growth shows much more variability. Yields at comparable salinity levels can vary greatly, the reasons for this variation are not yet known (although it coincides with variation found in controlled field experiments elsewhere). It could indicate the existence of other as of yet unknown other limitations during part of the season, and this may affect the reduction curves found. However, despite the high variability, it was possible to obtain reliable results for most crops about the threshold and slope values thanks to the high number of replicates and the chosen statistical analysis. This approach resulted in the 95% confidence intervals for threshold values. The fact that the lower bound of the 95% confidence interval in many cases was higher than zero makes it likely that threshold values for crop salt tolerance do indeed exist. In some cases (particularly when there were few observations below the tentative threshold value) our model did not produce reliable threshold estimates. In these cases, plant response to salinity was best described as a linear regression with a negative slope (for instance lettuce, data not shown). So for crops and varieties that produced a 95% confidence interval where the lower bound was zero it is indeed possible that no threshold exists. In most cases the lower boundary of zero is caused by a relative large variation in crop yield data (as can be seen by the large spread in EC values for the lower and upper boundary) and possibly additional testing with a larger number of repetitions and/or with a larger area of harvest can reduce this large differences between the upper and lower boundary of the 95% confidence interval and produce more reliable values of crop salt tolerance. The threshold-slope model is a model based on agronomical considerations, which allow for an easy, two–parameter (threshold and slope) description of crop salt tolerance but this model may not accurately reflect plant physiology. But when the results of the "threshold and slope model" are compared with the results of the Van Genuchten-Gupta model (which follows a more realistic plant physiological approach) then similarities can be seen. The Van Genuchten-Gupta model does not assume a threshold value, but values of the 90% yield can be directly compared to those of the Maas-Hoffman model. It appears that EC_e values with 90% and 50% yield are indeed comparable, as shown in Table 8. Especially the EC values for the 50% yield are very similar, whereas the 90% yield values show more variation. On average both model show comparable results.

Table 8. *Soil salinity levels, based on EC_e, that result in a 90% yield (10% reduction) or a 50% yield. Values are based on the Van Genuchten-Gupta model and the Maas-Hoffman model.*

		Soil salinity level (in dS/m) 90% yield		Soil salinity level (in dS /m) 50% yield	
Crop	**Variety**	**Van Genuchten**	**Maas-Hoffman**	**Van Genuchten**	**Maas-Hoffman**
Potato	Miss Mignonne	4.6	5.6	11.0	11.6
	Achilles	3.9	4.6	11.4	11.9
	Foc	4.0	4.0	11.1	11.7
	Met	3.7	3.9	11.3	12.0
	927	5.5	5.3	12.7	13.1
Carrot	Cas	5.7	6.3	13.2	13.4
	Ner	4.0	5.2	11.0	11.8
	Nat	n.d.	n.d.	n.d.	n.d.
	Ben	n.d.	n.d.	n.d.	n.d.
	101	3.9	4.1	7.9	8.6
	102	6.3	5.9	9.5	9.4
	Pri	4.7	3.2	7.6	7.6
Onion	Alo	4.7	3.7	8.6	8.9
	Red	6.8	6.8	9.9	10.2
	San	5.0	4.5	9.6	10.0
	Hyb	4.8	4.3	7.2	7.7
Lettuce	Batavia, heading, red	n.d.	n.d.	n.d.	n.d.
	Butterhead, Suzan	3.6	3.8	8.5	9.6
	Butterhead, Lob	1.5	3.5	6.6	10.3
Cabbage	White cabbage, early	6.0	6.0	11.5	11.7
	Broccoli	6.7	7.2	13.3	13.6
Barley	Que seed 2014	5.2	5.2	12.3	12.8
	Que shoot 2015	3.0	2.9	6.8	7.6

A comparison with the FAO data (Tanji and Kielen, 2002) can be somewhat tricky. It is stated in this FAO report that “the data serves only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending upon climate, soil conditions and agricultural practices”. For instance, in gypsiferous soils, plants will tolerate an EC_e about 2 dS/m higher than indicated. Soil analysis from the open-air lab of Salt Farm Texel (data provided separately, data in Dutch) shows that the soil is rich in available magnesium and sulphate but poor in calcium. In this regard the soil is non-gypsiferous and higher levels of salt tolerance as indicated by the FAO paper are not expected. Also Maas and Hoffman (1977), the publication that is mostly used as a reference to crop salt tolerance, concluded that “salt tolerance depends upon many plant, soil, water and environmental variables and, hopefully, a discussion of these interacting variables will caution both those using these data and those conducting salt tolerance investigations.” It is difficult to compare all literature that is used to set the guideline of the FAO and it will be even more difficult to compare different variables such as stage of growth, crop varieties, soil fertility, soil water and aeration, and environmental factors. Maas and Hoffman (1977) highlight that the most common method of measuring soil salinity is to determine the electrical conductivity of saturation extracts (EC_e) from the active root zone. Soil samples should be taken just after irrigation (Maas and Hoffman, 1977) and at the research facility of Salt Farm Texel the last irrigation event was never longer than 6 hours ago. In 2016 samples were taken exactly 5 hours after irrigation for each salinity treatment and this resulted in a very strong correlation between EC pore water and EC_e (EC_e=0,71*EC pore water, R^2=0.96). This indicates that the relative large variation seen in figure 3 is partly caused by the difference in time between irrigation and soil sampling, yet the average in figure 3 represents the true value very well. Using EC_e was recommended because the saturation percentage is easily determined in the laboratory and is related to the field-moisture range of soils varying widely in texture. For many soils, the soluble salt concentration of the soil solution at field capacity is about twice that at saturation. Of course this is a rough average since the correlation depends strongly on the timing of irrigation and sampling. The literature review of Maas and Hoffman makes no comments about reporting crop salt tolerance based on salinity levels of irrigation water and subsequently calculated back to soil salinity levels. So it appears that reported EC_e values in the Maas and Hoffman report are based on actual soil samples. This implies that values of EC_e and corresponding crop yields from the open-air lab of Salt Farm Texel and the crop salt tolerance data of Maas and Hoffman can be compared.

When the salt tolerance of the crops and varieties presented in this report are compared with the FAO reference (table 5) it appears that for some varieties of the crops the salt tolerance is at least a factor two higher and in some cases even a factor three. This suggests that crops grown at Dutch field conditions may be more salt tolerant than previously suggested.

More recently, *Stuyt et al*. (2016) reviewed all sources of information about crop salt tolerance that have become available in the Netherlands between 1950 and 2015. In table 6 the results of *Stuyt et al*. (2016) have also been included to make an additional comparison of crop salt tolerance. To make this comparison, the data presented in this report has been calculated from EC_e to EC pore water to EC irrigation water, using the correlation of figure 3 and 6. To calculate values of chloride, the correlation of figure 10 was used.

In table 6 also a comparison between the confidence intervals has been made but it should be noted that the confidence intervals presented in this report are based on 95% whereas the results in the *Stuyt et al*. report are based on 40%, making a direct comparison between the two intervals more difficult. However, the results clearly show that the differences in table 6 are considerable smaller than the differences in table 5 where the FAO reference is used to compare levels of salt tolerance. The results found by *Stuyt et al*. (2016) and the results presented in this report are comparable for various crops and varieties, although for potato, carrot and onion some varieties exist that appear to show greater levels of salt tolerance. For lettuce and barley it appears that the salt tolerance levels are lower then has been reported by *Stuyt et al*., although this comparison is difficult to make since the data set for these two crops are limited and results show considerable variation. Comparison of chloride concentrations may be tricky since the correlation that was based on the analyses of the actual irrigation water in this report is different from the standard correlation formula that is often used in The Netherlands (mg Cl^-/l irrigation water = $221*EC_{irrigationwater}^{1,1244}$ vs. $151*EC_{irrigationwater}^{1,31}$ (Van Dam *et al*., 2007), respectively). When values of chloride are based on calculations rather than actual analysis the comparison may result in positively or negatively biased differences. In fact, we feel that basing salinity policies on chloride is less preferable.

Considering the crops and varieties tested, i.e. potato, carrot, onion, lettuce, cabbage and barley, this report clearly shows that there is more potential for conventional crop production under “moderate saline” conditions than is generally assumed. Irrigation water with a salinity level between 2 and 10 dS/m (considered as “moderately saline” in table 1) has successfully been used in the described field experiments in this report, with yields close to 100% (compared to the control treatment) when an EC of 4 or even 8 dS/m is used. When soil salinity levels are considered, the results also indicate that moderate saline conditions (EC_e of 4-8 dS/m) can be suitable for crop production with yields close to 100%.

Conclusions

- **Root zone salinity can be controlled at the open-air laboratory of Salt Farm Texel and the salinity levels show minimal variation within the season and between years.**
- **Pore water salinity of the root zone is highly similar to the salinity level of the irrigation water.**
- **The model for the prediction of root zone salinity fits the observed salinity levels with a high accuracy.**
- **Based on the measurements of root zone salinity it is possible to conduct reliable experiments under actual field conditions at the open-air lab of Salt Farm Texel.**
- **Plant growth shows considerable variation at similar salinity levels but due to the high number of repetitions the salt tolerance indicators (based on threshold and slope values) can be charted in a reliable way**
- **Moderate saline conditions may be suitable for crop production under certain conditions, with yields close to 100%.**

Recommendations

- The natural variation in yield of field crops between plots results in variation in yield, which is one of the reasons for the rather large uncertainty range (95% confidence interval) of the threshold value. In addition, there is natural variation between years, because of varying meteorological conditions (a.o. temperature, rainfall). Therefore it is recommended to perform experiments for at least another year, in order to obtain more precise estimates of the threshold and the confidence interval.
- To facilitate the screening of many cultivars, and given the limitations in space and (financial) resources, it was for some crops necessary to limit the number of planted and harvested plants per cultivar, and sometimes the number of repetitions as well. It is recommended that future experiments with the most promising varieties use the present basic experimental set up of Salt Farm Texel, i.e. a minimum surface area of 2 m^2 with 8 repetitions (16 m^2 in total), to obtain the most reliable results.
- To obtain more insight in the plant physiological response to salinity and the salt tolerance of different growth stages it is advisable to perform several measurements and harvests during the growth season rather than to focus on a single end-harvest to determine crop salt tolerance.
- In case crops are sown from seed, salinity effects on seed germination may differ from that on crop development. For practical reasons irrigation with saline water may start once seed germination has been completed and similar sized young crop plants start to develop. Such, salt tolerance of the crop may be distinguished from salt tolerance of seed germination. Additional experiments regarding the salt tolerance of the germination phase may be needed.
- In all cases it should be attempted to distinguish direct soil moisture salinity effects on crops from indirect salinity effects on soil properties such as soil structure, soil drainage and aeration. On the sandy soil of Salt Farm Texel these indirect effects are limited, they may be more pronounced in heavier soils.
- In practice, soil salinity varies to some extent over time in response to irrigation, rainfall and capillary rise of saline groundwater. To determine the effect of a short period of increased salinity and the ability of a specific crop to recover after such a short period, additional controlled field experiments should be performed that focus on such conditions.
- Sprinkler irrigation can result in direct leaf damage or leaf uptake of salts, whereas the experiments in this report are based on drip irrigation. To distinguish between different types of irrigation and its effect on crop growth under saline conditions, additional experiments should be performed.
- The current crops and varieties that were tested do not always match the crop varieties that are used most frequently by Dutch farmers. This may cause reluctance to use the results to support agricultural policy or more flexible water management. Therefore, it would be desirable to test the salt tolerance of the most abundant crop varieties used by farmers under the controlled field conditions as provided by Salt Farm Texel.

- Results from this report suggest that the choice of the crop variety may contribute to maintaining good yields under saline conditions. Yet, yields and apparent salinity tolerance vary between varieties and between years, which may be due to fertilizer application, soil amendments, (the timing of) irrigation, drainage and many other factors. More research on these topics is advisable.
- The prediction of the effect of salts on crop growth starts with the actual measurement of the level of soil salinity. It is advisable that all actors in The Netherlands use the same standard for soil salinity. Although the soil saturated paste extract (measured as EC (in dS/m) is time consuming to perform, it represents the most robust standard.
- Focussing on the increasing danger of salinization in The Netherlands and the major salinity issues that the world already faces, the creation of a "Centre of Expertise" for salt tolerant crops and saline agriculture in The Netherlands can have a worldwide impact on food security. Not only can Dutch farmers benefit from such a Centre of Expertise, but also many Dutch agro-companies such as breeders can be part of this centre to open-up a worldwide market. With crop damage due to salinity already estimated at US$ 27.3 billion every year at present (Qadir *et al*., 2014), the solution to this challenging problem may be profitable as well.

References

Abrol IP, **Yadav JSP**, **Massoud FI**. *1988*. Salt affected soils and their management.
FAO soil bulltin 39. FAO, Rome.

Bruning B, **van Logtestijn R**, **Broekman R**, **de Vos AC**, **Parra Gonzales A**, **Rozema J**. *2015*. Growth and nitrogen fixation of legumes at increasing salinity under field conditions: implications for the use of green manures in saline environments. AoB Plants Special Issue: Physiology and ecology of halophytes-plants living in salt-rich environments, 1-8.

De Vos, **AC**. *2011*. Sustainable exploitation of saline resources. Ecology, ecophysiology and cultivation of potential halophyte crops. Thesis VU University Amsterdam, the Netherlands.

De Kempenaer JG, **Brandenburg WA**, **van Hoof LJW**. *2007*. Het zout en de pap, een verkenning bij marktexperts naar langetermijnmogelijkheden voor zilte landbouw. Utrecht.

Draper NR, **Smith H** *1966*. Applied regression analysis. Wiley, New York.

Flowers TJ, **Gaur PM**, **Gowda CLL**, **Krishnamurthy L**, **Samineni S**, **Siddique KHM**, **Turner NC**, **Vadez V**, **Varshney RJ**, **Colmer TD** *2010*. Salt sensitivity in chickpea. Plant Cell Environment 33, 490-509.

Ghassemi F, **Jakeman AJ**, **Nix HA**. *1995*. Salinization of land and water resources: Human Causes, extent, management and case studies. UNSW Press, Sydney, Australia, and CAB International, Wallingford, UK

Khrais T *1996*. Evaluation of salt tolerance in potato (Solanum spp.). Thesis. Department of Plant Science, Mcgill University, Macdonald Campus.

Lewis FL *1986*. Optimal estimation with an introduction to stochastic control theory. Wiley, New York

Ljung L *1987*. System identification – theory for the user. Prentice-HallEnglewood Cliffs, New Jersey.

Maas EV, **Hoffman GJ**, *1977*. Crop salt tolerance-current assessment. Journal of the Irrigation and Drainage Division, American Society of Civil Engineers 103: 115-134.

Montgomery DC, **Peck EA**, **Vining GG**. *2001*. Introduction to linear regression analysis. Wiley, New York

Qadir M, **Quillerou E**, **Nangia V**, **Murtaza G**, **Singh M**, **Thomas RJ**, **Crechsel P**, **Noble AD** *2014*. Economics of salt-induced land degradation and restoration. National Resources Forum, United Nations. DOI: 10.1111/1477-8947.12054

Rhoades JD, **Kandiah A**, **Mashali AM**. *1992*. The use of saline water for crop production. FAO irrigation and drainage paper 48. FAO, Rome.

Roest CWJ, **Van Bakel PJT**, **Smit AAMFR**. *2003*. Actualisering van de zouttolerantie van land- en tuinbouwgewassen ten behoove van de berekening van de zoutschade in Nederland met het RIZA-instrumentarium. Alterra. Actualisering zouttolerantie gewassen.

Rozema J, **Flowers T**. *2008*. Crops for a salinized world. Science 322: 1478-1480.

Stuyt LCPM, **Blom-Zandstra M**, **Kselik RAL**, *2016*. Inventarisatie en analyse zouttolerantie van landbouwgewassen op basis van bestaande gegevens. Wageningen, Wageningen Environmental research, Rapport 2739. http://edepot.wur.nl/391931

Tanji KK, **Kielen NC**. *2002*. Agricultural drainage water management in arid and semi-arid areas. FAO irrigation and drainage paper 61. FAO, Rome.

Van Dam AM, **Clevering OA**, **Voogt W**, **Aendekerk ThGL**, **van der Maas MP**. *2007*. Zouttolerantie van landbouwgewassen. Deelrapport Leven met Zout Water. PPO nr 32 340194 00.

Van Genuchten MTh. and **S.K. Gupta SK**. *1993*. A Reassessment of the crop tolerance response function. Journal of the Indian Society of Soil Science, Vol. 41, No. 4, pp 730-737.

Van Hoorn JW and **Van Alphen JG** *1994*. Salinity Control. In: H.P. Ritzema (Ed.), Drainage Principles and Applications, p. 533-600. ILRI publication 16, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. 1994. ISBN 90 70754 3 39.

Appendix 1.

Modelling root zone salinity to provide insight in the inter-sample behavior.

The water balance of the root zone reads:

$$I + R + Cr = E + P + \Delta w \qquad (1)$$

Here, I is the irrigation, R the rainfall, Cr the capillary rise of soil water from the underground, E the evapotranspiration, P the percolation of soil water to the underground, and Δw the change in soil water content. The units may be mm/day.

Under the Salt Farm conditions (daily amounts of irrigation water exceeding the evapotranspiration and the presence of an intensive subsurface drainage system keeping the water table continuously below the root zone and close to the drain depth), capillary rise of soil moisture from the underground into the root zone does not occur, the soil water content is permanently close to the saturation point and the change in soil water content is negligibly small. Hence Eq. 1 simplifies to:

$$I + R = E + P \qquad (2)$$

By multiplying the water flow with the salt concentration of the flowing water one obtains the salt balance. As the salt concentrations of rainfall and evaporation are negligibly small, the salt balance can be written as:

$$I.Ci = P.Cp + \Delta s \qquad (3)$$

Here, Ci is the salt concentration of the irrigation water, Cp the salt concentration of the percolation water, and Δs the change in salt storage in the soil. The units of salt concentration may be expressed in terms of electrical conductivity (EC) in dS/m or mS/cm.

The salt concentration of the percolation water Cp is in a complicated way related to the salinity history in the soil profile. As a simplification, it is postulated that the salt concentration is simply proportional with the salt concentration of the pore water:

$$Cp = F.Cs \qquad (4)$$

Here, Cs is the average salt concentration of the pore water, and F is an empirical (possibly time varying) parameter, called the leaching efficiency of the soil pore system. By definition the leaching efficiency represents the ratio of the salinity of the percolation water to the average salinity of the soil pore water.

The leaching efficiency accounts for irregular patterns of downward flow through the irregular soil pore system, which may also vary with depth, and for the irregular distribution over time of salts dissolved in the water inside the pore system.

At each time step, the change of the salt concentration of the soil water in the root zone equals:

$$Cf - Co = \Delta s/W \qquad (5)$$

where Cf is the final average salt concentration Cs of the soil water at the end of the time step, Co is the initial salt concentration Cs of the soil moisture at the beginning of the time step, and W is the amount of water contained in the soil pores of the root zone, equaling:

$$W = D.T \qquad (6)$$

where D is the depth of the root zone and T the total pore space of the soil in the root zone. In the actual calculation presented later the soil is divided in three layers, and the equations have been adapted accordingly.

During a small time step the average salt concentration of Cs can be taken as:

$$Cs = 0.5*(Co+Cf) \qquad (7)$$

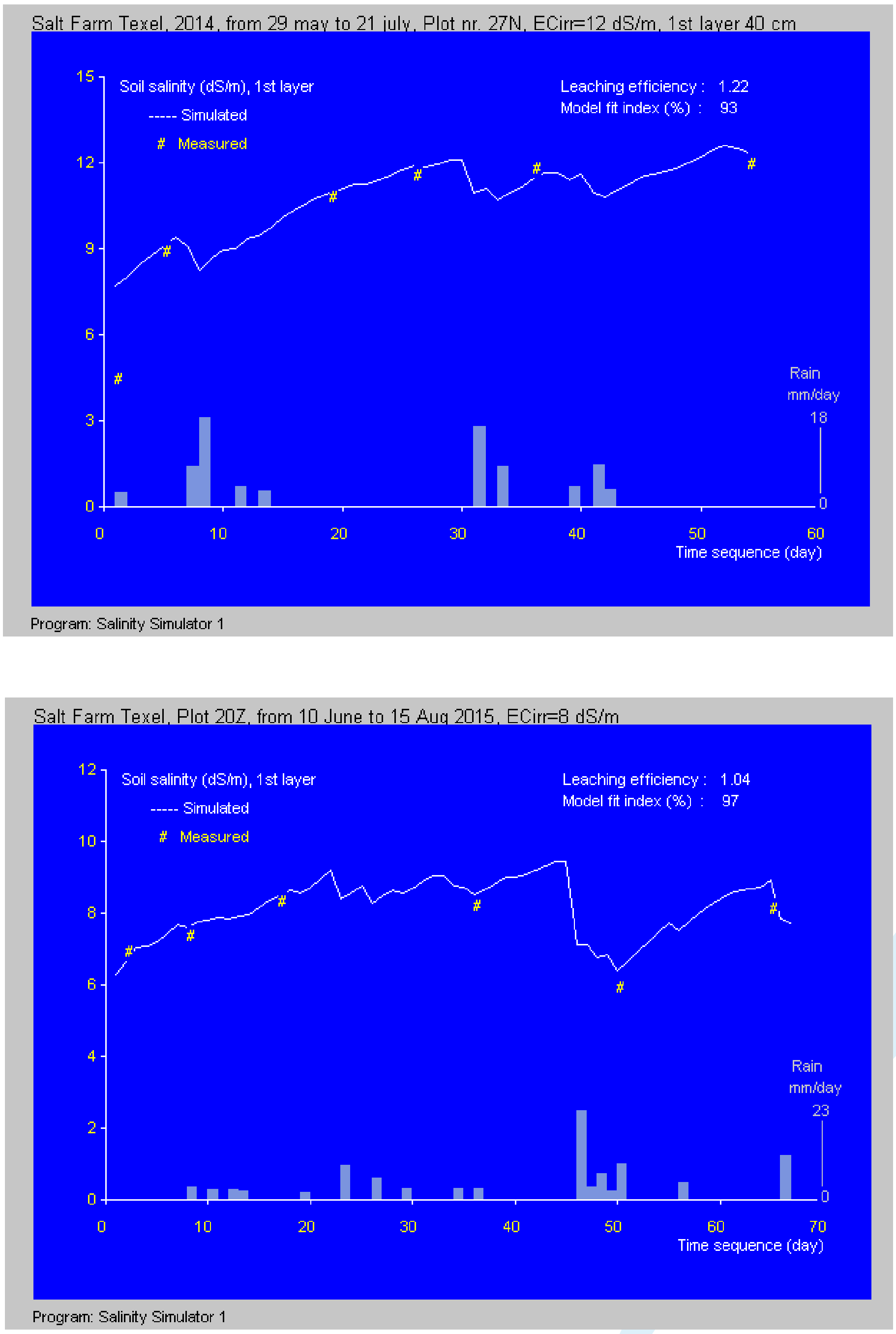
Combining Eq. 3, 4, 5, 7 and 7, one gets:

$$Cf = Co + I.Ci/D.T - 0.5*F.P.(Co+Cf)/D.T \qquad (8)$$

or explicitly in Cf:

$$Cf = [Co + I.Ci/D.T - 0.5*F.P.Co/D.T] / [1 + 0.5*F.P/D.T] \qquad (9)$$

This equation 9 is used for the soil salinity simulation model, see the 2 examples below. The solid line in these 2 examples represent the simulated pore water salinity. It is clear that little variation occurs during the season, even after intensive rainfall in the year 2015. Although there is a reduction in the root zone salinity level during this intensive rainfall period, this reduction remains within the 25% variation (regarding the salinity level of the irrigation water) that is normally present under field conditions (where field capacity often drops by 20% causing a 25% increase in soil salinity levels).



Example of simulation

Overview of the measured (hash: #) and modelled (solid line) root zone salinity (based on pore water salinity) during the season of 2014 (top figure, data shown of one plot irrigated with 12 dS/m) and during the season of 2015 (bottom figure, data shown of one plot irrigated with 8 dS/m).

Appendix 2.

The threshold model (Maas-Hoffman)

The threshold or breakpoint model is given by

$$Y = \begin{cases} Y_0 & ECe \le ECe_{thr} \\ Y_0 + S * (ECe - ECe_{thr}) & ECe_{thr} < ECe < ECe_{thr} - \dfrac{Y_0}{S} \\ 0 & ECe > ECe_{thr} - \dfrac{Y_0}{S} \end{cases} \tag{1}$$

where

Y	is the yield at a particular ECe (dependent variable)
ECe	is the associated ECe (independent variable)
Y_0	is the yield without saline stress (a parameter)
ECe_thr	is the threshold (breakpoint) ECe (a parameter)
S	is the slope, i.e. the loss in yield per unit ECe beyond the breakpoint (a parameter).

The yield is expressed in appropriate yield units (possibly different by crop), and the ECe is expressed in dS/m. The slope in the equation above is negative, and is expressed in appropriate yield units per dS/m.

Once an estimate of the unaffected yield Y_0 is available, a plot in terms of percentage of unaffected yield can be presented as

$$\frac{Y}{Y_0}(\%) = \begin{cases} 100 & ECe \le ECe_{thr} \\ 100 + S\% * (ECe - ECe_{thr}) & ECe_{thr} < ECe < ECe_{thr} - \dfrac{100}{S\%} \\ 0 & ECe > ECe_{thr} - \dfrac{100}{S\%} \end{cases} \tag{2}$$

where

S%	is the percentage yield loss per unit of dS/m beyond the breakpoint.

Note that in the breakpoint model there is a discontinuity in the derivative of the yield to ECe at ECe=ECe_thr.

The S-shaped model (Van Genuchten-Gupta)

This model is described by

$$Y = Y_0 \frac{1}{1 + \left(\frac{ECe}{ECe_{50}}\right)^p} \tag{3}$$

where the additional symbols are

ECe_{50} is the ECe at which the yield has dropped to 50% of the maximum yield Y_0 (parameter)

p is a dimensionless shape parameter.

Once an estimate of the unaffected yield $\widehat{Y_0}$ is available, a plot in terms of percentage of unaffected yield is given by

$$\frac{Y}{\widehat{Y_0}}(\%) = 100 \frac{1}{1 + \left(\frac{ECe}{ECe_{50}}\right)^p} \tag{4}$$

Note that in contrast to the breakpoint model, the parameters in the relative plot remain the same. Also, there are no discontinuities in the derivative of yield to EC_e.

Parameter estimation

The parameters have been estimated by minimizing the sum of squared differences between model and data. Given a set of observations EC_e *(i)*, *Y(i)*, *i=1,2,…,N* the sum of squares is defined by

$$V(\mathbf{p}) = \sum_{i=1}^{N} \left(Y(i;\mathbf{p}) - Y_{obs}(i)\right)^2 \tag{5}$$

where

p is the vector of parameters

$Y_{obs}(i)$ is the observed yield at the i-th EC_e value

$Y(i;\mathbf{p})$ is the modelled yield at the i-th EC_e value, for the parameters in vector **p**

The parameter estimates are found by minimizing p ; in mathematical terms

$$\hat{\mathrm{p}} = argmin\, V(\mathbf{p}) \tag{6}$$

where the carret indicates the estimated value.

Confidence intervals of the parametersThe co-variance matrix of the parameters is given by

$$\mathrm{P} = cov(\hat{\mathbf{p}}) = \frac{V(\mathbf{p})}{N - n_p}(J^T J)^{-1} \tag{5}$$

Here, *N* is the number of samples, n_p the number of parameters and *J* is the Jacobian matrix, formed by the derivatives of each output observation to the parameters. Hence, *J* is a *N* × n_p matrix. Consequently, the covariance matrix P is a n_p × n_p (symmetric) matrix.

The standard deviation of the estimate is

$$\sigma(p_j) = \sqrt{P_{jj}} \tag{6}$$

and the correlation coefficient for the off-diagonal elements is

$$\frac{\sigma_{12}^2}{\sigma_1 \sigma_2} \tag{7}$$

An approximate 95% confidence interval (Cramér-Rao lower bound) for parameter *j* when all other parameters are at their optimal value is

$$\widehat{p_j} - 2\sigma(p_j) \leq p_j \leq \widehat{p_j} + 2\sigma(p_j) \tag{8}$$

The percentage is approximate since the model is non-linear in the parameters.

It must be noted that the individual parameter confidence intervals can be used as such, but that combining individual parameter confidence intervals of several parameters can be misleading if there is correlation between the estimates. The confidence region is ellipsoidal, and the corner points of the region defined by Equation (8) are usually outside the confidence region. In practical terms: the estimates of the threshold and the slope are generally positively correlated, meaning that a lower threshold must be compensated by a flatter slope to maintain a good fit. But the combination of a threshold on the low end of the confidence region and a slope on the high end is unlikely.

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