Adapting to salty conditions in the Netherlands: A joint report on activities from the ‘Dealing with Salinization’ project (2023-2024)

Ayodeji O. Deolu-Ajayi, Judit Snethlage, Gert-Jan Wilbers, Marnix Poelman, Estefania Velilla, Willem de Visser, Dessi W Pasaribu, Casper Krijnse Locker, Kornelis Walma, Catharien Terwisscha van Scheltinga, Adrie van der Werf and Ingrid M van der Meer

WAGENINGEN UNIVERSITY & RESEARCH

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Summary

Salinization, characterised by the accumulation of excessive salts, poses a significant threat to global food security. Arable land affected by salinization continues to expand. These developments are also taking place in the Netherlands. Recognizing the urgency of addressing this challenge, various strategies can be explored for adapting to a saline environment. Within this context, the KB-34 "Dealing with Salinization" project dives into salinity adaptation strategies with a two-year initiative of greenhouse experiments and desk studies aimed at understanding the effects of salinity on the plant-water-soil nexus. Results from the project are presented in this joint condensed report of activities.

Chapter 1 introduces the concept of salinization in the Netherlands which is linked to rising seawater levels and land subsidence. Coastal regions of the Netherlands in the Wadden islands, Northern and South-Western part of the Netherlands are especially vulnerable to salinization. Impact of salinization on agriculture is devastating reducing crop yield, degrading soils, impacting income and generating unplanned costs to manage salt-affected areas. Because of this, associated economic losses due to salinization in the Netherlands may reach up to €600 million annually.

Crop experiments in semi-controlled saline conditions are reviewed in Chapter 2. Broccoli, potato and wheat showed varied yield and quality response under saline conditions. Combining the use of salt tolerant varieties with the application of organic and inorganic soil amendments has potential to mitigate the impact of salinity and boost crop quality and/ or yield under salt stressed conditions. The salt tolerant variety of potato had significantly better yield and quality under saline conditions. Application of seaweed extract and zeolite only slightly improved tuber yield under these conditions and did not close the yield gap caused by salinization.

Chapter 3 goes more in-depth on the interactions between soil salinity, soil moisture and application of soil amendments in the two years plant experiments. Zeolite application improved water retention and moderated the effects of salt stress on soil moisture. Additionally, the salt tolerant potato cultivar outperformed sensitive cultivar in maintaining soil moisture stability and reducing salinity variability in the soil pots. These findings highlight the potential of integrating soil amendments into sustainable water and salinity management strategies.

The cost-benefit analyses of chapter 4 highlights that the seaweed-based biostimulant offer the most consistent financial returns under saline stress, particularly for the salt-tolerant potato variety. Zeolite, despite improving yields, often fail to justify their high costs. These findings provide critical insights into the financial trade-offs faced by farmers, informing decisions about adopting soil amendments as part of salinity management strategies

Upscaling of salinization strategies to landscape, regional and (inter)national scale is important and discussed in chapter 5. The butterfly framework is used to systematically analyse key factors needed of upscaling. Furthermore, we discussed the experiences on upscaling salinity in international context, where a shift from short term field level agricultural improvement-oriented strategies addressing salinity, towards long term management at landscape level is required. Reflection on the situation in the Netherlands, indicate recommendations to explore upscaling along the same lines such as making linkages between field scale and short-term measures, and landscape, regional and (inter)national scale level and long-term measures.

Land-use transitions that balance ecological, economic, and societal objectives is explored in Chapter 6. Salinized areas may adopt solutions, such as saline agriculture or aquaculture, which provide ecosystem services like biodiversity conservation, carbon sequestration, nitrogen cycling and flood protection. Aligning these transitions with societal goals and planetary boundaries ensures environmental resilience and long-term economic viability.

Keywords: salinization, adaptation strategies, socio-economic costs, upscaling, land use transitions

1 Current damage to the agricultural sector due to salinization

Judit Snethlage, Kornelis Walma, Ayodeji O. Deolu-Ajayi and Catharien Terwisscha van Scheltinga

Salinization, the accumulation of excessive salts in soil and water, presents a growing challenge to global agricultural productivity and food security (FAO, 2021). This issue is not isolated to arid and semi-arid regions but has also become a concern in deltas such as the Netherlands, where factors like sea-level rise, land subsidence, and reduced freshwater availability increase the problem. Salinization negatively impacts crop yield, disrupts soil health, and creates among others, financial stress for farmers, especially in coastal areas of the Netherlands that are prone to saltwater intrusion. Addressing salinization is therefore important for the agricultural sector, including addressing its food security, environmental and socio-economic impact.

1.1 Extent of salinization in the Netherlands

Salinization poses a significant threat to global food security (FAO, 2020). Salinization in the Netherlands is driven by two key factors: sea level rise and land subsidence, both of which increase saltwater intrusion into coastal areas (Ruto et al., 2021). However increasing salinization is not limited to these two factors. Stuyfzand (2007) mentions other factors that contribute to salinization including evaporation, sea salt drift, poor agricultural management, soil contamination, sedimentation, saltwater infiltration into freshwater bodies, coning during freshwater extraction and dissolution of rock salt. The Wadden islands, Coastal areas of Friesland and Groningen, the South-West delta and North Holland are regions in the Netherlands that are at risk of salt intrusion (van den Burg et al., 2024). Model simulations indicate that by 2100, salt levels in these regions may double due to increased saline groundwater seepage (Oude Essink et al., 2010). This process is especially critical in low-lying, reclaimed coastal lands where groundwater is located close to the soil surface (Voorde and Velstra, 2009).

Salinization in the Netherlands operates through internal and external processes. Internal salinization occurs when saline groundwater rises to the surface, primarily due to land subsidence. External salinization on the other hand, is caused by seawater intrusion, where rising sea levels push saltwater into freshwater systems. Both mechanisms significantly pressure agricultural systems, particularly in coastal provinces such as Zeeland, Friesland and Groningen. These areas are additionally vulnerable due to their reliance on surface freshwater for maintaining crop productivity (Nillesen and van Ierland, 2006). Projections in the project led by Noordegraaf and Te Winkel (2021) estimate that salinization risks will increase significantly by 2050 impacting land use and agricultural productivity. A more in-depth analysis of salinity scenarios in the Netherlands are displayed with a projected change of 1 m of sea level rise (Fig 1.1).

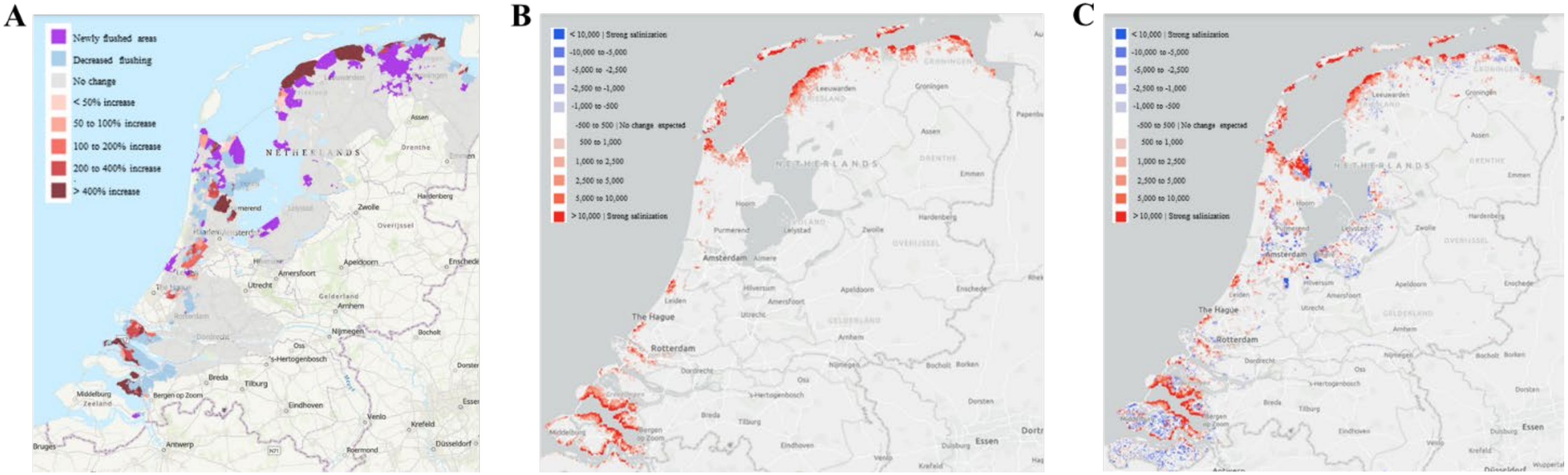

Figure 1.1: Model simulations on impact of salinization with 1 m sea level rise in the Netherlands. Projected change in demand for freshwater needed for salt flushing as a way to cope with increasing salinization (A), projected contribution of sea level rise to change salt load (kg/ ha/ year) pushing saline groundwater to the surface (B), and projected spatial distribution of salt load (kg/ ha/ year) flowing from groundwater into surface water (C). Figure sourced from Rijkswaterstaat et al., n.d

With increasing salinization, freshwater needed for salt flushing or leaching also increases (Fig 1.1A). Mostly impacted would be the Northern provinces of Friesland and Groningen requiring the highest volumes. Next to that are areas mostly located in the Northern part of the Netherlands that currently do not need salt flushing, but a 1 m sea level rise would create new scenarios where freshwater is needed to deal with the salinity. Due to seawater level rise, regions like Friesland, Groningen and Zeeland are projected to experience the biggest increase in salt levels (Fig 1.1B). Western urbanized areas including Rotterdam and the Hague, also face risks. Additionally, a significant increase of salt load in groundwater primarily in the coastal zones of Zeeland, the Northern provinces, and the Western urban regions is expected to occur (Fig 1.1C). Central and inland areas remain relatively stable, with limited changes in current levels of salinity. Severe salinization hotspots include Zeeland (Middelburg), Western Randstad (Rotterdam and the Hague), and the Friesland-Groningen coastlines. Moderate increases in salt load are projected for Flevoland and inland areas, showing emerging trends. One of these trends is water getting less saline as observed in scattered blue zones near IJsselmeer and parts of Friesland (Fig 1.1C). Furthermore, periods of drought and seawater flooding increase salinization by reducing freshwater availability. The effects of climate change including rising temperatures and shifts in precipitation pattern, further expand this issue, leading to more frequent and prolonged events of salinity stress.

It becomes clear that the increase in salinity is evident. To deal with this increase, many salinity strategies could be implemented (Deolu-Ajayi et al., 2024; van den Burg et al., 2024). However, there is often a lack of clarity regarding the benefits of implementing salinity strategies (e.g., soil amendment and biostimulant application), particularly in terms of crop yield gains and economic costs. Plant experiments that test these proposed salinity measures coupled with developing cost-benefit analysis for these measures is important to understanding the scalability and identifying possible pathways for broader adoption. A cost-benefit framework can provide valuable insights into the economic viability of salinity adaptation strategies, benefiting not only farmers but also external parties e.g., funding bodies. Knowledge of the associated benefits and risks can reduce perceived uncertainties, motivating adoption of salinity strategies. When such solutions are proven in practice and lead to tangible yield increases, their expected returns can be better evaluated alongside associated costs (Merton et al., 2023). These results on crop productivity and associated cost benefit analysis are presented in chapters 2 and 4 of this report.

1.2 Economic impact of salinization

The economic impact of salinization can be analysed across multiple scales- at the farm level, regionally, and nationally- through reduced crop productivity, increased costs, and restricted crop choices (Ruto et al., 2021). In the Netherlands, the financial impact of salinization is substantial, with significant variations depending on the type of crop and severity of the saline conditions. According to de Boer and Radersma (2011), different factors such as agricultural activities, saltwater intrusion, pollution of surface water and dissolution of rocks have different impacts on crops in different parts of the Netherlands.

Agricultural activities such as fertilizer application, result in chloride concentrations up to 200 mg Cl/ L of water (de Boer and Radersma, 2011). This salt level only affects the most salt sensitive crops such as ornamental crops and occurs across the country. Saltwater intrusion via open river mouths occurs temporarily in South Holland, notably along the Nieuwe Waterweg and the Hollandse IJssel. Surface water chloride levels can reach up to 250 mg/ L, with potentially higher levels in soils due to combined effects of salinization and evaporation during summer droughts. These conditions impact the most salt sensitive crops. Infiltration of polluted surface water, sea salt deposition along the coast, and local soil contamination (e.g., from leaking sewers or landfills) can result in chloride levels between 300 and 600 mg Cl/ L of water. This range negatively impact cultivation of salt sensitive crops including vegetables, fruits and tree crops.

Furthermore, seawater intrusion along the coast and mobilisation of seawater cause chloride concentrations ranging from 2,000 to 18,000 mg Cl/ L(de Boer and Radersma, 2011). These levels impact all crops except halophytes, resulting in reduced crop growth and productivity. Seawater intrusion directly affects up to 6 km inland along the western and northern coasts, while seawater migration impacts a broader area of 25 to 75 km inland, with variable salinity levels depending on the location. Dissolution of rock salt produces chloride levels with a wide range between 2,000 and 200,000 mg Cl/ L. When rock salt near the surface mixes with freshwater, it creates chloride levels unsuitable for the most sensitive crops and at higher concentrations, may reduce productivity of all crops. In Twente and the Achterhoek, rock salt deposits are located at a 400 m depth.

The economic impact of salinization should not be limited to crop losses alone. Additional costs come from land reclamation, soil remediation and implementation of other salinity adaptation strategies such as use of tolerant varieties and improved irrigation innovations. Addressing salinization through preventive and adaptive measures would yield substantial savings by minimising yield loss and reducing long-term opportunity costs. At the farm level, salinity reduces crop yield and increases the costs of inputs such as freshwater and soil amendments. On a regional scale, salinization affects larger agricultural zones, particularly in coastal provinces such as Friesland, Zeeland and Groningen. In these areas, staple crops like potato and barley suffer considerable yield losses. During extreme drought years, potato yields in these regions can decline by 25 to 30% leading to economic losses that further strain the livelihoods of farmers (Ruto et al., 2021). At the national level, salinization in the Netherlands also result in broader economic impacts. particularly for the agricultural sector. The annual cost of salinity-related damage is estimated at €577 to 610 million, with the bulk of the losses linked to agricultural revenues due to reduced yield, land degradation and increased expenses for soil remediation and adaptation measures (Ruto et al., 2021, Tzemi et al., 2019). Other authors have previously given a similar estimate of €600 million annually due to agricultural revenue losses (Bosello et al., 2012, Richards and Nicholls, 2009).

Globally, economic costs of salinization have been extensively studied. Research by Ghassemi et al. (1995) estimated annual global income losses due to salinization of only irrigated areas at $11.4 billion. A more recent assessment by Qadir et al. (2014) suggest that the losses from salt-affected irrigated lands could amount to $27.3 billion annually. In both cases, these estimations are based mainly on crop yield reductions. Although these estimates focus primarily on irrigated regions, the costs would still likely increase if environmental and social impacts were also considered along with economic losses from crop yield. In Europe, other studies highlight the economic costs associated with salinization. For example, Montanarella (2007) estimated that annual costs of soil salinization in Spain, Hungary and Bulgaria ranged from €158 to €321 million.

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2 Improving crop productivity under salinity stress by use of tolerant varieties and amendments

Ayodeji O. Deolu-Ajayi, Casper Krijnse Locker, Willem de Visser, Dessi Waty Pasaribu, Adrie van der Werf and Ingrid M. van der Meer

2.1 Introduction

Most crops are selectively bred are glycophytes that can only survive in low sodium ecosystems (Cheeseman, 2015). Salinity negatively impacts crop growth and yield. Salt (NaCl) disrupts metabolic processes and reduce photosynthetic efficiency in plants typically leading to a reduction in shoot growth (Negrão et al., 2017). Plants have developed mechanisms to combat the physiological impact of salinity stress such as producing osmolytes, Na^+ exclusion and Na^+ compartmentalisation (Munns & Tester, 2008). Irrespective of this, salt-stressed crops still have reduced yield and quality, and in dire cases, total yield loss may occur (Deinlein et al., 2014). Several strategies have been identified that promote crop adaptation to salinity. These strategies include cultivation of halophytes- plants that have underlying mechanisms that allow them thrive in highly saline conditions, cultivation on raised soil beds, phytoremediation and bioremediation of salinized soils, micro-irrigation systems, drainage innovations, water desalinization technologies, propagating salt tolerant species and cultivars, and use of soil and crop amendments, including biostimulants (van den Burg et al., 2024). The underlying salt tolerance mechanisms in plants were the basis for development of some of these adaptation strategies.

We assessed the extent to which application of these salinity strategies may boost crop production under salinized conditions in this project. In 2023, we investigated the response of three different crops- broccoli, potato and wheat, to application of three soil amendments- a seaweed extract, a silicon-based biostimulant and an inorganic amendment (zeolite). Here, we assessed whether the use of the amendments can promote yield and quality of salt-stressed crops. The following year (2024), we evaluated whether the crop yield and/ or quality gap caused by salinity can be closed by combining two strategies- the use of tolerant cultivars and amendments. Here, we tested only one crop but two different cultivars- salt sensitive and tolerant potato cultivars, under the three previously investigated amendments. The methodology, results and perspective of this study is presented in this chapter.

Plants vary in their response to salinity. Different species show differential salinity thresholds where crop yield is severely affected (Maas et al., 1977). Thus, our inclusion of three crop types: potato (tuber), broccoli (vegetable), and wheat (cereal) which should be the most salt tolerant of the three crops. Cultivars within a species have been developed by breeders for salt tolerance (Fita et al., 2015). In 2024, we focused on cultivars within one species- potato, with contrasting salt sensitivity and tolerance.

The three amendments used in our study were selected based on their potential to promote crop growth under saline conditions. Seaweed-based biostimulants can reduce the negative effects of salinity to promote crop yield and/ or quality (Deolu-Ajayi et al., 2022). *Ascophyllum nodosum* extracts are popular seaweed biostimulants that stimulate phytohormones to improve nutrient uptake and reduce oxidative damage (Shukla et al., 2019).

Furthermore, seaweed extracts have chelators and alginates which contribute to soil aeration and water-holding capacity. Silicon is another source of biostimulants (Rouphael & Colla, 2020). Silicon ameliorates salt stress in plants by restricting Na^+ and Cl^- uptake via root, improving photosynthesis, maintaining redox homeostasis, and improving nutrient efficiency (Liu et al., 2019). Zeolites are microporous crystalline aluminosilicate that increase cation exchange capacity by binding Na^+ ions thereby preventing salt entry into the plants (Noori et al., 2006). Additionally, it improves hydraulic conductivity of the soil therefore, ensuring a higher soil moisture content that allows dilution of toxic Na^+ and Cl^-.

2.2 Methodology

2.2.1 Experimental design

Experiments took place in UNIFARM greenhouses Nergena, Wageningen University and Research (Address: Building 112, Bornsesteeg 10, 6721 NG Bennekom). Plant experiments were setup in a block design. The first set of experiments were from late April to end of July, or August (broccoli only) 2023 while the second set of experiments in 2024, occurred from end of May to end of July. Plants were cultivated in individual pots to maintain salt concentration, ensure that salt treatment remained contained and did not cause cross-contamination (Fig 2.1). Plants were grown in 23 cm diameter pots with potting soil and growth nutrients administered periodically. Only one seed or tuber was germinated per pot (Fig 2.1).

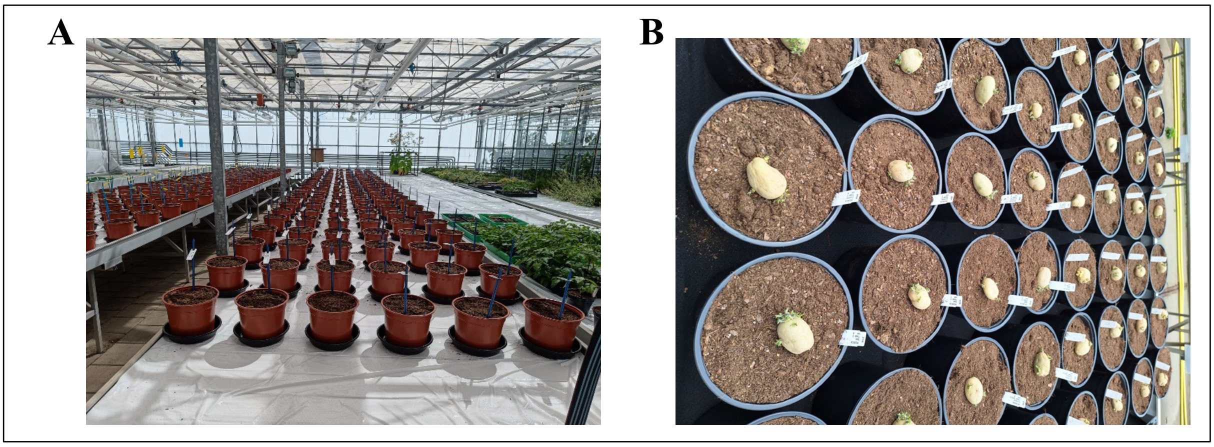


Figure 2.1: Plants were cultivated in 23 cm diameter pots with trays under each pot. Bottom irrigation was used- water, nutrients and salt treatment were placed in the trays for plant absorption. The 2023 experiment took place in a closed growth chamber (A) while 2024 experiments took place outside and under a plastic poly cover (B). Only one seed or tuber was added per pot.

The 2023 experiments were performed in a semi-controlled closed growth chamber. Relative humidity, temperature and light intensity were mostly maintained for the duration of the experiments. In the growth chamber, factors such as columns, hanging sensors, slight table height differences, location of door, and distance between plants may still affect plant growth and development. The 2024 experiments were performed in an open shed under a plastic poly cover preventing interference from rainfall. Here, relative humidity, temperature and light intensity varied according to climatic conditions of the location.

Three crops were assessed in the 2023 experiment. Common (salt sensitive) varieties of broccoli (*Brassica Oleracea* var. Calabrese Natalino), potato (*Solanum Tuberosum* var. Lady Claire) and wheat (*Triticum Aestivum* var. Calixo) were cultivated in salinized conditions. In the 2024 experiments, two potato varieties- a salt sensitive and a salt tolerant variety were assessed.

2.2.2 Crop treatments

Two different conditions-control and saline, and three different soil amendments were used in the experiments. Control refers to conditions where crops are continuously irrigated with freshwater while in saline conditions, crops were irrigated with water containing high levels of NaCl. Three amendments i.e., a silicon (Si)-based biostimulant, a seaweed-based biostimulant and clinoptilolite zeolite- $(NaK)_6Al_6Si_{36}O_{72}\cdot 20(H_2O)$, were tested. The Si biostimulant is a liquid biofertilizer. It is based on stabilised and bioavailable silicic acid mixed with micronutrients, and improves crop yield and quality (Thimmappa & Basavarajappa, 2021), while the seaweed extract is a liquid biostimulant composed of brown seaweed *A. nodosum* extract and amino acids (Tabet et al., 2021). This seaweed-based biostimulant mitigates the negative effects of abiotic stress in crops.The amendments were added directly to the soil and dosage based on manufacturers' recommendations. For the business as usual case that serves as a reference, crops were treated with water.

Combining the two conditions with the use of three amendments, we end up with eight different treatments, T1= control + water; T2= control + seaweed biostimulant; T3= control + Si biostimulant; T4= control + zeolite; T5= salt + water; T6= salt + seaweed biostimulant; T7= salt + Si biostimulant; and T8= salt + zeolite. There were 12 technical replicates per crop (broccoli, potato or wheat) per condition (control or salt) per treatment (water, seaweed biostimulant, Si biostimulant or zeolite) in the 2023 experiments. In 2024, there were 8 technical replicates per potato cultivar (salt sensitive or salt tolerant variety) per condition (control or salt) per treatment (water, seaweed biostimulant, Si biostimulant or zeolite).

In the 2023 experiments, salt treatments started by applying NaCl solution to 30-day plants of all crops. Salt levels were increased weekly until concentrations reached ~80 mM NaCl with salt treated plants showing signs of salt stress observed as leaf wilting (Fig 2.2). Plants in control conditions were irrigated with similar volumes but in this case, water without salt. Plants were salt-treated much earlier in the 2024 experiments at only 14 day old. Salt concentrations were increased weekly from 40 mM to 80 mM and stabilised and maintained at higher salt concentrations of 120 mM NaCl by the third week from start of salt treatment, inducing salinity stress for most of the crop's growing period (Fig 2.3).

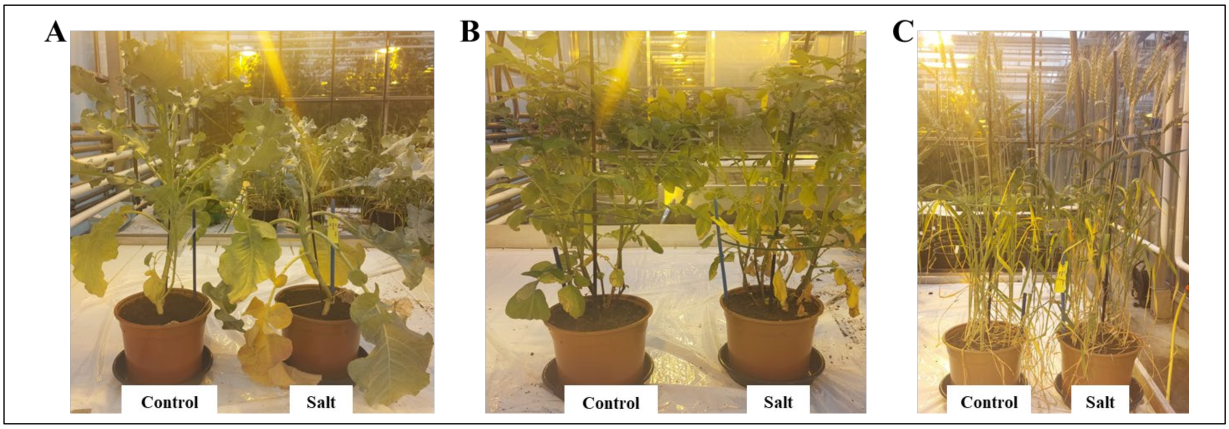


Figure 2.2: Plant response to salt induction. Broccoli (A), potato and wheat (C) in control and salt conditions after 3 weeks of NaCl irrigation in the 2023 experiments.

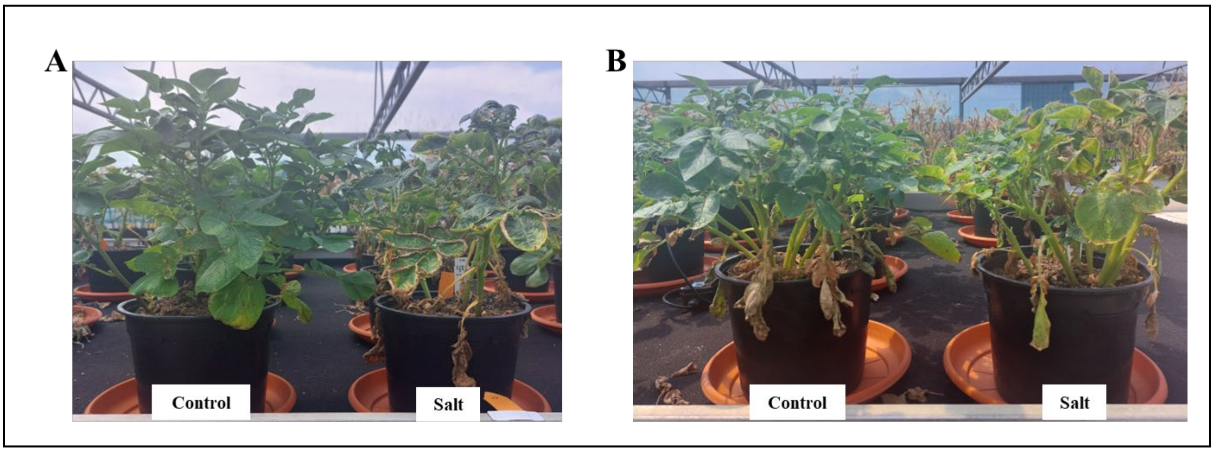


Figure 2.3: Potato response under control and saline conditions without biostimulant treatments. Sensitive (A) and tolerant (B) potato varieties under experimental conditions after 4 weeks of NaCl irrigation in the 2024 experiments.

2.2.3 Crop analysis

2.2.3.1 During growth

Electroconductivity (EC) in µS, soil moisture content in % and soil temperature in °C were continuously measured using sensors. EC levels reported by the sensors showed clear increase at the onset of salt treatment. Throughout most of the experiments, the EC in salt condition, was roughly 22 times higher on average, than EC values in control condition. Further details are discussed in chapter 3 of the report.

Temperature did not significantly differ between the conditions. However, soil moisture content differed: it was on average 2 times higher in saline conditions than control conditions. This was also observed during pot handling since salinized pots were heavier than their corresponding control pots. Since the pots typically received the same amount of water, it means that the plants in salt condition transpired relatively less than the plants in the control condition. This is likely due to stunted or reduced growth of the salt-stressed plants (Tian et al., 2020).

2.2.3.2 Crop yield

Crop yield was determined at the end of the experiments. Each of the 12 plants per condition (control or salt) per amendment (water, seaweed biostimulant, Si biostimulant or zeolite) per crop type (broccoli, potato or wheat) were measured for crop yield in the 2023 experiments. Broccoli did not yield florets in our experiments which may be due to higher temperatures and humidity in the greenhouse compartment. Therefore, vegetative parameters such as main stem length (cm) and dry weight (g), leaf dry weight (g) were assessed. Here, the vegetative parts were exposed to standard drying of plant material at 70°C for 24 to 48 hours.

Potato tuber fresh weight (g) and total tuber number were evaluated. For wheat- ear number, ear dry weight (g), and grain dry weight (g) were measured. Wheat ears and grains were also dried at 70°C for 24 hours prior to their measurements.

It should be noted that in the 2024 experiments, crop harvest was performed earlier than expected ~1 month before planned harvest. This was to salvage the tubers since there was pest (thrips) and disease infestation due to the wet conditions during summer 2024. The sensitive varieties under saline conditions were especially affected (Fig 2.4) thus, the decision to harvest earlier. The result was smaller sized tubers. For the 2024 experiments, all 8 plants per condition (control or salt) per amendment (water, seaweed biostimulant, Si biostimulant or zeolite) per potato variety (salt sensitive or salt tolerant) were measured.

Figure 2.4: Potato response with ongoing pest and disease infestation in the 2024 experiments. Sensitive potato variety only under control and saline conditions prior to early harvest (A) and after shoot indicated with white arrows has been cut off during tuber harvest (B).

2.2.3.3 Crop quality

Quality analysis was performed on the plant parts relevant for human consumption. Thus, potato tubers and wheat grains were assessed. In the case of broccoli, leaves with petioles were evaluated. In total, for each crop there were 96 plants, 12 plants per treatment, to be analysed. For potato and broccoli four plants per treatment were pooled, resulting in three pooled samples per treatment. For wheat, the amount (weight) of kernels per plant were too low to perform all analyses. We therefore pooled the kernels of six plants together to make one sample resulting in two samples per treatment. The kernels and potatoes could be analysed as such (fresh because of low water content) but in the case of broccoli, it was the dried leaves and petioles.

In total, 15 different categories of plant compounds were analysed in wheat grains, broccoli leaves and potato tubers. Crop quality analysis were performed by Eurofins (eurofins-agro.com), using standardised, accredited methods for energy (in kJ and in Kcal), sodium (Na) content, salt concentration without Na, total solids, saturated fats, unsaturated fats (PUFA and MUFA), total fats, glucose content, fructose content, saccharose content, sum of reducing sugars, small sugars based on methods NEN 3571 and EU152/2009, dietary fibres, total nitrogen (N) content, and total carbohydrates. Additionally, crude protein content was calculated as N*6.25. Moisture and ash content of the samples were also measured in the analysis.

For the 2024 experiment only potato tubers (two different varieties: one salt tolerant and one salt sensitive) were cultivated. Plants were pooled resulting in three replicates of three pooled plants per treatment. The same analyses were performed as mentioned for the 2023 experiments and on top of that, vitamin C analysis (Food Chemistry, 94 (2006) 626-631) was added since potatoes are a known source of vitamin C in our diet.

2.2.3.4 Data analysis

Statistical analysis was performed in R. R-studio packages ‘plyr’ and ‘ggplot2’ (Wickham, 2009, 2011) were used for data processing and graphs, while packages ‘nlme’ and ‘multcomp’ (Hothorn et al., 2008; Pinheiro et al., 2023) were used for calculating statistics significance for the difference in means. Statistics was performed by one-way (factor= soil amendment) or two-way (factors= condition and soil amendment) ANOVA with Tukey post hoc where different letters represent p-values of ≤ 0.05.

2.3 Results

Potato and wheat yield and quality were assessed in the 2023 experiments. Additionally, since broccoli did not produce florets but instead continued to grow vegetatively due to unfavourable conditions in the greenhouse especially in summer, we assessed dry weight of the stem and leaves as well as, the quality of the leaves. Only potato yield and quality were evaluated in the 2024 experiments. Only the most diverging results are presented in this report.

2.3.1 Seaweed extract and zeolite boosted wheat yield in control conditions only

In control conditions, some of the soil amendments improved weight of wheat ear and grain (Fig 2.5). Application of seaweed biostimulant caused a significant increase in ear (+10%) and grain (+12%) productivity, compared to treatments where no amendments where added (i.e., water) in control non-stressed conditions. Zeolite showed a similar trend as when seaweed biostimulant was added, although a significant increase was only observed for fresh weight of the grain. Despite application of Si-based biostimulant, wheat yield remained similar as when amendments were not added. On the other hand, application of the biostimulants or zeolite caused no significant changes to crop yield under saline conditions.

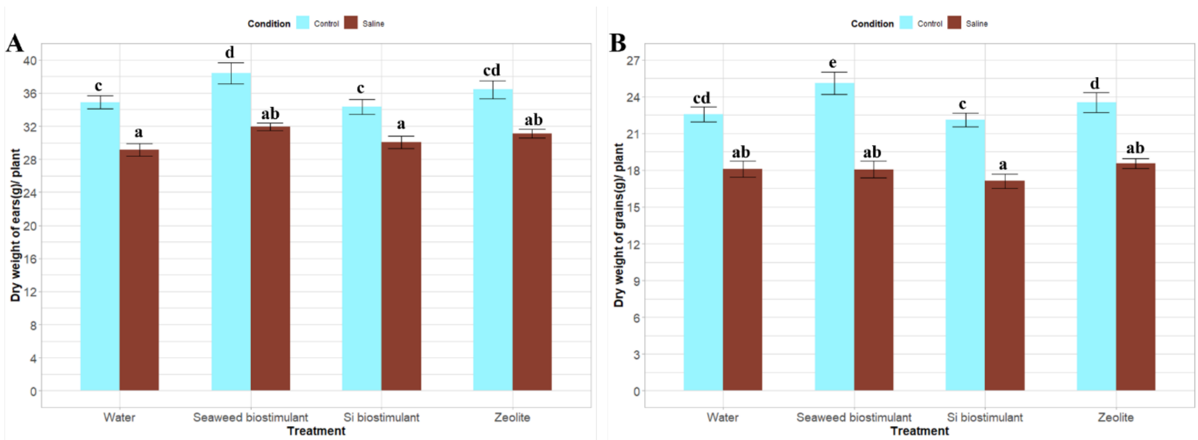


Figure 2.5: Wheat yield in 2023 experiments. Dry weight of wheat ears (A) and dry weight of wheat grains (B). Control conditions are represented with blue bars while saline conditions displayed as red bars. Plants were treated with water representing the business as usual case or no treatment conditions. In other cases, the plants were treated with a seaweed-based biostimulant, silicon (Si)-based biostimulant or zeolite. Application occurred via addition of all amendments directly to the soil according to manufacturer recommendations. There were 12 technical replicates per crop (broccoli, potato or wheat) per condition (control or salt) per treatment (water, seaweed biostimulant, Si biostimulant or zeolite). Statistics was performed by two-way ANOVA with Tukey post hoc where different letters represent p-values of ≤ 0.05.

2.3.2 Biostimulants and zeolite application did not significantly alter broccoli growth

There were generally bigger variations among replicates in broccoli (Fig 2.6). Although there were slight increases in main stem due to application of seaweed biostimulant and zeolite in control conditions, it was not significant (Fig 2.6A). Plants treated with Si biostimulant remained unchanged and showed similar response as the non-treated plants. Treatment with any of the biostimulants or zeolite did not result in changes to the main stem length under saline conditions. In control conditions, dry weight of the leaves reduced although only significant under Si biostimulant application (Fig 2.6B), indicating that this biostimulant may have an inhibitory effect on broccoli. Under saline conditions, dry weight of leaves had no significant changes associated with biostimulant or zeolite application.

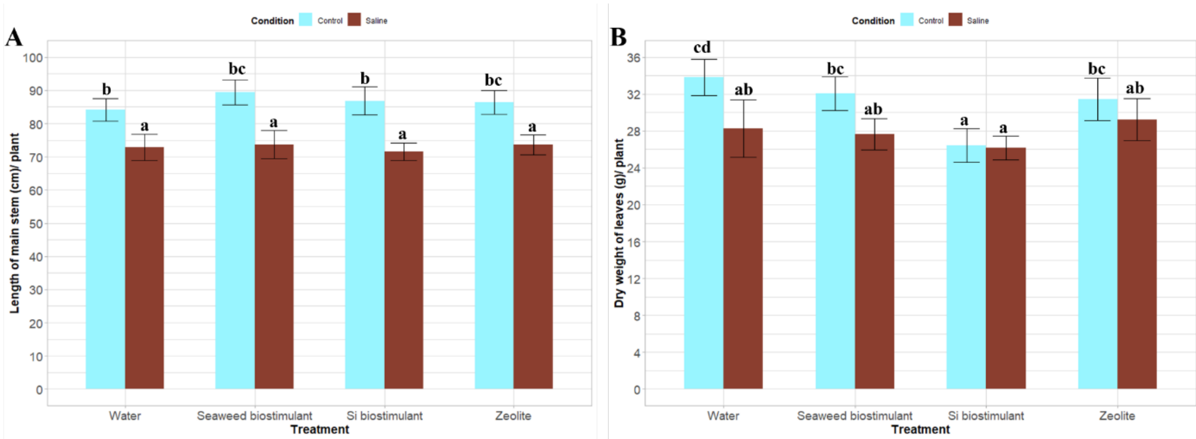


Figure 2.6: Broccoli growth in 2023 experiments. Length of main stem (A) and dry weight of leaves (B). Control conditions are represented with blue bars while saline conditions displayed as red bars. Plants were treated with water representing the business as usual case or no treatment conditions. In other cases, the plants were treated with a seaweed-based biostimulant, silicon (Si)-based biostimulant or zeolite. Application occurred via addition of all amendments directly to the soil according to manufacturer recommendations. There were 12 technical replicates per crop (broccoli, potato or wheat) per condition (control or salt) per treatment (water, seaweed biostimulant, Si biostimulant or zeolite). Statistics was performed by two-way ANOVA with Tukey post hoc where different letters represent p-values of 0.05.

2.3.3 Potato varieties respond differentially to treatment with biostimulants or zeolite

In the 2023 experiments, fresh weight of tubers remained similar under control conditions, independent of treatments (Fig 2.7A). Under saline conditions tuber weight significantly decreased in replicates treated with either biostimulants or zeolite. This same trend under saline conditions was observed for total number of tubers although not significant, due to huge variation among technical replicates (Fig 2.7B). Application of the Si biostimulant resulted in an increase in number of tubers harvested per plant compared to non-treated plants while the use of seaweed biostimulant or zeolite had the opposite effect.

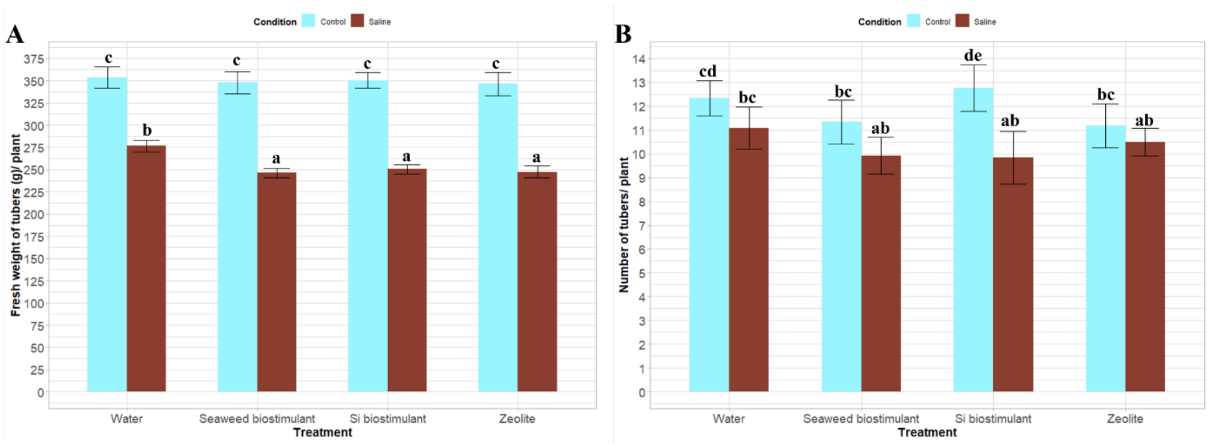


Figure 2.7: Potato growth in 2023 experiments. Fresh weight of tubers (A) and number of tubers (B). Control conditions are represented with blue bars while saline conditions displayed as red bars. Plants were treated with water representing the business as usual case or no tretment conditions. In other cases, the plants were treated with a seaweed-based biostimulant, silicon (Si)-based biostimulant or zeolite. Application occurred via addition of all amendments directly to the soil according to manufacturer recommendations. There were 12 technical replicates per crop (broccoli, potato or wheat) per condition (control or salt) per treatment (water, seaweed biostimulant, Si biostimulant or zeolite). Statistics was performed by two-way ANOVA with Tukey post hoc where different letters represent p-values of ≤ 0.05.

Salt sensitive potato cultivar in the 2024 experiments had bigger yield reductions under salinized conditions compared to the salt tolerant variety (Fig 2.8). For example, average tuber weight per pot of the salt sensitive variety dropped by at least double that of the salt tolerant variety- the former reduced by 39% while the salt tolerant variety only had an 18% reduction (Fig 2.8A, B). Treatment of salt sensitive variety with biostimulants or zeolite did not cause significant changes to tuber weight compared to non-treated potato plants, independent of control or salt stress conditions (Fig 2.8A). Interestingly, treatment of the salt tolerant variety with biostimulants and zeolite caused a significant increase in average tuber weight per pot under control conditions, compared to non-treated plants (Fig 2.8B). This same trend again occurred under saline conditions, although not significant. There were huge variations in tuber number among replicates making it difficult to make concrete inferences (Fig 2.8C, D). In control conditions, application of biostimulants or zeolite decreased average number of tubers per pot for the salt sensitive variety but this increased in the salt tolerant variety, compared to control. There were no significant changes in the salt tolerant or salt sensitive varieties under saline conditions.

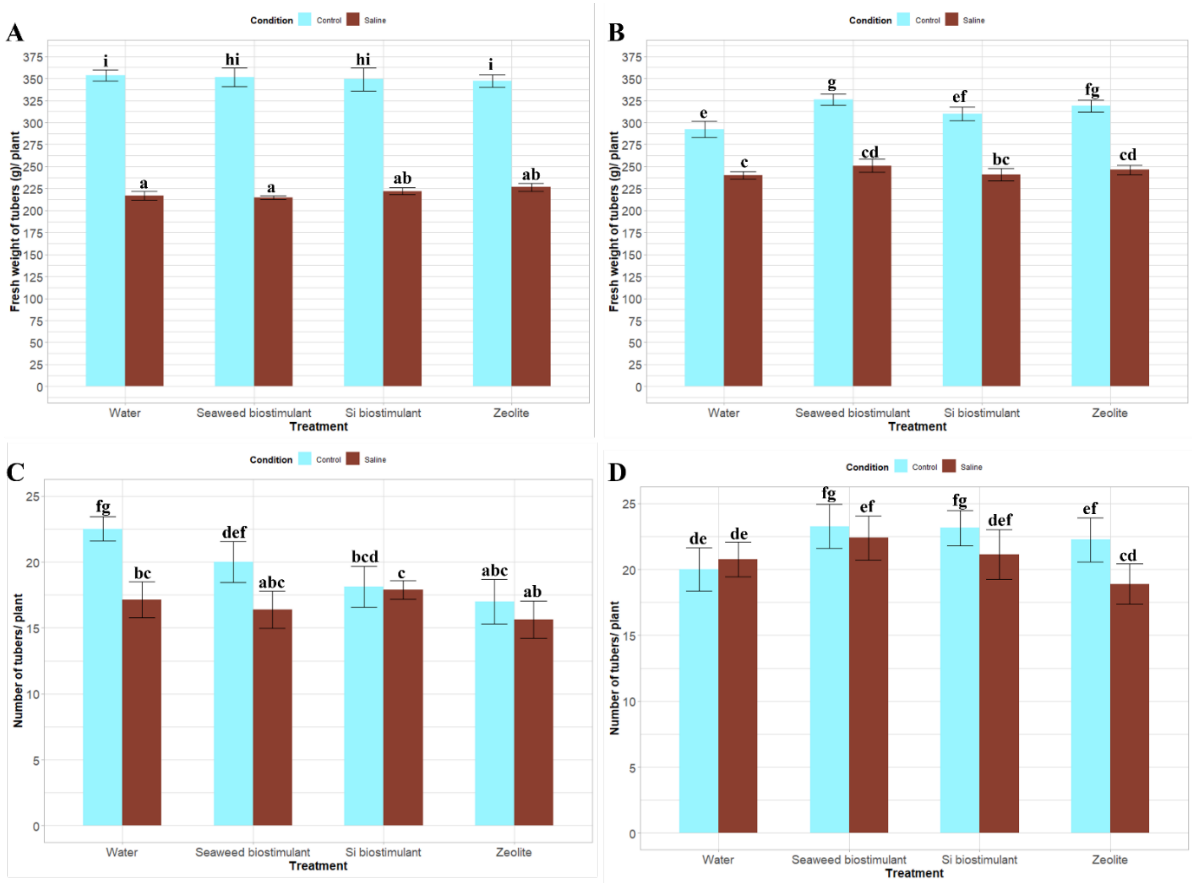


Figure 2.8: Potato growth in 2024 experiments. Fresh weight of tubers (A, B) and number of tubers (C, D) of salt sensitive (A, C) and salt tolerant (B, D) variety. Control conditions are represented with blue bars while saline conditions displayed as red bars. Plants were treated with water representing the business as usual case or no treatment conditions. In other cases, the plants were treated with a seaweed-based biostimulant, silicon (Si)-based biostimulant or zeolite. Application occurred via addition of all amendments directly to the soil according to manufacturer recommendations. There were 8 technical replicates per variety (salt sensitive or salt tolerant) per condition (control or salt) per treatment (water, seaweed biostimulant, Si biostimulant or zeolite). Statistics was performed by two-way ANOVA with Tukey post hoc where different letters represent p-values of ≤ 0.05.

2.3.4 Salt stress generally caused accumulation of sodium and had a slight effect on carbohydrate and small sugar content.

Broccoli: accumulation of sodium (Na) in the leaves of all salt-treated broccoli plants can be detected (Fig 2.9A). The salt condition additionally has a clear negative effect on the small sugar and carbohydrate content (Fig 2.9C-D). However, there is no clear effect of the different amendments (Fig 2.9).

Potato: similar to the broccoli leaves, a clear accumulation of Na in the potato tubers of all salt-treated plants occurred (Fig 2.9A, 2.10A). Potato tubers are not ‘known’ for high protein content (2%), and it is mainly a carbohydrate source (Fig 2.10C, E). Overall, there was almost no effect of the salt condition on the tuber quality as only a slight reduction of dietary fibres and no significant reduction of carbohydrates was observed (Fig 2.10B-C). Again, there was no clear significant effect of the different amendments on potato crop quality, except for a non-significant reduction of dietary fibres content under salt condition in seaweed biostimulant treated plants only

(Fig 2.10). These observations may be due to the large variation in combination with the low number of replicates analysed for crop quality of the potato plants.

Wheat: in the 2023 experiments, wheat grains show only negative effect of salt treatment on small sugars content when comparing control versus saline conditions for all treatments (Fig 2.11). Although for the non (water)-treated plants, reduction in small sugars under salt stress is not significant due to huge variation between the two replicates (Fig 2.11D). Interestingly, we did not see a similar accumulation of Na in all the differentially treated plants under saline conditions although we do not find clear-cut results. There might be a putative positive effect of seaweed biostimulant on carbohydrates under control condition (Fig 2.11C), but this cannot be substantiated using statistical analysis since only two pooled replicates (of six pooled plants) could be analysed. Crude protein content seems to increase under salt condition in all three amendments (Fig 2.11E), but this can also not be statistically tested. As conclusion, a clear significant effect of stress application on wheat grain quality cannot be established, nor a clear effect of alleviating the stress effect on grain nutritional quality using amendments in the 2023 experiments.

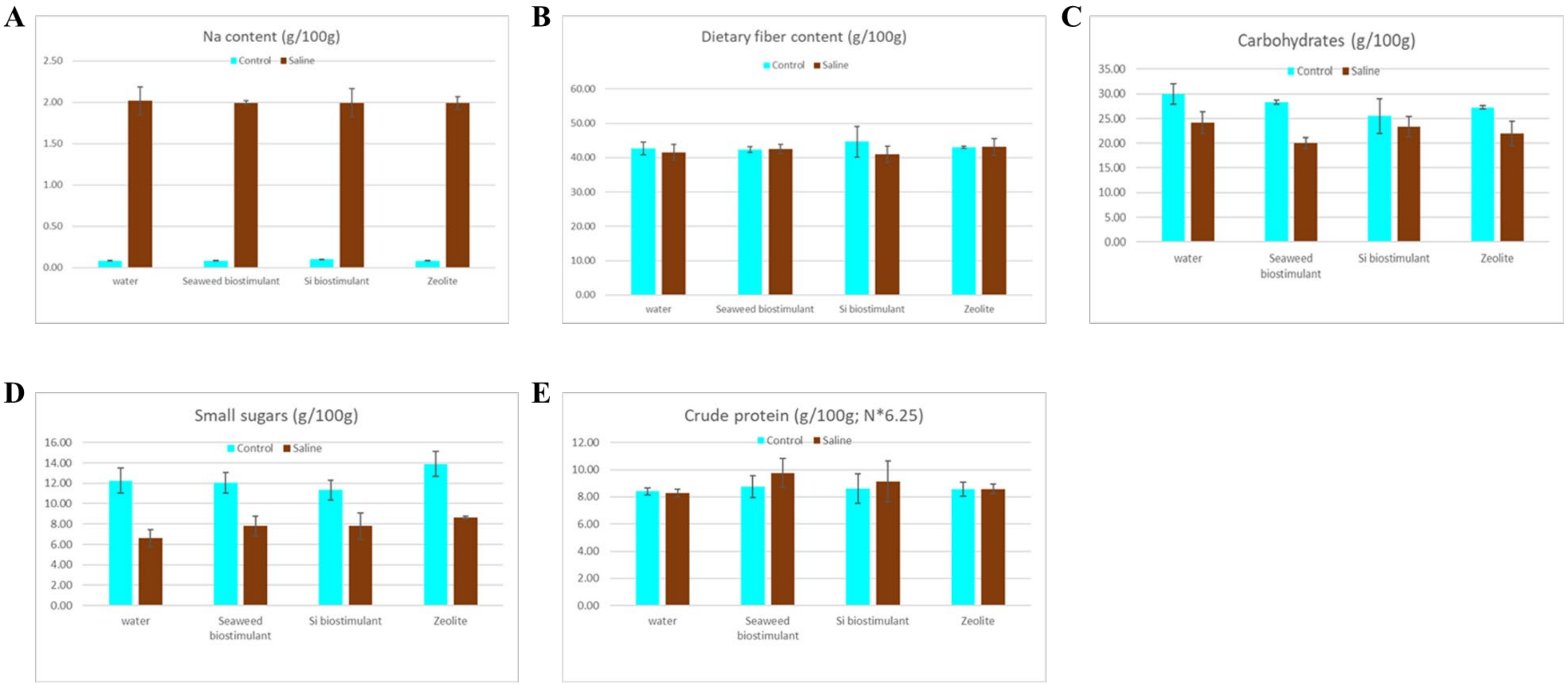


Figure 2.9: Broccoli nutritional quality in 2023 experiments. Shown is sodium (Na) content (A), dietary fibre (B), carbohydrate (C), small sugars- a combination of total mono- and disaccharides (D), and crude protein content as total nitrogen times 6.25 conversion factor (E) in oven-dried leaf and petiole material. Control conditions are represented as blue bars and salt conditions as red bars. The plants were treated with water representing the business as usual case or no treatment conditions. In the same experiment, plants were also treated with a seaweed-based biostimulant, silicon (Si)-based biostimulant or zeolite. Application occurred via addition of all amendments directly to the soil according to manufacturer recommendations. Per treatment, the leaves and petioles of four individual plants were pooled, leading to three technical pooled replicates per condition per treatment.

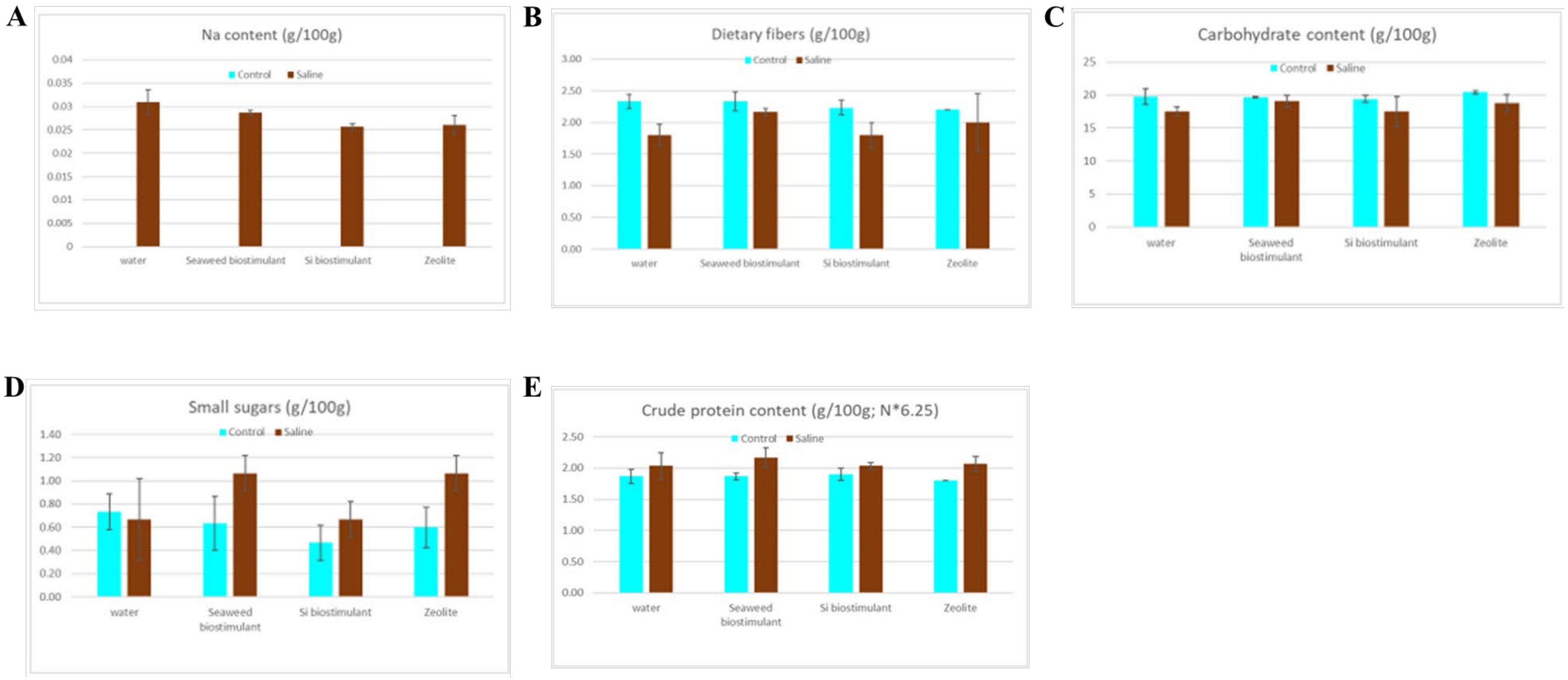


Figure 2.10: Potato nutritional quality in 2023 experiments. Shown is sodium (Na) content (A), dietary fibre (B), carbohydrate (C), small sugars- a combination of total mono- and disaccharides (D), and crude protein content as total nitrogen times 6.25 conversion factor (E) in fresh potato tubers. Control conditions are represented as blue bars and salt conditions as red bars. The plants were treated with water representing the business as usual case or no treatment conditions. In the same experiment, plants were also treated with a seaweed-based biostimulant, silicon (Si)-based biostimulant or zeolite. Application occurred via addition of all amendments directly to the soil according to manufacturer recommendations. Per treatment, the tubers of four individual plants were pooled, leading to three pooled replicates per condition per treatment.

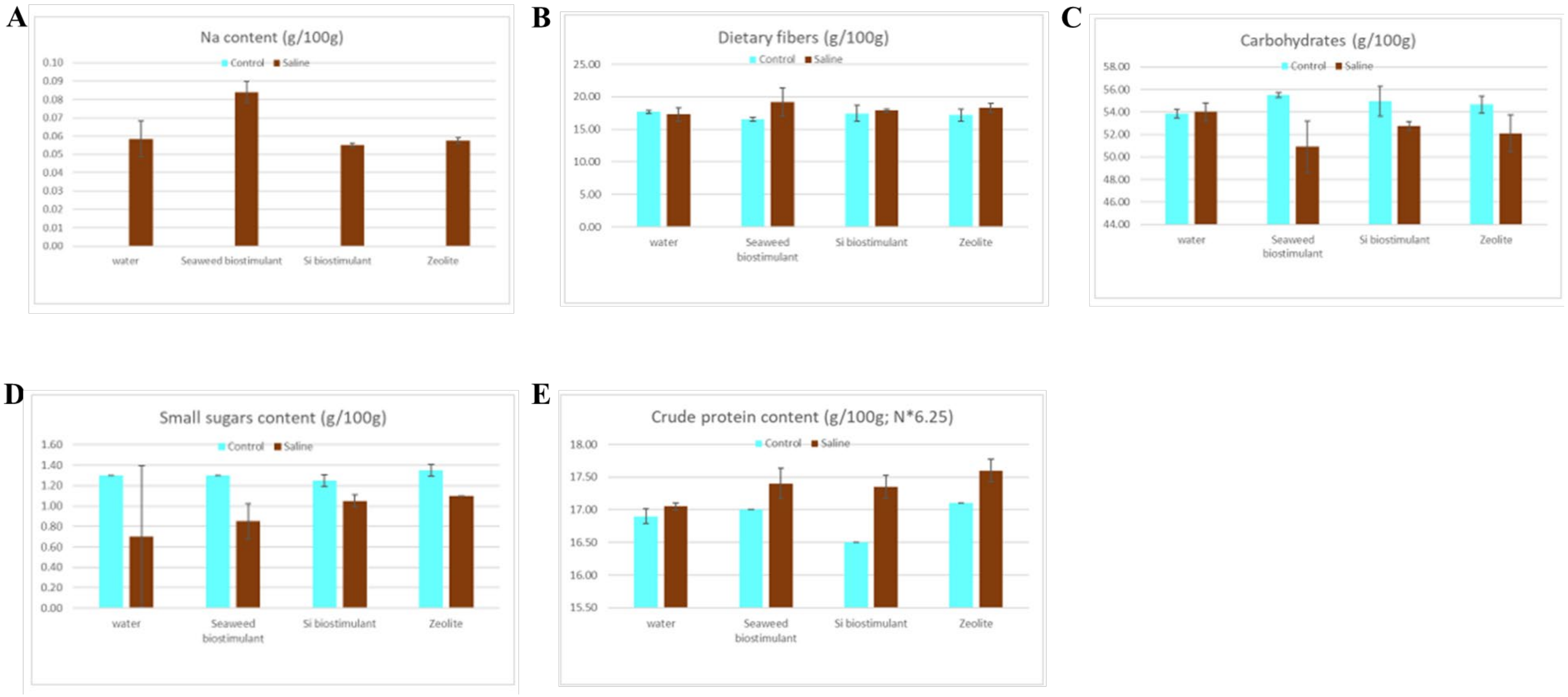


Figure 2.11: Wheat nutritional quality in 2023 experiments. Shown is sodium (Na) content (A), dietary fibre (B), carbohydrate (C), small sugars- a combination of total mono- and disaccharides (D), and crude protein content as total nitrogen times 6.25 conversion factor (E) in oven-dried wheat grains. Control conditions are represented as blue bars and salt conditions as red bars. The plants were treated with water representing the business as usual case or no treatment conditions. In the same experiment, plants were also treated with a seaweed-based biostimulant, silicon (Si)-based biostimulant or zeolite. Application occurred via addition of all amendments directly to the soil according to manufacturer recommendations. Per treatment, the grains of six individual plants were pooled, leading to two technical pooled replicates per condition per treatment.

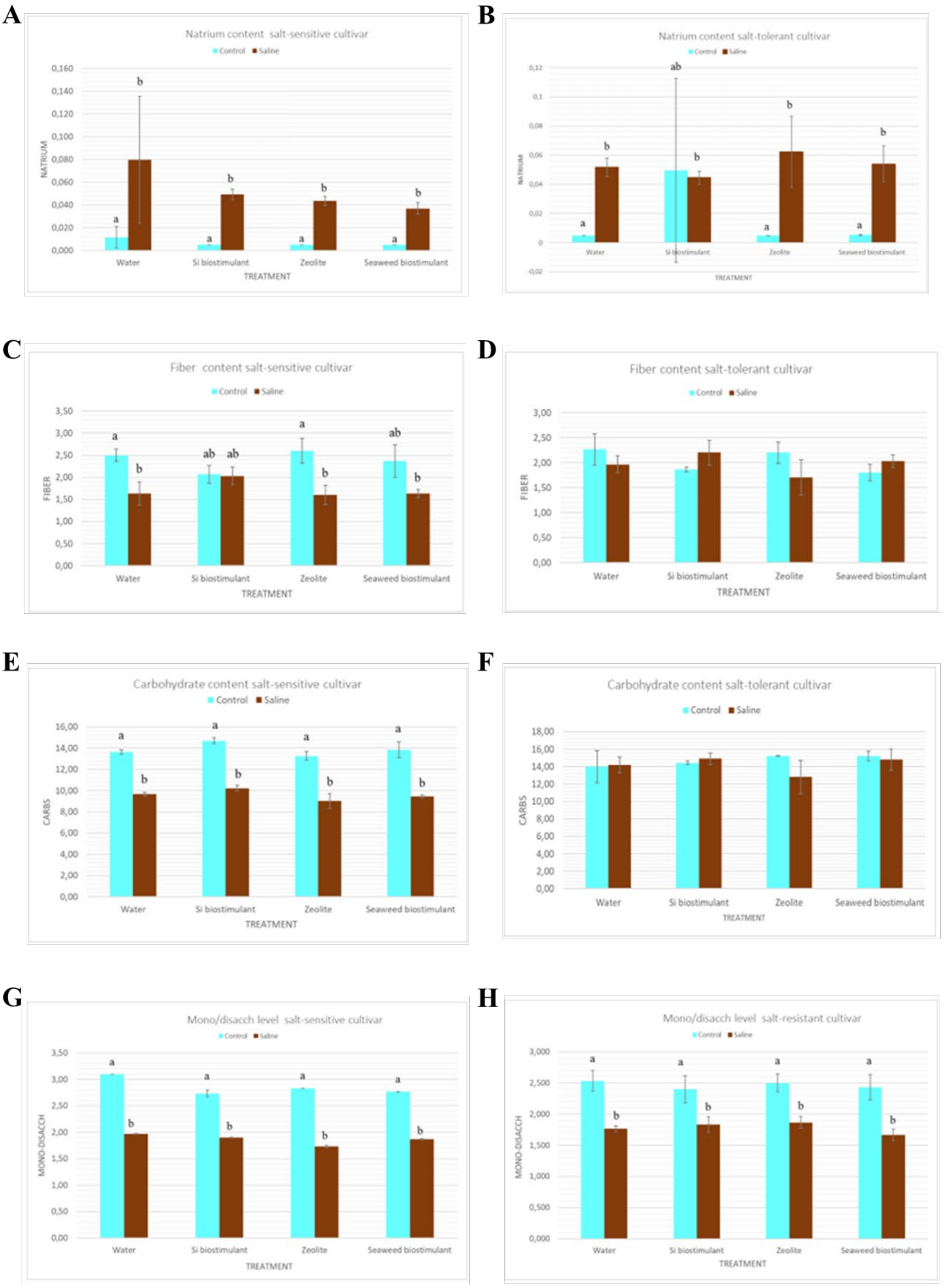
2.3.5 Crop quality varied under saline condition depending on the potato genotype

Although Na consistently accumulated in the plants under saline conditions compared to the control conditions, there was no clear difference in levels of Na accumulation in the tubers of both salt sensitive and salt tolerant cultivars (Fig 2.12A-B). One pooled sample of the salt tolerant cultivar- Si biostimulant treatment under control conditions, showed a large variation (Fig 2.12B) which might be due to sample swopping of samples during sample pooling.

In the salt sensitive variety, a significant reduction of dietary fibres is caused by the salt stress, except for the Si biostimulant treated plants (Fig 2.12C). On the other hand, for the salt tolerant cultivar there is no significant difference found in dietary fibre content independent of the conditions or treatments applied (Fig 2.12D). Similar to observations for dietary fibre, only the salt sensitive cultivar had reduced carbohydrate content under saline conditions, and this was observed independent of the treatments used (Fig 2.12E-F). Salt stress generally reduced total small sugar content of the tubers (Fig 2.12G-H). Both potato varieties had significant differences in small sugar (mono and disaccharides) content across treatments with the salt tolerant variety having slightly lower levels of small sugars in all cases.

There was no significant difference found on crude protein content of the differentially treated salt sensitive cultivar (Fig 2.12I). However, in the salt tolerant cultivar, crude protein levels slightly increased (although not significant) consistently under saline conditions compared to control conditions (Fig 2.12J). On the other hand, Vitamin C content of the salt sensitive cultivar only slightly decreased under saline conditions compared to the corresponding control conditions (Fig 2.12K-L).

Overall, quality profile of the potato varieties differed depending on the compound analysed but there were no clear differences in crop quality based on soil amendments used to treat the plants. Thus, again suggesting a bigger effect of the genotype on crop responses under saline conditions rather than just application of the biostimulants or zeolite. Nevertheless, under saline conditions carbohydrate, dietary fibre and vitamin C consistently reduced only in the salt sensitive variety.


A
Natrium content salt-sensitive cultivar
Control
Saline
NATRIUM
TREATMENT
Water
Si biostimulant
Zeolite
Seaweed biostimulant
B
Natrium content salt-tolerant cultivar
C
Fiber content salt-sensitive cultivar
FIBER
D
Fiber content salt-tolerant cultivar
E
Carbohydrate content salt-sensitive cultivar
CARBS
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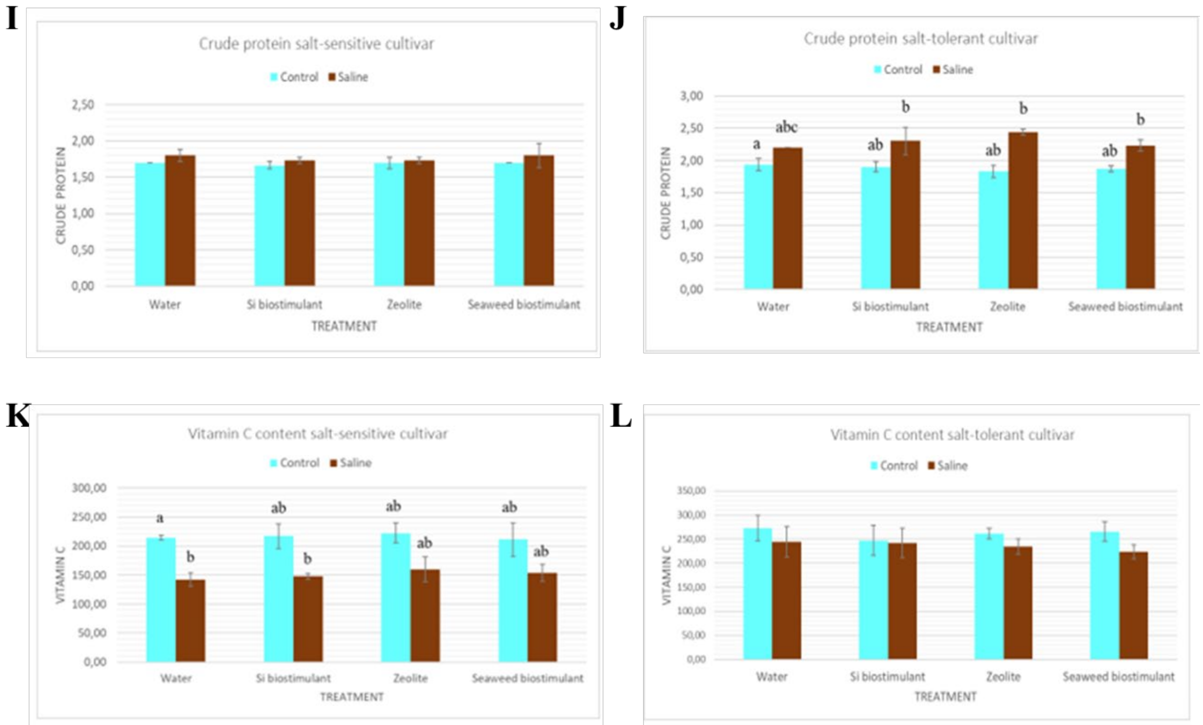

Figure 2.12: Potato nutritional quality in 2024 experiments. Shown is sodium (Na) content (A-B), dietary fibre (C-D), carbohydrates (E-F), small sugars- a combination of total mono- and disaccharides (G-H), crude protein content calculated as total nitrogen times 6.25 conversion factor (I-J), and vitamin C content (K-L) in tubers of a salt sensitive (A, C, E, G, I, K) or salt tolerant (B, D, F, H, J, L) potato variety. Control conditions are represented as blue bars and salt conditions as red bars. The plants were treated with water representing the business as usual case or no treatment conditions. In the same experiment, plants were also treated with a seaweed-based biostimulant, silicon (Si)-based biostimulant or zeolite. Application occurred via addition of all amendments directly to the soil according to manufacturer recommendations. Per treatment, three individual plants were pooled, leading to three technical pooled replicates per potato variety per condition per treatment. Here, statistics was by one way ANOVA where different alphabets represent $p \leq 0.05$.

2.4 Discussion

Prolonged salinity stress during cropping seasons lead to reduced crop growth and yield. In our experiments for both years, there was always a decrease in crop yield under saline conditions although the impact on crop yield was more visible in the 2024 experiments. Effects of the salt conditions and of the tested amendments that might influence crop tolerance to abiotic stress were also evaluated via nutritional composition analysis of the treated (and untreated) plants. Salt stress is not only expected to influence growth and yield of crops but might also affect the biochemical composition of the plants and thereby, their nutritional quality. Crops vary in their response to salinity and have different thresholds to tolerate soil salinization thus, showing varied productivity under saline conditions (Zörb et al., 2019). Wheat is described as moderately salt tolerant while broccoli and potato are moderately sensitive to saline conditions (Shannon, 1997; Shannon & Grieve, 1999). Therefore, yield of wheat should be less affected than that of broccoli and potato. This was observed in our 2013 experiments since at the same levels of salt stress, average wheat grains reduced by ~20% while potato tubers reduced by 30% (Fig 2.5B, 2.7A).

Interestingly, the impact of salt stress on broccoli growth was much smaller than expected (Fig 2.6). This observation may be connected to a combination of salt and heat stress that led to delayed switch from vegetative to reproductive stage of broccoli plants as well as, no production of florets for the duration of the experiment (~4 months). Irrespective of the crop response, plants in our 2023 experiments (Fig 2.5-2.7, 2.9-2.11) were only moderately salt stressed since the difference between crop yield, and quality represented as nutritional analysis, under control and saline conditions were small (Shannon & Grieve, 1999; Siddiqui et al., 2017). Thus, saline conditions were increased in the second year of experiments resulting in further tuber yield reduction (~40%) of the sensitive variety of potato (Fig 2.8A).

Application of the seaweed biostimulant and zeolite caused an increase in wheat productivity under control conditions only in the first-year experiments, and this positive result was not replicated for potato or broccoli (Fig 2.5-2.7). In some cases in the first year experiment, the biostimulants or zeolite even inhibited crop growth or yield, especially under saline condition. Positive biostimulant effect of the amendments in the second-year experiment was observed notably in the salt tolerant potato variety (Fig 2.8). Previous studies have shown the positive effect of applying the same biostimulants to the soil to boost crop yield and quality, although these positive results were obtained under non-saline conditions. Application of the seaweed biostimulant improved banana yield by 20% (Tabet et al., 2021) while the Si biostimulant increased tomato fruit yield by ~30% and significantly enhanced fruit quality observed as higher sugar and lycopene content (Thimmappa & Basavarajappa, 2021). Nevertheless, other studies under saline conditions also indicate that addition of biostimulants or zeolite may improve crop yield and/ or quality (Al-Busaidi et al., 2008; Di Stasio et al., 2018; Noori et al., 2006; Shah et al., 2013; Yasmeen et al., 2013). Even though most reports highlight the positive effect of biostimulants, application of these inorganic amendments do not always boost crop productivity but instead may cause no changes in crop yield and in fewer reported cases, inhibit crop growth (Deolu-Ajayi et al., 2022; Michalak et al., 2016; Rouphael & Colla, 2020). In addition, results on biostimulant use vary per crop type (Deolu-Ajayi et al., 2022), and even per variety as observed in our experiments.

Overall, the best effects on crop yield were seen in the addition of seaweed extracts or zeolites to wheat and the salt tolerant potato variety (Fig 2.5B,Fig 2.8B). Salt tolerant varieties are usually lower yielding while high yielding crop varieties are typically sensitive to stress due to a molecular trade-off between stress tolerance and crop yield (Sanwal et al., 2022; Yang & Guo, 2018; Zörb et al., 2019). Thus, application of amendments have potential to further close the yield gap created due to crop variety as well as, the saline conditions. Although the seaweed or zeolite treatments slightly boosted crop yield, neither of these treatments were still able to fully close the yield gap created under saline conditions, when compared to their corresponding yield under control conditions. Moreover, the "variety or genotype" factor presents the most compelling positive impact on potato productivity under saline conditions, compared to the factor of "addition of the soil amendments" since the tolerant variety still had a significantly higher yield than the sensitive variety while the application of biostimulants only resulted in a small increase in tuber yield (Fig 2.8A-B). Earlier harvesting due to onset of pests and diseases may have prevented achieving results of significantly better yielding potato under saline conditions and with the addition of soil amendments, as tubers had not yet reached their peak sizes. Therefore, understanding the underlying molecular mechanisms especially interactions between the plants and soil amendments may further boost crop productivity under saline conditions leading to significant differences in crop yield.

2.5 Conclusion and Recommendations

Our results indicate the potential of combining multiple strategies such as use of salt tolerant varieties and application of soil amendments, to adapt to increasing salinization. Potato is an important crop cultivated in areas of the Netherlands experiencing increasing salinization (Bresser et al., 2005; Tzemi et al., 2020). We give some insights into opportunities of using seaweed extracts and zeolite to further boost production of salt tolerant potato varieties in these areas. Long term multiyear (field) experiments are needed to further validate the results since crop responses may vary yearly due to changing climatic conditions. Solutions for salinization should also take into account other stresses such as warmer temperatures and infestation from pests and diseases, both of which occurred at different timepoints of our experiments and impacted the results. Cultivating varieties that have multi-stress tolerance or application of biostimulants with synergistic action to minimize the effects of multiple stresses including salinity, should be considered. Critical assessment to determine what the percentage yield increase leads to, in terms of income for farmers annually should also be addressed to provide some socio-economic backing for selection and implementation of the proposed salinity adaptation strategies by farmers. A cost benefit- analysis is elaborated in Chapter 4.

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3 Soil moisture dynamics in saline environments

Judit Snethlage

3.1 Introduction

Various strategies can be explored to improve crop productivity in saline environments (van den Burg et al., 2024). In the KB34 research program, a two-year initiative on salinization where greenhouse experiments evaluating the use of different crop (cultivars) and soil amendments to improve plant resilience under saline conditions was performed. Given the connection between salinization and soil-water dynamics, understanding water movement and behaviour in saline environments is essential (Feng et al., 2016; Minhas et al., 2020). In the first year (2023) of the program, two key objectives were identified: (1) assessing whether crop types subjected to saline conditions and treated with soil amendments maintain adequate soil moisture levels, and (2) comparing soil moisture content between control groups irrigated with freshwater and those exposed to salinity. Year 1 findings indicated the influence of various parameters on soil moisture and salinity measurements, leading to refinements in measurement techniques and equipment for the second year (2024).

Building on these insights, the second year focuses on determining whether different cultivars of potato under saline conditions and treated with soil amendments, maintain balanced soil moisture levels. We also assessed whether the applied water management strategies are effective. Furthermore, differences in soil moisture retention between plants under control vs. saline conditions to evaluate the amendment impact on soil moisture levels were investigated. Only the most diverging results are presented and discussed in this report.

Outcomes of these greenhouse experiments provide a foundation for understanding the way forward for water management strategies that integrate soil amendment application for sustainable agriculture. These findings contribute to addressing salinity challenges both in the Netherlands and on a global scale.

3.2 Methodology

3.2.1 Establishing baseline understanding of soil moisture and salinity dynamics in year 1 (2023) experiment

In the first year (2023), three crop types- broccoli, potato, and wheat- were selected based on their varying salinity tolerances and significance to Dutch and global agriculture. Broccoli was chosen as a high-value cash crop, while wheat and potato represented staple crops. Water management was an important aspect of this experiment (see Section 2.2.1 for detailed experimental design). To maintain consistent soil moisture levels, crops were watered once daily with the frequency increasing to twice during periods of elevated temperatures. Soil moisture content, temperature and salinity levels were monitored using sensors. Decisions regarding increased watering frequency were informed by expert input.

Two key assumptions were made regarding the water management strategy. The first was for the water application estimation where the volume of water applied was estimated by measuring time and amount of water delivered at specific intervals. It was assumed that these measurements accurately reflected the daily water volume per pot. While this method allowed for controlled watering regimes, it may introduce variability when compared to automated irrigation systems. The second assumption was for the irrigation frequency. Here, on hot days, crops were watered twice daily to account for increased water demand. This approach mimicked realistic conditions, though temperature fluctuations and crop-specific behaviours might influence water requirements. Daily watering amounted to 600 mL per pot (6.14 seconds of irrigation). On hot days, this increased to 1.2 L per pot based on irrigation performed twice.

To monitor soil conditions, high-frequency Dragino LSE01 soil sensors were installed to monitor soil moisture and EC in real-time. Data were recorded every 2 to 5 minutes, measuring temperature, EC levels and soil moisture levels. The sensors were placed in two pots per crop type- one irrigated with freshwater (control) and the other with saline water (treatment). These sensors recorded soil moisture, temperature, and electrical conductivity (EC) data for the duration of the experiment from April to July. Key objectives for year 1 were:

1. Determine whether soil amendment-treated plants under saline conditions maintain sufficient soil moisture levels.
2. Compare soil moisture differences between control (freshwater) and saline conditions.

3.2.2 Refining and improving the experimental design in year 2 (2024) experiment

Building on insights from Year 1, the second year focused on potato cultivars, specifically comparing a salt tolerant variety with a salt sensitive one. The soil substrate showed loam-like properties, combining Swedish peat, Baltic peat, structured bark, and clay. This mixture optimized water retention, aeration, and nutrient availability (de Visser, personal communication, February 02 ,2024).

The irrigation system was changed to a bowl-based approach, allowing plants to absorb water at their own pace. This decreased manual intervention and provided a more natural water uptake process. Salinity treatments were incrementally applied, beginning at 40 mM NaCl, increasing weekly to 80 mM, and stabilizing at 120 mM NaCl. This gradual increase replicated realistic salinity stress progression.

The high-frequency Dragino LSE01 soil sensors were installed to monitor soil moisture and EC in real-time. Data were recorded every 2 to 5 minutes, measuring temperature, EC levels and soil moisture levels. Key objectives for year 2 were:

1. Evaluate whether amendment-treated plants maintain stable soil moisture levels under saline conditions.
2. Compare soil moisture retention between control (freshwater) and saline conditions.
3. Explore differences in salinity responses between different cultivars when treated with soil amendments.

3.2.3 Data analysis

A combination of data analysis tools were used, namely Microsoft Excel, Power BI and CROPWAT. The CROPWAT program was used to get insights on the theoretical water demands for the different crops. The excel output served as input for Power BI that was used to create visual overview of the sensor data. For year 2 no CROPWAT calculations are made as year 2 focused on in-depth understanding of the sensor data.

3.2.3.1 CROPWAT

CROPWAT[1] is developed by the Food and Agriculture Organization (FAO) and is a software tool designed specifically for agricultural water management and crop modelling. It has worldwide recognition for its capability to assess crop water requirements, irrigation scheduling and water use efficiency. CROPWAT was used in our year 1 research for determining crop water requirements, irrigation schedule and data evaluation.

CROPWAT was used to calculate the precise crop water requirements of our selected crops- broccoli, potato, and wheat. This information may be used for optimising water management strategies ensuring that the crops received sufficient water while dealing with salinity-induced stress. CROPWAT also constructed precise irrigation schedules, aligning watering frequency with the specific needs of each crop type and experimental condition.
Calculations of the CROPWAT model are based on specific input parameters, including climate data, soil characteristics and the exclusion of rainwater contribution. Our assumption is that these settings represent the conditions within the greenhouse. Any variations from these settings may impact the accuracy of the theoretical water requirements. Outputs generated by CROPWAT provided a way of cross-referencing and validating data collected within our greenhouse experiments.
Although a very useful tool, CROPWAT also has some limitations. The climate data used in our CROPWAT simulations was retrieved from CLIMWAT version 2.0. Thus, the accuracy and representativeness of this data source depend on the quality and coverage of the underlying meteorological information. Any inaccuracies or limitations in the source data affects the reliability of the water requirement calculations. Especially consider that we performed greenhouse experiments and climate data is based on open field conditions. Furthermore, for calculations, rainwater was completely excluded from our calculations as it did not contribute to irrigation within the greenhouse, and the entire irrigation schedule was based on water requirements of the crops only. While this assumption simplifies the experimental setup, it may not fully represent realistic scenarios where rainwater affects soil moisture levels.

3.2.3.2 Microsoft Excel

For both years, Excel was used to arrange the acquired sensor data into organised datasets. Datasets included data on crop growth, soil moisture levels and environmental factors such as temperature and humidity. The excel sheet served as input for the Power BI analysis.

For year 1 specifically and to ensure higher data accuracy, double measurements by the sensor in the excel were addressed by calculating the differences between the two values, with a focus on maintaining acceptable margins. The dataset with the lowest soil moisture levels was selected. The driest conditions on the double measurement points on 11th and 12th of June, 2023 and partially on the 19th of June, 26th of June, 2nd of July, and some early morning measurements on the 3rd of July, 2023 were selected for further processing, as these dry conditions were particularly relevant to the salinity risks.

3.2.3.3 Power BI

Power BI (Business Intelligence)[2] is a business analytics tool developed by Microsoft. It enables users to visualise and analyse data, identify trends, and extract insights through interactive and customizable dashboards. Power BI was used

[1] https://www.fao.org/land-water/databases-and-software/cropwat/en/
[2] https://powerbi.microsoft.com/en-us/desktop/

in this report for visualising relations within the data, identify patterns, and extract insights. As mentioned before, the analysis focussed on analysing soil moisture levels.

3.3 Results

3.3.1 Crops in the first year of experiments had differential water requirements

CROPWAT analysis revealed that the highest theoretical irrigation demands for all three crops occurred within the months of May to July, and aligned with a period of higher temperatures as shown by the KNMI data[3] (Fig 3.1). The different crops showed varying peak watering demand periods, with broccoli reaching its peak in July, potato in June, and wheat in late May (Fig 3.1A-B). Notably, despite these variations, a general trend in water requirements was observed, resonating with the similarity in theoretical planting dates (April 18 2023) and environmental conditions (similar soil and climate variables) across all crops (Fig 3.1). This trend shows that the observed differences may primarily originate from the characteristic water demand of each crop. Potato and wheat show increased water needs earlier in the growing season, while it occurs later in the growing season for broccoli (Fig 3.1A-B). Additionally, wheat needs the most water during the early stages of the season.

Readings under saline conditions always remained higher than in control conditions however, analysis of salinity data showed anomalies in the readings. For sensor in saline conditions, the salinity values were unreasonably high, reaching levels as extreme as 1415 mS. However, after the 21st of June 2023, the salinity values experienced a significant drop, falling within a range of relatively normal values (around 24 mS). It is important to note that even these lower values remain too high for plant survival. Similarly, sensor installed in the saline pot displayed abnormally high salinity values, with the highest reading recorded at 2752 mS. The only period of stability in salinity levels occurred between the 13th and 19th of June, where the values were close to 40 mS, which, while relatively lower, it is still too high for plant growth. Moreover, based on the salinity treatments given and the associated plant response under saline conditions in the first year experiments (discussed in Chapter 2), the measured salt levels are abnormally high. Therefore, indicating that the sensor needs to be recalibrated to detect correct salinity readings that can be used for further analysis in the second year experiments.

[3] https://daggegevens.knmi.nl/klimatologie/daggegevens

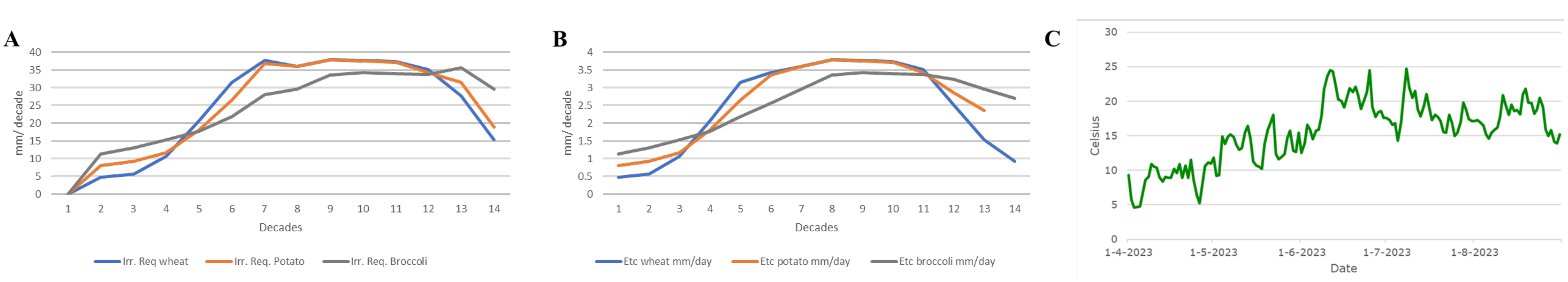

Figure 3.1: Emerging trends based on 2023 analysis. Theoretical irrigation requirement (A) and theoretical crop evapotranspiration- Etc (B) per 10 days of plant development from planting to harvest for wheat, potato and broccoli in the first year experiment. Daily mean temperature of the observed by KNMI weather station "de Bilt" from April until September 2023 synonymous with the period for the first year experiment (C).

3.3.2 Soil moisture content differed between conditions in the second year of experiments

Reflecting on the soil moisture dynamics for the salt sensitive variety (Fig 3.2A), several observations can be made. Under control conditions, soil moisture levels remain relatively stable, fluctuating around 30 to 40% throughout the observation period. This trend indicates consistent water availability and suggests that the plants maintained steady water uptake in a non-saline environment. In contrast, salinity stressed conditions display even higher soil moisture levels, ranging between 35 to 45% on average, with periodic fluctuations (Fig 3.2A). These increased levels suggest that osmotic stress impaired plants' ability to extract water from the soil, leaving more moisture retained within the substrate. Notable soil moisture spikes, particularly early in the observation period and around late June and July 2024, likely corresponded to irrigation events. These fluctuations reflect the adjustments in water application to manage soil moisture levels under saline conditions.

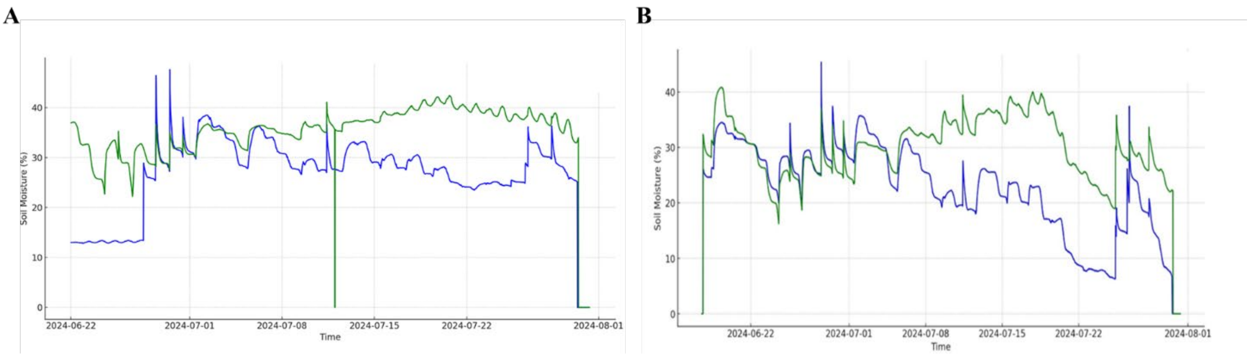

Figure 3.2: Soil moisture trends for salt sensitive (A)- and salt tolerant (B)- potato variety without any amendment treatment under control (blue line) vs. salinity stressed (green line) conditions in the second year experiment.

For the salt tolerant variety (Fig 3.2B), control conditions show soil moisture levels ranging between 20-30%, with variability throughout the observation period. This fluctuation may reflect differences in water uptake patterns, possibly influenced by root architecture or varying water demand. A gradual decline in soil moisture after early July 2024 aligns with increased water consumption as the plants mature and their physiological water requirements intensify. Under saline conditions, soil moisture levels are on average higher, between 30-40%. This increased range may be due to the saline conditions limiting plant's water uptake from the soil, resulting in higher soil moisture content. The gradual decline observed towards the end of the observation period likely reflects changes in irrigation practices, although the moisture levels still remain higher than in the control conditions.

Focusing on treatments with zeolite (Fig 3.3A), soil moisture retention under control conditions fluctuates between 10 to 50% throughout the observation period, displaying variability. These fluctuations suggest a dynamic response to water inputs such as irrigation, which could be retained more effectively due to the effect of treating the soil with zeolite that has some buffering capacity. Peaks in early July 2024 align with external irrigation events. Under saline stressed conditions, soil moisture levels are consistently lower than under control conditions but remain within the range of 25 to 40%. This indicates that while salinity limits water uptake, the gradual decline towards the end of the growing period reflects expected decreasing water uptake by plants.

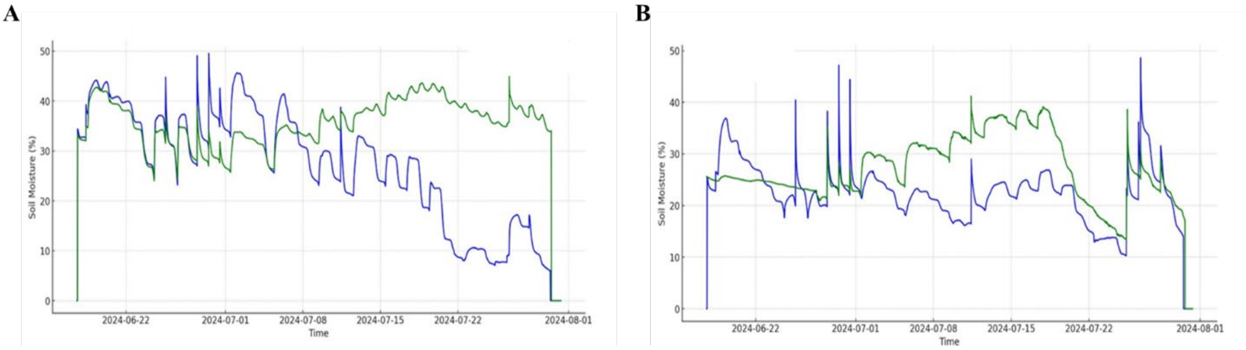

Figure 3.3: Soil moisture dynamics for salt sensitive (A)- and salt tolerant (B)- potato variety treated with zeolite under control (blue line) vs. salinity stressed (green line) conditions in the second year experiment.

For the salt tolerant variety with zeolite treatment, control conditions show soil moisture levels ranging between 20 to 30% (Fig 3.3B), with fewer fluctuations compared to the same variety without zeolite treatment (Fig 3.2B). This trend suggests that zeolite increases water retention, maintaining a more stable moisture level. Under salinity stressed conditions, soil moisture levels are consistently higher between 30 to 40% (Fig 3.3B), with improved stability compared to non-zeolite treated plants (Fig 3.2B). The buffering effects of zeolite help to maintain consistent water availability, even in the face of salt stress (Noori et al., 2006; Rahimi et al., 2021).

3.3.3 Soil temperature varied between the varieties in the second year experiment

Temperature fluctuates in salt sensitive potato variety under both control and saline conditions, ranging between 20 to 40°C throughout the monitoring period (Fig 3.4A). The temperature trends are largely aligned, with minimal deviation between the two conditions. An increase in temperature towards the end of the period is likely linked to increasing temperature towards the latter part of the experiments in summer 2024.

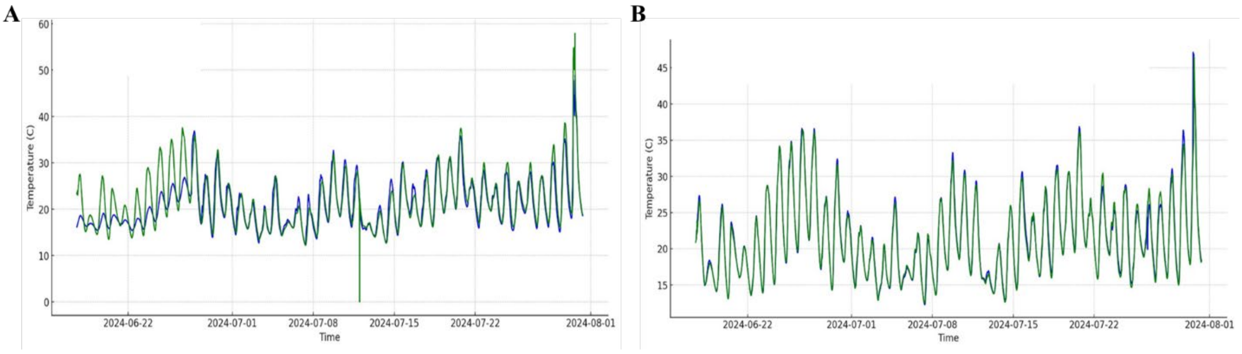

Figure 3.4: Temperature trends over time salt sensitive (A)- and salt tolerant (B)- potato variety without any amendment treatment under control (blue line) vs. saline conditions (green line) in the second year experiment.

For the salt tolerant variety, temperature under control and saline conditions show a similar pattern, with values ranging from 15 to 40°C (Fig 3.4B). Compared to the salt sensitive variety, the temperature peaks are slightly lower, rarely exceeding 45°C (Fig 3.4). This difference may reflect physiological or structural variations between the two varieties. Periodic fluctuations correspond to external environmental cycles, with a notable increase in temperature towards the end of the period likely driven by seasonal changes. The addition of zeolite to the soil does not significantly impact the temperature dynamics for the salt tolerant variety reinforcing that soil amendments has minimal impact on soil thermal dynamics.

3.3.4 Both potato varieties experienced similar salt stress conditions but respond differently

Under control conditions, the EC levels for the salt sensitive variety remain consistently low, fluctuating around 0.5 mS throughout the observation period (Fig 3.5A). This trend reflects a stable salinity environment, as expected under non-stress control conditions. In contrast, under saline conditions, EC levels increase significantly, ranging from 1 to 3 mS, with sharp peaks observed around mid-July 2024. Towards the end of the measuring period, a declining trend in EC levels suggests potential salt leaching or reduced salinity stress due to environmental or irrigation adjustments.

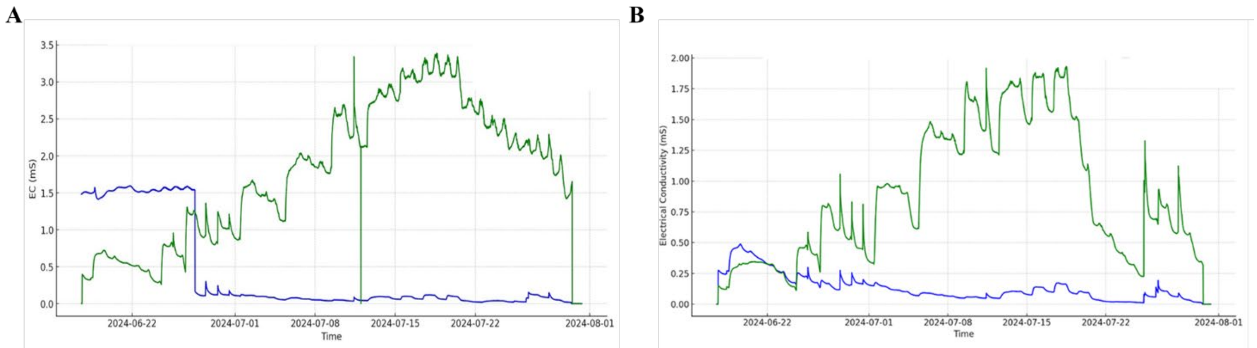

Figure 3.5: Salinity levels experienced over time by the salt sensitive (A)- and salt tolerant (B)- potato variety without any amendment treatment under control (blue line) vs. saline conditions (green line) in the second year experiment. The salt concentrations in the pot was estimated by the electrical conductivity (EC) in mS.

For the salt tolerant variety EC levels under control conditions also remain consistently low, fluctuating between 0.25 and 0.5 mS throughout the observation period (Fig 3.5B). Under saline conditions, EC levels rise ranging from 0.5 to 1.75 mS. While both varieties show relative stability under control conditions, their responses to salinity stress differ (Fig 3.5). The salt sensitive variety reaches higher EC levels up to 3 mS. In contrast, the salt tolerant variety demonstrates a more moderated response, with EC levels stabilizing below 2 mS, reflecting its enhanced adaptive capacity to mitigate salinity stress between the two varieties.

Both varieties treated with zeolite and under control conditions display low EC levels with zeolite treatment, ranging between 0.2 and 0.7 mS (Fig 3.6A). The salt tolerant variety shows slightly lower values and smoother trends compared to the salt sensitive variety. EC levels under saline conditions show the salt tolerant variety had lower and more stable EC levels compared to the salt sensitive variety (Fig 3.6B), with values ranging between 1 and 2.5 mS. Zeolite treatment increases these dynamics for both varieties, moderating sharp spikes and maintaining smoother EC trends.

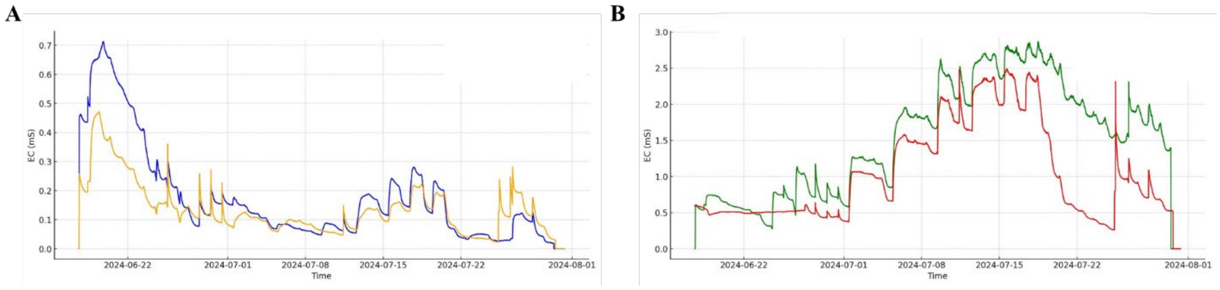

Figure 3.6: Salinity levels observed experienced over time when the potato plants were treated with zeolite under control (A) and saline (B) conditions for salt sensitive (blue or green line) vs. salt tolerant (yellow or red line) variety in the second year experiment. The salt concentrations in the pot was estimated by the electrical conductivity (EC) in mS.

3.3.5 Interaction between soil moisture and salinity

Under saline conditions, EC levels are consistently higher, accompanied by increased soil moisture (Fig 3.2-3.3, 3.5-3.6). This observations can be explained by the osmotic effect of salt stress lowering the water potential in the soil, restricting plant uptake of water from the soil (Munns & Tester, 2008). As a result, while soil moisture appears higher in saline conditions, the water becomes less accessible to plants. For both the salt sensitive and salt tolerant varieties, the addition of zeolite seems to moderate the impacts of salinity (Fig 3.6). The data show smoother EC trends and more stable soil moisture levels in zeolite-treated conditions compared to those without zeolite treatment. This suggests that zeolite can buffer against salt-induced stress by improving water retention and mitigating osmotic effects thus, helping stabilise soil moisture dynamics and creating a less variable environment (Al-Busaidi et al., 2008; Rahimi et al., 2021).

However, it is important to note that the increased soil moisture observed under saline conditions does not translate to improved water availability for plants. The osmotic stress caused by salinity limits the plants' ability to use this water effectively (Munns & Tester, 2008; Yang & Guo, 2018), creating a paradox of abundance without usability.

3.4 Discussion

The findings from the first year in 2023 provided insights into the relationship between soil moisture, salinity, and application of soil amendments. However, several limitations should be considered when interpreting the results. One primary constraint lies in the assumptions underlying the CROPWAT model, which assumes uniform planting dates and environmental conditions for all crops. In real-world agricultural systems, this level of uniformity is rarely achieved, introducing variability that the model does not fully capture.

Discrepancies between different data sources also highlighted the need for a more cohesive approach to data integration. While KNMI data and the climate input files from CLIMWAT used in CROPWAT offer useful information, these datasets originate from varying sources. For instance, open-air temperature data recorded at "De Bilt" reached a daily maximum of 24.7°C on July 8th, while the greenhouse sensor data indicated peaks on June 11th and July 9th. Such variations in microclimates and localised weather conditions significantly influence plant responses, particularly given the inherent differences between greenhouse and open-air environments. Furthermore, the assessment of soil moisture and salinity levels shows the need for more precise data collection methods. While soil moisture data displayed consistent trends, salinity measurements showed significant variability. For example, sensor under saline conditions consistently reported very high salinity levels (factor 100x too much) , suggesting potential calibration issues or localised differences in salinity dynamics. Moreover, unexpected values in the salinity dataset could be attributed to external factors such as temperature fluctuations or measurement inconsistencies.

The findings from the second year in 2024 provided deeper insights into the association between soil moisture, salinity, and application of soil amendments, yet several limitations need to be acknowledged when interpreting the results. One constraint arose from the premature end of the experiments due to pest infestations. This shortened the measurement period, reducing the number of data points and potentially limiting the robustness of the analysis. A longer observation period would have allowed for more comprehensive trend analysis and validation of the results.

The limited number of sensors (a total of nine) posed challenges in capturing accurate and representative data. Ideally, each pot should be equipped with a sensor, allowing for a more detailed understanding of the variability and trends across all soil amendment treatments. The restriction on sensor availability may have introduced gaps in the data and reduced the ability to identify subtle differences in soil moisture and salinity dynamics. Another factor to consider is the semi-controlled nature of the experimental setup. While it represents an important step closer to real field conditions, it does not fully replicate the complexities of open-field environments where multiple uncontrolled factors such as wind, soil heterogeneity, and natural precipitation significantly influence crop responses.

3.5 Conclusion and Recommendations

The results from Year 1 (2023) and Year 2 (2024) highlight the interactions between soil moisture, salinity, and application of soil amendments. Increased salinity levels were observed with increased soil moisture levels, yet this did not necessarily translate into improved water availability for plants. The salt tolerant variety demonstrated greater resilience under saline conditions compared to the salt sensitive variety, with improved stability in soil moisture and reduced salinity variability. Application of zeolite showed more stable results, contributing to water retention and supporting crop performance, particularly under saline conditions. These findings show that there is a need for researching the potential of integrating soil amendments into saline soil and water management practices to mitigate stress and improve crop productivity.

To build on these findings, several key areas for improvement and future research should be prioritised. This includes conducting pre-measurement sensor calibration, focusing on salinity and soil moisture levels to improve sensor calibration, and data validation. Additionally, periodically verify sensor readings to detect and address any inconsistencies, particularly for salinity measurements. Another point is to develop irrigation schedules that take into account the interaction between soil amendments (and other biostimulants) and soil salinization. This allows optimisation of soil moisture levels and minimize negative effects of salt stress. Irrigation practices can also be boosted by exploring installation of precision irrigation systems to deliver water and soil amendments more effectively. The research scope can be expanded by conducting more environmental conditions focused on field conditions and crop varieties to ensure scalability and adaptability of findings. Furthermore, investigate the long-term impacts of soil amendments and biostimulants on soil health, crop productivity, and salinity management in different agroecosystems.

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4 Socio-economic assessment of salinity adaptation strategies

Gert-Jan Wilbers and Kornelis Walma

4.1 Introduction

Addition of amendments directly to the soil or plant foliage, and introduction of salt tolerant crops offers a potential solution for reducing the negative impact of salinization as these substances may enhance crop resilience to abiotic stress and help minimise the yield gap caused by such adverse conditions (Ahmad et al., 2022; Li et al., 2022). Evaluating the financial or economic impacts of soil amendments is critical to promoting their adoption by farmers, especially in regions where salinity threatens agricultural productivity. By improving crop yield, soil health and long-term farm sustainability, soil amendments and new salt tolerant varieties may present a compelling case for inclusion in farming practices. However, farmers are more likely to adopt these saline strategies when the financial gains, in terms of increased crop revenue, clearly outweigh the associated costs and the potential risks involved.

The use of soil amendments including biostimulants, and salt tolerant varieties have the potential to affect both yield and quality parameters, potentially increasing the market value of the crop. However, to assess their economic viability, it is important to better understand the related net benefits of amendment application.

4.2 Methodology

The cost benefit analyses employed in the 2023 and 2024 experiments were tailored to align with their distinct objectives and scope. While the first year (2023) study evaluated the impact of amendments on a diverse crops- wheat, potato, and broccoli under both control and saline conditions, the second-year (2024) experiment concentrated exclusively on different potato varieties. The 2024 experiments narrowed the scope and refined the methodology by incorporating two potato varieties- one salt-sensitive and one salt-tolerant, to explore how genetic differences influence amendment effectiveness. Only the most diverging results are presented and discussed in this report.

Between both experiments, there are several methodological differences, stemming from the experimental design, crop focus and data specificity. In 2023, 12 pots per treatment were used for each crop, allowing cross-crop comparisons but limiting depth within individual crops. The 2024 study employed eight replicates per potato variety, with each pot covering a smaller surface area, to improve statistical reliability for a single crop while introducing varietal comparisons. Input parameters for economic analyses were also updated in 2024 to reflect market conditions specific to potato cultivation, while the 2023 study used generalised economic data across multiple crops. Furthermore, the 2023 experiment emphasised broad crop comparisons to evaluate broad spectrum use of amendments, whereas the 2024 methodology focused on salinity-induced yield gaps and how these could be mitigated by amendments in salt-sensitive and salt tolerant potato varieties. These refinements in 2024 allowed for a more focused and nuanced analysis of amendment performance in saline environments.

4.2.1 Analysis of amendments application for wheat, potato and broccoli in first year experiments

Input parameters: direct costs and benefits are derived per hectare. Direct costs associated with wheat, potato and broccoli cultivation include i) seed costs, ii) fertilisation and crop protection price and application costs, iii) irrigation costs, iv) crop insurance mainly for extreme weather events, v) crop harvesting, drying and cleaning costs; v) processing costs such as labour, machinery and fuel, and vi) amendment costs (NAV, 2023). As potatoes and broccoli are often stored after harvesting, a storage costs is included for these crops. The costs for irrigation, €225 per ha, is based on common irrigation costs in the Netherlands (van den Burgt and Verstand, 2021). Costs for amendments are estimated based on unit prices (per kg or L) that was available online. Zeolite price per kg by Geosism (2023), seaweed biostimulant price per L by Swefa Agro Sciences (2023), and silicon biostimulant price per L by Advanced Biotechnology and Products B.V. (AB Products, 2023). Typically, cost price sheets for the three crops were derived from NAV, the Dutch Arable Farming Association (NAV, 2023), but costs on mortgage, bank loans and building maintenance were not included in our analysis as these vary between farmers and are not regarded as a direct costs impacting crop cultivation.

With respect to the benefits, main revenue is obtained from crop yield. This was quantified based on crop yields (in kg) of 12 pots per batch which is equivalent to an area of 0.5 m^2. Here, yield was then converted to kg per hectare. The market price of the crops for farmers was based on literature with values: wheat €0.27 per kg (Akkerwijzer, 2023), wheat straw €60 per ton (Boerenbond, 2023), average potato price over a year €0.25 per kg (Nieuwe Oogst, 2023), broccoli €0.50 per kg based on an interview with a farmer in RTL Nieuws (2019). In addition, Dutch farmers receive a contribution from the government when they apply manure (NAV, 2023). This amount is €25 per hectare for wheat and €50 per hectare for potatoes (NAV, 2023).

Output: based on input data, the net benefits and benefit-cost ratio (BCR) of wheat, potato and broccoli production was derived for control and saline conditions. The net benefits of crop cultivation is derived by subtracting production costs from the derived crop revenues while the BCR is derived by dividing costs with the benefits. Net benefits and BCR values are derived for both control and saline conditions. The salt induced yield gap was derived by the difference in net benefits of crop cultivation under control conditions compared to the saline condition. The analysis was first performed for the business as usual case where no amendment (referred to as “water”) was applied. Additionally, the analysis also compares effect of different amendment application on closing yield gap as a result of salinization.

Cost-effectiveness representing the crop quality parameters, was defined for protein and omega-3 with the latter only available in broccoli. Cost-effectiveness was derived by dividing average protein or omega-3 content (g per kg wheat, potato and broccoli) with production cost of wheat, potato and broccoli (€ per kg).

4.2.2 Amendment analysis for potato varieties in the second year experiments

Input parameters: throughout the analysis, direct costs (and benefits) were derived per hectare. Direct costs associated with potato are mentioned in the previous section 4.2.1, and were updated for 2024. The costs of all soil amendments were derived based on their updated unit prices (per kg or L) that were available online. In the experiments, a silicon-based biostimulant, a seaweed-based biostimulant and zeolite were applied as soil amendments to boost potato productivity. The silicon-based biostimulant price per L was obtained from Advanced Biotechnology and Products B.V. (AB Products, 2023), the seaweed biostimulant price per L from Ocean Glass (La Tienda del Agricultor, 2024), and the zeolite price per kg from Geosism (2024). Potential additional labour costs associated with biostimulant application was not included since they are typically applied concurrently with scheduled irrigation regimen thus, without requiring additional labour or resources.

All other input parameter costs were derived from NAV cost price of consumption potatoes for the 2024 harvest on clay soils in the Netherlands, excluding value-added taxes (NAV, 2024). Again, expenses such as mortgages, bank loans, and building maintenance were excluded from this analysis as they vary between farmers and are not considered direct costs of crop cultivation.

The main source of revenue was derived from potato tuber yield. This value was calculated from the tuber yields (in kg) observed in the pot experiments, where each pot represents an area of 0.3324 m^2 with eight replicates per potato variety per treatment. These yields were converted to kg per ha. The market price of consumption potatoes was updated to €0.14 per kg based on recent data (NAV, 2024; Agrimatie, 2024). Additionally, farmers in the Netherlands receive a government contribution of €50 per ha for manure application to potato fields (NAV, 2024).

Output: to assess the economic impact of the various treatments under different conditions, a comparative analysis was conducted using relative values rather than absolute figures. This approach enables a clearer understanding of the financial effectiveness of each treatment under specific environmental circumstances, aiding in the comparison across different amendments and varieties.

Based on the input data, the net benefits and BCRs of the two potato varieties were calculated under both control and saline conditions. Net benefits were determined by subtracting direct cultivation costs from crop revenues, while the BCRs calculated by dividing benefits by costs. The yield gap induced by salinity was quantified by assessing the difference in net benefits between crop cultivation under control conditions and saline conditions.

4.3 Results

4.3.1 Use of amendments mostly lowers the economic benefit from crop production in first year experiments

The benefit-cost ratio (BCR) for wheat, potato and broccoli under control and saline conditions provides an overview on whether salinity adaptation practices of using different amendments result into a positive business case or not (Table 4.1). All values above 1 are considered positive while numbers below 1 indicate a negative business-case for farmers.

Table 4.1: BCR values for wheat, potato and broccoli under control and saline conditions, with the addition of amendments. BCR defined by dividing total revenues with total costs.

Crops	Control (no biostimulant)	Zeolith	Seaweed-based	Silicid-acid based
Wheat water	1.47	0.83	1.53	1.22
Wheat salt	1.18	0.65	1.11	0.95
Potato water	2.28	1.98	2.22	2.20
Potato Salt	1.79	1.42	1.58	1.58
Broccoli Water	2.85	1.44	2.55	1.92
Broccoli Salt	2.42	1.35	2.22	1.91

The BCR values show that wheat, potato and broccoli cultivation is profitable under either condition, although lower BCR values are achieved under saline conditions. This was expected due to well-known adverse impact of salinity on crop yield (Katerji et al., 2003). The addition of amendments mostly results in lower BCR values indicating worsening situation of business case for amendment application on the three crops. The only exception is for seaweed-based biostimulant use in wheat cultivation under control conditions with a 0.06 BCR increase. Thus, this amendment has a slightly positive effect on the business case for wheat farming. On the contrary, addition of zeolite and silicon-based biostimulant to wheat results in BCR values below 1 indicating a business loss when either of these amendments are applied. This is due to additional costs from amendments even though there is limited positive impact of the amendments on crop revenue.

4.3.2 Zeolite showed the biggest positive effect on the economic salt yield gap of wheat and broccoli

Salinity negatively affects crop yield and thus, the revenues and net benefits that farmers experience for their cultivated products. Addition of amendments may provide a solution as such substances increase crop resilience to abiotic stress (Ahmad et al., 2022) and thereby reduce the yield gap that arises under saline conditions. The values under control conditions show the business as usual situation with relation to the economic salinity-induced yield gap (Table 4.2). It was expected that with amendment application, the yield gaps would be reduced, or ideally closed to zero. However, all of the applied amendments mostly have little or no effect on closing this yield gap for the three selected crops. Only the zeolite based amendment has positive impact observed as lower values for wheat (- €42) and broccoli (- €116) only, relative to values generated in control conditions.

Table 4.2: Economic salt induced yield gap. Values represent the difference in net benefits of crop cultivation under control vs. salt stress conditions calculated as crop revenues in control conditions - crop revenues under saline conditions with(out) amendment application.

Crops	Control (no biostimulant)	Zeolith	Seaweed-based	Silicid-acid based
Wheat	€ 406	€ 364	€ 407	€ 494
Potato	€ 4,644	€ 6,402	€ 6,462	€ 6,209
Broccoli	€ 666	€ 550	€ 740	€ 921

4.3.3 Cost-effectiveness of nutritional quality differed in wheat, potato and broccoli

The cost-effectiveness for protein and omega-3 content is generally lower under salt conditions compared to control conditions as expected (Fig 4.1). Under control conditions, 652 g of protein are produced per Euro with an observed increase to 686 g protein/ Euro when wheat plants were treated with a seaweed-based biostimulant (Fig 4.1A). This means that this amendment has a positive effect on protein concentrations in wheat. It also shows that wheat cultivation is more cost-effective for protein, even though production costs using the seaweed biostimulant addition is higher. Contrarily, this trend is opposite for zeolite and silicon-based amendments where protein content per Euro is lowered (Fig 4.1B-C).

The cost-effectiveness of protein production for potato is 170 and 145 g protein/ Euro under control and salt conditions respectively, without the use of any amendment (Fig 4.1B). Although seaweed and silicon-based amendments have a positive impact on protein content (increase between 0.5-2 g protein/ kg potato), the cost-effectiveness is similar or even lower compared to no treatment conditions due to additional production costs induced by amendment usage. It should further be noted that protein levels in potatoes are higher under saline conditions compared to control i.e., 18 to 19 g protein/ kg potato fresh weight and 20 to 22 g protein/ kg potato fresh weight under control and saline conditions respectively (Fig 2.10E). Nevertheless the cost-effectiveness of protein is still lower under saline conditions as total potato production (in kg/ ha) is much lower compared to yield in control conditions, while production cost per hectare remains similar (Fig 2.7A, 4.1B).

The protein content of broccoli in the business as usual case is 84 and 86 g protein/ kg broccoli for control and saline conditions respectively (Fig 4.1C). When amendments are applied, protein level increases from 2 to 15 g protein/ kg broccoli, with seaweed-based biostimulant application showing the biggest increment. Nevertheless, cost-effectiveness under amendment usage is still lower compared to business as usual case due to extra costs associated with amendment application. The only exception occurs for seaweed-based biostimulant application under saline conditions where cost-effectiveness increases to 434 g protein/Euro, from 399 g protein/ Euro under control conditions. Broccoli omega-3 content in business as usual situation is around 17 g/ kg broccoli for both control and saline conditions respectively (Fig 4.1D). However, cost-effectiveness for omega-3 under saline conditions is lower as yield decreases while production costs remain similar. The cost-effectiveness for omega-3 under control conditions increases to over 99 g omega-3/ Euro when the seaweed based biostimulant is added. This is explained by an increase in omega-3 content of over 2 g/ kg broccoli.

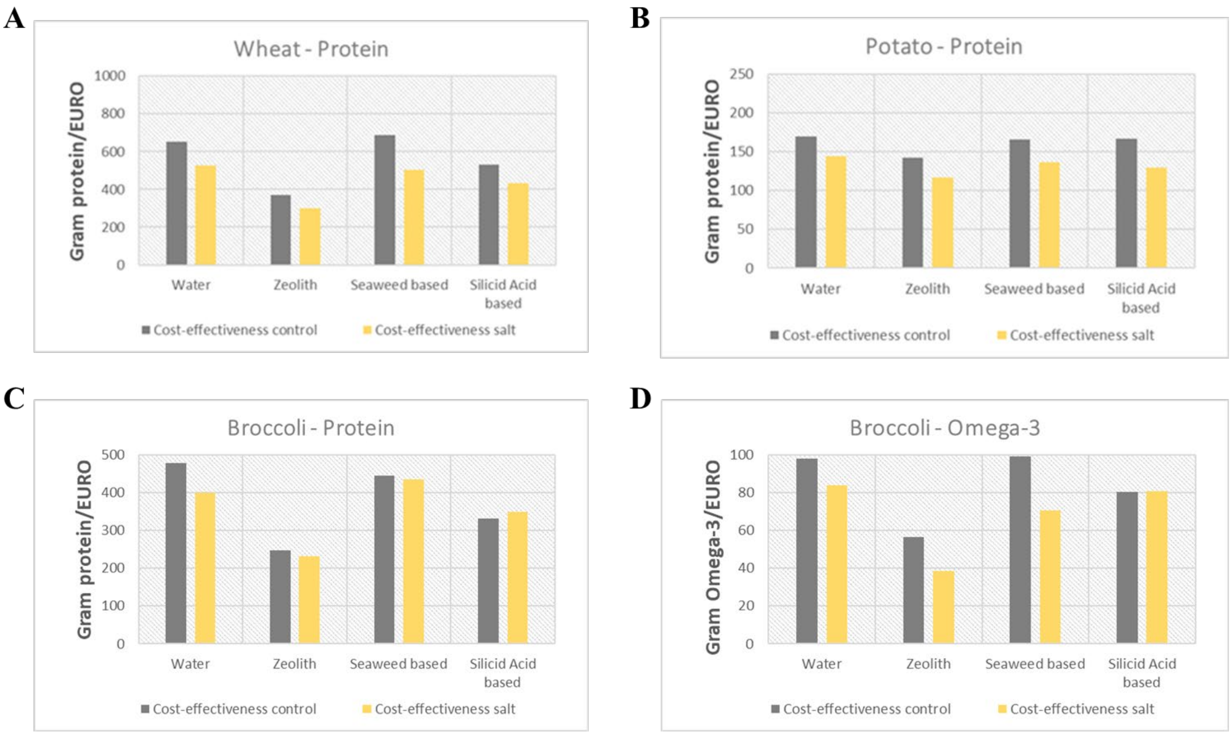

Figure 4.1: Potential cost-effectiveness based on crop quality. The cost-effectiveness of protein in wheat defined as g protein produced per Euro production costs for wheat (A), of protein in potato defined as g protein produced per Euro production costs for potatoes (B), of protein in broccoli defined as g of protein produced per Euro broccoli production costs (C) and omega-3 in broccoli defined as g of omega-3 produced per Euro broccoli production costs (D).

4.3.4 Seaweed-based biostimulants boosted the net benefits of potato varieties

Application of a seaweed-based biostimulant in salt sensitive potato plants showed a minor positive effect under control conditions but revealed reduced net benefit under saline conditions (Fig 4.2A). This suggests that, while the seaweed-based biostimulant offers financial benefits under non-stress environments, their effectiveness decreases when salinity occurs. The zeolite treatment consistently had the lowest net benefits across both control and saline conditions, with the magnitude of loss being more pronounced under saline conditions. Although the tuber yield improved slightly under saline conditions, the high costs associated with zeolite outweighed any potential gains in revenue (Fig 2.8A, 4.2A). In contrast, the silicon-based biostimulant displayed mixed results showing negligible net benefits under control conditions but a modest positive impact under saline conditions (Fig 4.2A).

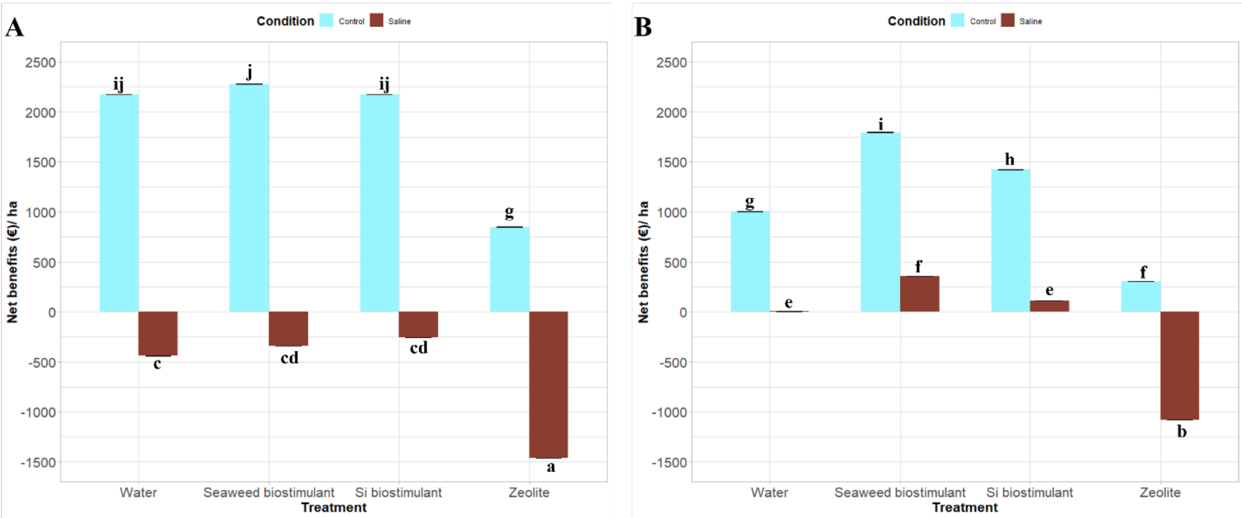

Figure 4.2: Cost-benefit analysis of different potato varieties. Net benefits of salt sensitive (A)- and the salt tolerant (B)- potato variety (B, right), both under control and saline conditions in the 2024 experiments.

For the salt tolerant potato variety, the seaweed-based biostimulant demonstrated a positive net benefit under control conditions, aligning with expectations in non-saline environments (Fig 4.2B). However, under saline conditions, its net benefits diminished considerably but was still remained positive. The silicon-based biostimulant exhibited positive net benefits under both control and saline conditions, although their effectiveness was not as high as observations in the seaweed biostimulant. Zeolite treatments again resulted in the lowest net benefits, underscoring their limited utilisation due to high economic costs.

Overall, the seaweed-based biostimulant emerges as the most consistently feasible option across varying conditions, particularly for saline environments where it offers economic and agronomic advantages. The silicon-based biostimulant also show potential but require context-specific application to ensure economic feasibility. Application of zeolite on the other hand, was not advisable given their consistently poor financial outcomes. Therefore, selection of amendments should consider not only the environmental conditions but also the cost-benefit dynamics specific to the crop variety and stress factors present.

4.3.5 Economic benefits improved best in the salt tolerant variety from the 2024 experiment

The 2023 greenhouse experiment on broccoli, wheat and potato, used a salt-sensitive potato variety allowing for comparison with the 2024 experiment with two potato varieties- a salt sensitive and a salt tolerant variety. In 2023, the experimental results revealed consistently negative net benefits across all treatments (Table 4.3). Under control conditions, net benefits ranged from -3.7% to -13.7%, while saline conditions exacerbated these challenges resulting in net benefits between -53.9% and -63.4%. These outcomes underscore the substantial stress imposed by salinity on crop performance and highlight the limited efficacy of the amendments deployed in this experimental setup.

In contrast, the 2024 experiment demonstrated a significant shift in outcomes (Table 4.3). Under control conditions, the salt sensitive variety displayed marginal improvements, with net benefits ranging from 0.1% to 5%. The salt tolerant variety however, exhibited remarkable performance achieving net benefits as high as 78.6%. When averaged, the 2024 results under control conditions indicated a positive net benefit of 20.8%, marking a stark departure from the uniformly negative results of 2023.

Table 4.3: Cost benefits comparison of potato in both experimental years. Net benefit of different potato varieties in the 2023 experiment and 2024 both under control and saline conditions, as relative values (in %) based on their corresponding control conditions with no amendment application, described as the business as usual case.

			Control situation			Saline conditions		
Year	Crop	Variety	Silicon-bas	Zeolite	Seaweed-b	Silicon-bas	Zeolite	Seaweed-b
2023	Potato	Salt-sensit	-0.04	-0.14	-0.04	-0.54	-0.63	-0.55
2024	Potato	Salt-sensit	0.00	-0.61	0.05	-1.12	-1.67	-1.16
2024	Potato	Salt-tolera	0.42	-0.70	0.79	-0.89	-2.08	-0.65
2024	Potato	*Average*	0.21	-0.65	0.42	-1.00	-1.88	-0.90
2023	Potato	Salt-sensit	-3.7%	-13.7%	-3.7%	-53.9%	-63.4%	-54.7%
2024	Potato	Salt-sensit	0.1%	-60.9%	5.0%	-111.8%	-167.4%	-115.7%
2024	Potato	Salt-tolera	41.6%	-69.8%	78.6%	-89.1%	-207.8%	-64.6%
2024	Potato	*Average*	20.8%	-65.4%	41.8%	-100.5%	-187.6%	-90.1%

Under saline conditions, the 2024 results exhibited greater variability. The salt sensitive variety continued to experience substantial negative impacts, with net benefits ranging from -111.8% to -115.7% (Table 4.3). Nevertheless, the salt tolerant variety demonstrated a notable capacity to mitigate the adverse effects of salinity, yielding net benefits between -89.1% and -64.6%. The overall average net benefit under saline conditions in 2024, although still negative at -100.5%, represents a notable improvement relative to the 2023 average of -58.5%. This improvement is attributed primarily to the inclusion of the salt-tolerant variety.

These findings underscore the critical role of genetics in addressing the challenges posed by saline environments. Our marked differences in performance between salt sensitive and salt tolerant varieties highlight the necessity of breeding and adopting crops specifically adapted to such conditions. Furthermore, interactions between amendments and crop genotypes were shown to exert a significant influence on net benefits, emphasising the importance of optimising these interactions to maximise the potential benefits of amendment application in saline agricultural systems.

4.4 Discussion

The financial economic results derived from yield data of 2023 greenhouse experiments are mostly in contradiction with existing literature on biostimulant efficiency. It should however be noted that most of the referenced studies above have completely excluded data from greenhouse pot experiments. Moreover, these studies do not also estimate potential cost benefit analysis of amendment application to boost yield under saline conditions. A review paper quantifying 180 global field studies worldwide revealed that average crop yield (which is associated with direct crop revenues) increases between 8.5 and 30.8% with an overall average of 17.9%, with largest increase observed for vegetables grown in low soil organic matter, non-neutral, saline, nutrient-insufficient and sandy soils (Li et al., 2022). Another study by Sirbu et al. (2022) showed that wheat yield increase ranged between 50-60% when treated with algae biostimulant. Instead, this increase was around 22% in our study.

Amendments imply additional costs for purchasing, and may also incur additional labour costs for application. Therefore, farmers require much higher yield gains due to amendment application to outweigh these costs in order to have a positive agricultural business case. Kocira et al. (2020) indicated that farmer net income increases due to usage of amendments for bean cultivation. The profitability of amendment use can range from €49.51 to 1059.96/ ha (Szparaga, 2019), although these results were not measured under saline conditions. Our 2024 experiments show that even in the best scenario under saline conditions with cultivation of a tolerant variety treated with a seaweed-based biostimulant, net benefits only reached ~ €350/ ha of potato, which is lower than corresponding benefits of ~ €1800/ ha netted in non-stress condition, and even much lower than observations in the business as usual case when the salt sensitive but high yielding potato variety is cultivated resulting in ~ €2,300/ ha net benefits (Fig 4.2).

While the positive impacts of amendments on crop yield and quality are well-supported by field studies, the financial-economic benefits remain less discussed and conclusive. Although soil amendments have the potential to increase yields, particularly under stress conditions such as salinity, further research is required to optimise their application in different agricultural settings and to better understand the economic trade-offs for farmers.

Conclusion and Recommendations

The net benefits for wheat cultivation increases only when seaweed-based biostimulant is applied under control conditions. For potato and broccoli none of the amendments showed a positive impact on farmers business cases. Therefore, indicating that amendment responses differ per crop and therefore amendment dosages should also reflect this. Manufacturers' dosage recommendations should not be a "one size fits all" but should be adjusted per crop to optimise positive yield and quality improvements. Literature reveals multiple examples of biostimulant use that results into improved crop productivity both under control and saline conditions. These results are usually in contradiction with results obtained from this study. However, it is clear that results obtained from greenhouses are significantly different compared to uncontrolled field experiment. Therefore drawing conclusions on amendment effectiveness from the pot experiment should be taken with care. In this context it is recommended to repeat the experiments under saline conditions in an open field settings to acquire more realistic results.

The economic feasibility of using biostimulants and soil amendments in potato farming strongly depends on the type of amendment used, the salt levels in the environment, and the potato genotype's tolerance to salt. The seaweed-based biostimulant in the 2024 experiment consistently deliver the best economic returns, especially in saline conditions, where they help reduce yield losses and maintain positive net benefits. On the other hand, zeolite is not economically viable in any condition, as its high costs far outweigh any potential yield improvements, particularly under saline stress. In summary, use of saline adaption strategies such as tolerant varieties and soil amendments, require careful cost-benefit analysis in addition to results on improvement in crop yield and quality.

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5 Scaling adaptation strategies to deal with increasing salinization

Catharien Terwisscha van Scheltinga and Ayodeji O. Deolu-Ajayi

5.1 Introduction

Salinization should not only to be addressed at field scale level. Upscaling to landscape, regional and (inter)national scale is important. In order to address this, we first define upscaling, based on literature research, after which we introduce a framework for upscaling. We also introduce experiences on upscaling salinity in international context, after which we reflect on the situation in the Netherlands.

Upscaling of adaptation strategies is expressed in numerous ways. The Global Centre on Adaptation in their flagship report 'Adapt Now' describes upscaling as a way to accelerate the pace and ambition of adaptation. They stress focusing on understanding climate risks, improving planning for policy and investment decisions, and mobilizing required funding (Global Centre on Adaptation, 2021). Research on scaling up urban agriculture to leverage transformative food systems change stresses the importance of an integrated conceptual framework, reflecting multiple disciplinary domain (Qui et al, 2024). Key considerations for scaling up urban agriculture are to include diversity, heterogeneity, connectivity, spatial synergies and trade-offs, nonlinearity, scale and polycentricity. Parmentier (2014) indicates that the challenges for scaling up agroecological approaches are to unlock ideological barriers to political recognition, support farmer-to-farmer networks, provide an enabling public policy environment; take specific actions for empowering women and improving agricultural and food governance. A USAID project's reflection on scaling up agricultural technologies stresses that the process of scaling requires focus, besides the agricultural technology to be scaled. Scaling often continues beyond the results and duration of projects (USAID and Bureau for Food Security, 2014).

Therefore, upscaling adaptation strategies refers to methods and processes to successfully expand adaptation interventions and practices from a local, field level scale to a broader scale, for instance at regional or national level. Several adaptation strategies to deal with salinization and enhancing food production have been reported. These strategies include breeding and selection of salt tolerant varieties, cultivating halophytes, management of crop cultivation systems management, phytoremediation and bioremediation of salt-stressed soils, application of soil amendments, biostimulant application, combined micro-irrigation and drainage systems, and water desalination technologies (Deolu-Ajayi et al., 2024). In this project, we focused on two strategies- use of tolerant varieties and application of soil amendments. A lot of studies on saline agriculture focus on testing the strategies in a farm-field context as experiments in controlled greenhouse conditions or in fewer cases, demonstrations in field conditions (Deolu-Ajayi et al., 2022; Li et al., 2022). Going beyond application of strategies for saline agriculture in single fields, but rather adoption of these strategies by multiple farmers locally or regionally. Thus, delving into factors and requirements for upscaling saline adaptation strategies.

5.2 Factors to consider for upscaling saline adaptation strategies

Upscaling of saline agriculture strategies is complex. It requires looking beyond the technology of saline adaptation strategies and taking further consideration and incorporation of both environmental and socio-economic factors, including relevant stakeholders in the Netherlands and beyond. In a review on upscaling, Guentchev et al. (2023) indicate that scaling up can be done in various ways e.g., through replication to reach many termed horizontal scaling, linking the initiative to policy and embedding it institutionally termed vertical scaling, or through broadening the scope of an adaptation initiative known as functional scaling. For horizontal scaling of saline agriculture, replication of the intervention is done to reach many users without too much change. Horizontal scaling can take place from the greenhouse to the farmer fields, or from one farmer to another. When linking the adaptation strategies with policy and institutional measures, and an enabling environment is created, we talk about vertical scaling. For instance, if a government makes funding available to adopt saline agriculture strategies, as part of a policy, this is considered vertical scaling. When combining the intervention with other activities, functional scaling takes place. A combination of vertical and functional scaling is suitable for the Netherlands, since challenges of salinization are beyond field scale level and solutions need to be diversified, synergistic and linked to ongoing agricultural activities in the region while simultaneously connected to national policies.

Several frameworks such as the butterfly framework (Bos et al., 2022), FSA- food system approach (Borman et al., 2022) and PROMIS- PRactice-Oriented Multi-level perspective on Innovation Scaling (Wigboldus et al., 2016) give an overview on the bigger picture on connections between institutions from the socio-ecological, socio-technical, and socio-institutional sub-systems. The butterfly framework differs from the others by highlighting the action perspectives of the linked sub-systems by taking into consideration transition to circularity with high-level ambitions like climate neutrality (Bos et al., 2022). Here, we use the butterfly framework as starting questions to give insight on principal factors to consider when upscaling saline agriculture (Table 5.1).

Figure 5.1: General assessment questions on salinization in the Netherlands based on the butterfly framework. The elements and delving questions are in the corresponding table in the left and right columns respectively.

Butterfly Framework Elements	Assessment Questions
1. Scale of the problem	1.1 What regions in the Netherlands are vulnerable to salinization?
	1.2 What is the total arable area currently salinized in these regions?
	1.3 What is cultivated there and what are current productivity levels?
2. (Societal) goals	2.1 What are the drivers (climate change, food security) for introduction of saline agriculture?
	2.2 What are international, national, regional and societal goals that support saline agriculture?
	2.3 What are policies to support new sustainable production and processing systems adapted to salinization and/or mitigating the effects of salinization?
3. Drivers	3.1 What are (changes in) society preferences to support saline agriculture (e.g., flavour profile of saline-adapted crops, diversifying diets, local and sustainable lowering their carbon or water footprint)?
	3.2 What technologies are currently applied to deal with salinization in the Netherlands and how could that change or improve (from water-based technologies to strategies that incorporate the water-soil-plant nexus)?

4. Interventions	4.1 What saline agriculture strategies are feasible in the Netherlands?
	4.2 Who are the relevant stakeholders in the crop production value-chain needed for saline agriculture?
5. Technical System	5.1 How would traditional and/or new saline agriculture strategies affect optimisation and balancing material flows at different geographical locations, at different scales, (with less) land use, (less) nutrient use, (less) water use, (less) agrochemicals?
6. Ecological System	6.1 What is the expected impact of introducing saline agriculture on existing ecosystem elements?
	6.2 What are the synergies, and trade-offs that should be known, and possibly quantified, with regards to resource use (e.g., land, water, nutrients, crop protection agents) and material flows?
	6.3 At what scale can saline agriculture strategies be combined and what are the consequences?
	6.4 Are there any hazardous (bio)substances cumulating from short and long-term implementation of these strategies?
7. Socio-economic System	7.1 Are or are there any ethical issues to address due to application of the strategies?
	7.2 What are the short- and long-term economic costs associated with saline agriculture?

5.2.1 Scale of the problem

The actual extent of salinization in the Netherlands currently remains unknown. Mapping for soil salinity in the Netherlands has not yet been performed on large scale, and only rather small-scale point measurements are currently available (Tzemi et al., 2020). Therefore, it is difficult to estimate the actual total arable area affected by salinity in real time. In the Netherlands, salinization is a regional problem affecting several coastal areas. Groningen, Friesland, North Holland and the south-west of the Netherlands have been identified as areas currently dealing with salinization (Tzemi et al., 2020), exposing these regions to long-term risks of irreversible soil damage and food production systems' collapse. At the same time, currently several salt sensitive crops such as potato, flower bulbs etc. are cultivated in these regions, also putting current agricultural production at risk.

5.2.2 Societal Goals

Climate change further increases salinization of arable land due to sea level rise and saltwater intrusion. Salinization puts food security at risk by causing severe crop losses and limiting freshwater availability (FAO, 2021). Saline agriculture should be directly linked to current and future policies as early as possible, to facilitate mass adoption of these strategies by farmers and society, as large. The problem of salinization has been getting more traction in the Netherlands in recent years leading to initiatives that provide saline agriculture solutions (NFP & NWP, 2022; Redactie OTAR, 2023). In preparation is a knowledge and research agenda on dealing with salinization in the Netherlands supported by the Dutch Ministry of Agriculture. The importance of saline agriculture needs to be clearly emphasized to governments and policy makers and linked to existing policy frameworks (van Holst et al., 2023). Once the importance of saline agriculture has been established, agenda setting for short and long-term actions and goals is the next concrete step. Policies supporting saline agriculture should be inclusive and thus co-created by a variety of local, regional and international stakeholders.

In the context of saline agriculture in the Netherlands, a transformative innovation policy framework for scaling up saline agriculture that is sustainable and equitable has recently been proposed for future EU policy (van Holst et al., 2023). The proposed saline agriculture policy framework can be linked to existing EU policies such as the Common Agricultural Policy (CAP), European Climate Pact, EU Green Deal, including the Farm to Fork Strategy (F2F) and Biodiversity and Soil Strategy for 2030. Goals for saline agriculture for the Netherlands may be linked to existing policies and ongoing initiatives like National Climate Adaptation Strategy (NAS) and the National Delta programme (LNV, 2020).

5.2.3 Drivers and Interventions

Several global and regional drivers for salinization exist (Snethlage et al., 2023). Rising seawater levels, increasing temperatures, continuous freshwater abstraction and land subsidence all contribute to increasing salinity intrusion into arable land in the Netherlands. With changing societal perspective on the need to improve agricultural sustainability and reducing carbon footprint due to food production, environmental factors including existing biophysical conditions- climate, soil, water of salinized areas in the Netherlands should be tackled. Many, if not all, of the saline adaptation strategies have large scale potential in the Netherlands but this usually comes with some trade-offs in the ecological or socio-economic domain (van den Burg et al., 2024). Several of the aforementioned saline adaptation strategies are already used in the Netherlands. Examples in Zeeland and the Wadden islands such as halophyte cultivation and use of are summarized in van den Burg et al., 2024, although most are still experimental and used on small scale.

Stakeholder perspective needs utmost consideration, especially changing their perception on adoption of saline agriculture. Farmer preferences and openness, markets and business models, government and policy, consumer preferences, and public opinions and collaboration, should be addressed (van Berkum et al., 2018). Dutch farmers in salinized areas are mostly hesitant to transition towards saline agriculture except in dire cases where production process is severely impacted by salinization (Beauchampet, 2022; Bergkamp et al., 2018). Additionally, regional stakeholders such as the federation of agriculture and horticulture (LTO), water authorities and provinces do not support most saline agriculture adaptation strategies but focus on maintaining freshwater bodies. Other entrepreneurs including farmers, that additionally focus on other parts of the food supply chain such as processing and creating products, apart from crop cultivation, are more open to saline agriculture and may be entry points for upscaling these strategies (Bergkamp et al., 2018).

Collaboration between different stakeholders, such as the agricultural sector (e.g., branch organisations of farmers like LTO, KAVB), waterboards, provinces, and even Ministries, Rijkswaterstaat, and knowledge institutes is needed since they all have a stake or (potential) role in addressing the issue (Beauchampet, 2022). Education of stakeholders on the benefits of saline agriculture is necessary to promote change. Stakeholders should be jointly responsible for adoption and implementation of saline agriculture: from co-analysis of saline adaptation strategies to co-learning from long-term evaluation and monitoring of the adaptation strategies (Verhagen et al., 2022).

5.2.4 Technical, Ecological and Socio-economic systems

In terms of optimisation and balancing material flows, some adaptation strategies such as bioremediation and phytoremediation, may reduce land expansion to other places since remediated salinized areas may be repurposed for agriculture (Panta et al., 2014), thus minimising land abandonment due to salinization. Additionally, several saline agriculture strategies promote soil health and water use efficiency thereby have the potential to decrease nutrient, water and agrochemical use. Although, the impact of saline agriculture on the environment still remains unclear, combining adaptation strategies may even reduce the mid- or long-term environmental risks while simultaneously boosting crop production to levels synonymous with non-saline conditions and. Models such as a methodological framework for designing scenarios for upscaling (Selbonne et al., 2022), may be used to estimate to what extent implementation of saline agriculture in a region may boost crop productivity and socio-economic status while mitigating environmental impact.

The transition towards saline agriculture is a costly one, that would require subsidies from the government and private sector as well as, development of associated markets. Additionally, there is still limited research on practical application of several saline agriculture strategies. Results observed under controlled lab conditions have not been easily transferable to field conditions especially considering the financial investment related to adoption of these strategies by farmers (Beauchampet, 2022). Moreover, research on saline agriculture also requires long-term funding making the problem more complex.

Socio-economic and ecological assessment of saline agriculture shows the potential for upscaling various strategies. Linking saline agriculture to other sectors may also facilitate broader adoption by stakeholders and thus, promote upscaling of the adaptation strategies (Alphen et al., 2024). Reference is made to chapter 6 regarding multifunctional land use transitions. Another example is linking salinity and agritourism. Here, saline agriculture is coupled with the tourism industry to strengthen the local economy and employment. Agritourism then provides additional income, while it may also make farming attractive to the younger generation (Bergkamp et al., 2018). Also, broader linkages with other entrepreneurs can be made e.g., connections to restaurants.

5.3 Process of upscaling of salinity adaptation measures in other deltas

In upscaling, integration of water and food systems plays an important role. While in this strategic WUR research project the focus is on the Netherlands, other WUR research on other deltas with cases in Vietnam and Bangladesh (www.wur.eu/food-in-deltas), developed guidelines for transition pathways in which a process formulating a vision for the future, jointly with stakeholders, was propagated, to start change processes (Verhagen et al, 2022). Another part of this research on deltas shows how adaptive pathways for food systems are similar to adaptive delta management where adaptive pathways in the water system are more central (Terwisscha van Scheltinga and Timmerman, 2020).

Another example related to upscaling and saline agriculture and water management in Bangladesh is the COAST project in Bangladesh. Here, at local level capacity saline agriculture strategies such as enhancing cropping technologies (mulching, drip irrigation) and the choice of suitable crops and specific saline tolerant varieties were implemented to deal with salinity. Water and agriculture related strategies were mapped in a reflection study on water related adaptation in saline agriculture (Terwisscha van Scheltinga et al., 2024, Fig 5.1). Several short-term adaptation strategies related to agriculture were at field level, like using saline tolerant varieties, mulching and drip irrigation. Upscaling these would compare to horizontal upscaling. Longer term strategies, like water management, water infrastructure and institutional development measures, come into purview when scaling up to regional level (Fig 5.1). This would require vertical or even functional scaling.

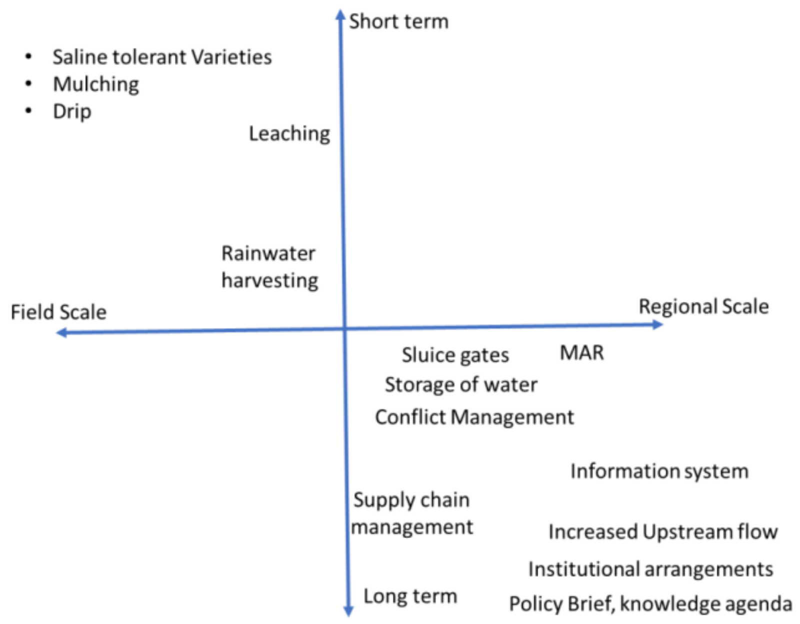

Figure 5.2: Overview of potential solutions in agriculture practices and water management addressing salinity at different spatio-temporal scale.

Further, it appeared that local level stakeholders in this project were involved with the shorter-term field level strategies, while the regional and longer-term strategies were not much in the project's focus (Terwisscha van Scheltinga et al., 2024). In other words, the project mainly aimed for horizontal scaling while vertical scaling (embedding in institutions and policies) and functional scaling (linking to other activities) were also relevant strategies for upscaling, though sometimes complex and not easy to achieve.

The lesson learned is therefore, that upscaling can be done through horizontal, vertical and functional scaling. In the case above, automatic focus was more on horizontal scaling, while vertical and functional scaling also may provide interesting opportunities.

5.4 Reflecting on upscaling salinity actions in the Netherlands

In a previous paper, ongoing initiatives on saline agriculture in Texel, Terschelling and Zeeland (van den Burg et al., 2024) were studied. Based on the example in Bangladesh in paragraph 5.2, we reflect on the Dutch case studies. It will be interesting to explicitly map the strategies taken in various locations in the Netherlands and explore field versus regional scale, and short versus longer term strategies. And then reflect on the involvement of various stakeholders. Upscaling creates complex situations since it requires huge developmental investments, and stakeholders do not benefit equally. For example, Sanchez-Achilla et al (2022) stress that for coastal restoration it is important to implement at larger scales, but that upscaling requires ecosystem restoration, and dealing with technical, economic and management barriers, stemming from sectoral and poorly coordinated local interventions which are insufficiently monitored and maintained (Sánchez-Arcilla et al., 2022).

Saline adaptation strategies in the Netherlands can be upscaled from greenhouse to field level and beyond, through both vertical (using policy support and financial measures) and functional scaling (agritourism by combining saline agriculture with tourism). Livestock production is the main agricultural focus on the island of Terschelling. Therefore, saline agriculture should be linked to strategies that promote animal warfare. This can be in terms of promoting salt tolerant grass varieties, cultivation of halophytes as feed, and saltwater desalinization to increase the availability of freshwater for livestock use. Propagation of salt tolerant varieties of common crops, cultivating halophytes for food and implementation of drainage systems to preserve freshwater is practiced in Texel and Zeeland. Application of biostimulants and other (in)organic soil amendments may also boost food crop and forage grass production under saline conditions (Deolu-Ajayi et al., 2022; Mackiewicz-Walec & Olszewska, 2023). Still experimental is the use of halophytes as feed, since halophytes cannot typically be consumed in large quantities due to their high salt concentrations. Halophytes may be cultivated for alternative purposes such as for land remediation allowing the area to again be used for crop cultivation after several years (Sarath et al., 2021), and for production of fuel and pharmaceuticals (Lopes et al., 2023).

Salinity strategies in the specified regions would ideally involve synergistically combining all or multiple of these adaptation strategies to create sustainability and possibly reduce the risk of negative environmental impact of the transition. These large-scale adaptation strategies would require long-term investment from the farmers, provinces, companies, water authorities and national ministries since the benefits of the strategies are typically not always obvious in the short term (> 5 years). Costs of agricultural inputs such as salt tolerant seeds and (in)organic amendments accumulate over time and may not be able to compensate for the yield gap and its resulting income reduction caused by salinity, especially in the first few years where investments into setup are typically higher. Moreover, water desalinization technologies are still relatively expensive, and create other challenges in the production of waste as brine, that can be repurposed to other industries.

However, upscaling also leads to multiple stakeholders sharing the socio-economic costs thus, making implementation more practical. All stakeholders invest financially since it is of interest to them, while playing additional roles. Policy advisors from the ministries create frameworks and directives to promote saline agriculture with a long-term outlook on the future of saline systems.

The use of multiple strategies simultaneously such as, tolerant varieties with and application of (in)organic amendments may facilitate higher crop production to close the yield gap under saline conditions while desalinized water can be repurposed for agriculture, eventually boosting income in the long run. Agritourism may be a way to further offset the socio-economic costs of salinization and at the same time, promote societal awareness of salinization challenges and acceptance of the deployed adaptation strategies to deal with salinity intrusion. For example, salt marches in Terschelling where halophytes are cultivated are also known tourist attraction sites (Bergkamp et al., 2018). Connecting saline agriculture products to markets is also of high priority. Rebranding of the products to highlight their taste or nutritional benefits may further create awareness on salinization for end-users or consumers and also boost sales of products obtained from saline agriculture (Custódio et al., 2021; Panta et al., 2014). In conclusion, for the Netherlands, the example of combining saline agriculture with tourism is an example of functional scaling. Other 'out of the box' examples can be thought of, together with stakeholders when switching between and combining options of horizontal, vertical and functional scaling.

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6 Perspective on land use functions and transition on salinized soils

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6.1 Introduction

When soils become too salinized, it may not be possible to support crop cultivation and agricultural practices become unprofitable. The salinization threshold that limits agricultural practices is dependent on the crops being grown, with some crops being better suited for saline conditions e.g., beets and quinoa (Blom-Zandstra, 2014). The process of converting land use from one use function to another is referred to as land use transition. Apart from agricultural land becoming unusable due to salinization that is further exacerbated by climate change, land-use transitions can be driven by many factors such as new agricultural policies e.g., EU regulation on pesticide reduction, increase in tourism leading to creation of recreation centres, and urbanisation (Snethlage, 2023). In the case of salinization as a driver of land-use change, the farmer (or agricultural landowner) has the decisive power to initiate the land-use transition. This is, however, not the case for all land-use transition drivers. For example, government and policy initiatives could ultimately result in land use transitions that are not initiated or supported by the farmers themselves.
Agricultural ecosystems, however, provide humans with food, bioenergy and pharmaceuticals (Power, 2010). In addition to their provisioning services, agroecosystems can also provide regulating and cultural services including food, water quality control, carbon storage, climate change mitigation via reduction of greenhouse gas emissions, disease regulation, waste treatment (e.g., nutrients, pesticides), scenic beauty, education, recreation and tourism (Power, 2010). So, when cessation of agricultural practices is necessary due to soil salinization, the ecosystem services provided by agriculture come to a halt, prompting the question of which other functions can be carried out on highly salinized soils? What ecosystem services do these functions provide? And how do the different functions benefit people, planet and profit?

6.1.1 Land use transition concepts

To answer the questions above, several concepts need to be defined and their interactions explained. There are several definitions of ecosystem services (Fisher et al., 2009). Here, we adopt the broad definition of the Millenium Ecosystem Assessment (MA) 2005 which defines ecosystem services (ES) as "the benefits people obtain from ecosystems". The MA uses the following categories to classify ecosystem services: provisioning, regulating, cultural and supporting services (See Table 7.1 for categorisation). Provisioning services refer to the direct benefits of the products obtained from ecosystems such as food or feed. Regulating services are benefits obtained from the regulation of ecosystem processes i.e., indirect benefits. Cultural services are the non-material benefits obtained from ecosystems e.g., intrinsic value or scenery, while supporting services constitute resources necessary for production of all other ecosystem services (Millenium Ecosystem Assessment, 2005). The land use functions that provide these ecosystem services can alone or when combined benefit people, planet profit to the extent of their sustainability.

Sustainability has been operationalised through the Sustainable Development Goals (SDGs) established by the United Nations. These 17 goals provide a blueprint for addressing global challenges such as poverty, inequality, climate change, environmental degradation and justice, aiming to create a more sustainable and equitable world. Complementing this approach is the concept of planetary boundaries, which defines the safe environmental limits within which humanity can continue to thrive. As we explore new economic activities, especially on unsuitable agricultural lands, there is a growing imperative to align these ventures with the SDGs and adhere to the principles of planetary boundaries. This means prioritising bio-based developments that not only reduce environmental impact but also enhance the buffering functions of ecosystems such as carbon sequestration, water purification and biodiversity conservation. By fostering activities with a positive environmental footprint- where the positive impacts outweigh the negative- we can contribute to sustainability in a manner that respects the natural limits of our planet, support human well-being, and promote long-term economic resilience.

6.1.2 Ecosystem services assessment

Ecosystem services (ES) contribute directly and indirectly to human welfare and therefore, represent part of the total economic value of the planet (Costanza et al., 1997). Ecosystems are important to human society for different reasons thus, valorising ES in monetary units may assist in conveying the (relative) importance of ecosystems and biodiversity to nature management organizations and policy makers (de Groot et al., 2012). For example, in identifying where protection and restoration is economically most important, and further discussions on ES in the context of people, planet, profit.

Valuation of ES in economic terms is assessment of monetary worth of non-market ecosystem benefits. It can be conducted using market price information or non-market valuation method such as revealed and stated preference techniques. Revealed preference methods estimate values based on observed behaviour such as travel cost or property prices related to environmental goods, while stated preference methods use surveys to gauge willingness to pay for hypothetical scenarios. The contingent valuation method is a popular stated preference technique that estimates the monetary value of ES, including passive values that are not reflected in market behaviour. Additionally, combined methods like contingent behaviour models, integrate elements of both revealed and stated preferences to provide a more comprehensive valuation (OECD, 2018). After its implementation, valuation of ES has made a significant development in quantification and qualification approaches.

As summarised by van Loon-Steensma and Goldsworthy (2022) in recent years, numerous studies, including those proposing conceptual frameworks, have advanced the understanding of the relationship between sustainability and nature based solutions (NBS) (Raymond et al., 2017), which also highlighted the implications for policy, science, and practice for the complex and heterogenous nature of NBS (e.g., Eggermont et al., 2015; Kabisch et al., 2017; Nesshöver et al., 2017). Furthermore, considerable efforts are being made to establish comprehensive evidence and knowledge base for development of indicators for evaluating the effectiveness of NBS (e.g., Kabisch et al., 2016; Raymond et al., 2017), and the conceptualisation, mapping or modelling of the economic, social and environmental benefits associated with NBS (e.g., Lafortezza and Sanesi, 2018). Here, focus lies on ES as indicators for assessment and evaluation, however long term and structured data to evaluate environmental performance in land use function of salinized areas are not available for our case study.

Examples of capitalisation for ES assessment are indicated as flood regulation, recreational and aesthetic value, carbon sequestration, habitat and nursery provision, and sediment retention and erosion control. Ecosystems such as floodplains and wetlands contribute to flood regulation by absorbing and slowly releasing water, thereby reducing the risk and severity of floods. The economic value of this service can be quantified by the reduced cost of flood damages and the savings on flood defence infrastructure (Kousky and Walls, 2014). Coastal ecosystems like beaches, coral reefs and estuaries offer significant recreational opportunities and aesthetic enjoyment. The valuation of these services is often derived from travel cost methods or willingness-to-pay studies that measure how much individuals are willing to spend to access and enjoy these nature areas (Woodward and Wui, 2001). Ecosystems such as mangroves, seagrasses and salt marshes are highly effective at sequestering CO_2 from the atmosphere and storing carbon in their biomass and sediments. The economic valuation of carbon sequestration can be determined by calculating the monetary value of carbon credits or the social cost of carbon emissions avoided due to carbon storage provided by these ecosystems (Pendleton et al., 2012). Coastal habitats like mangroves, seagrasses and coral reefs provide critical nursery grounds for many marine species, supporting fisheries and biodiversity. The valuation of these habitat services can be measured by contribution of these ecosystems to the productivity of commercial and subsistence fisheries as well as, their role in maintaining marine biodiversity (Barbier et al., 2011). Mangroves, salt marshes and seagrass beds play a vital role in trapping sediments and reducing coastal erosion, which helps maintain coastal landforms and prevent land loss. The valuation of sediment retention and erosion control services involves estimating the costs avoided from reduced sedimentation in waterways and the maintenance of coastal infrastructure (Barbier et al., 2013). In our study we focus on the internationally standardized CICES-classification (Common International Classification of Ecosystem Services) of the European Union, which serves as a reference for the Atlas Natuurlijk Kapitaal (ANK) and is used to model and quantify ecosystem services and ecosystem stocks (ANK, 2023).

6.2 Methodology

To facilitate the steps to an integral discussion on land use transitions, a selection of land use options was collected based on case studies in the Netherlands. All land use options in a salinized area were inventoried and listed and was the basis for further conversion to land use functions (Table 7.1). To further explore and define potential land use options for agricultural coastal polders in salinized areas, specific interventions in the coastal zone were identified. Different case studies were identified as an option to assess potential boundary conditions and trade-offs. Trade-offs and synergies were identified as adequate however, the case studies mainly provided information on land use functions and potential indicators for short-term assessment. Therefore, the case studies primarily target short term objectives and impact on the environment. Information on long term indicators were less available which resulted in a change of approach. The project redirected to verify the functionality of Atlas Natural Capital (Atlas Natuurlijk Kapitaal (ANP)), and Common International Classification of Ecosystem Services (CICES) Indicators.

This resulted in a list of 72 indicators (primarily ANP), which to some extent, could contribute to a future framework of indicators and thus, is able to assess characteristics of transitions of salinization interventions in coastal transition zones. A wrap-up by 6 interviews with relevant stakeholders was planned (Table 7.2). The aim of the interviews was to identify how different stakeholders such as freshwater farmers, saltwater farmers, water managers, spatial planners, and water boards envision the future of salinized agricultural areas. How they see the progress of salinization in their area of influence. These questions (Table 7.2) were aimed at understanding both the current and future landscape of salinization, and how various stakeholders are responding to this environmental challenge. Therefore, highlighting stakeholders' future needs.

6.3 Results

The step to select land use options were collected based on case studies in the Netherlands. All land use options in a salinized areas were inventoried and categorically listed (Table 6.1). This was the basis for further definition of land use functions that occur when salinization occurs, compared to the baseline scenario where salinization does not occur and freshwater agriculture is the norm (state zero).

Table 6.1: Land use functions and defined options suitable for saline areas in the Netherlands.

Land use function	Land use option
Soil based freshwater agriculture	Crop production is only freshwater based (state zero)
Soil based salt adapted agriculture- crop	Crop species, varieties and practices adapted to salt/ brackish conditions (double dykes, wisselpolders)
Soil based salt adapted agriculture-livestock	Animal species and breeds are tolerant to high salt stress (double dykes, wisselpolders)
Soil based salt tolerant agriculture-halophyte	Production of salt loving crop species inside the dikes, on salinized land (double dykes, wisselpolders)
Aquaculture – animal based	Production of (shell)fish in saltwater systems (double dykes, wisselpolders, Waterdunen)
Aquaculture - macroalgae	Production of seaweed in saltwater systems (double dykes, wisselpolders; Waterdunen)
Aquaculture - microalgae	Production of microalgae in saltwater systems (double dykes, wisselpolders)
Sediment entrapment / clay collection	Double dykes, wisselpolders
Coastal protection – nature based	Nature based approaches for coastal protection systems, tidal saltmarsh restoration (pilot experiments, Schorer/ Welzinge)
Coastal protection – smooth transitions	Coastal transition using gradual slopes, and multiple steps for waves and damping
Coastal protection – hard barriers	Coastal protection using e.g., hard dykes and/or seawalls
Coastal protection – hard barriers ecological	Coastal protection using e.g., hard dykes with grass, or other structures such as gabions filled with shells or stones. (Oesterdam, Viane)
Oyster reef for coastal production	Oyster reef as ecosystem engineer- its role in coastal protection or erosion inhibition, and wave dampening effect (Oesterdam, Viane)
Coastal protection - Salt marshes	Densely vegetated patches in front of the dyke to dampen wave forces and facilitate sedimentation rise to soil bed level
Nature – supporting coastal systems integrity	Interventions to support ecosystem or ecological functioning for a smoother transition from one habitat or ecosystem to another. This is the ability of a coastal ecosystem to maintain its ecological functions, biodiversity and

	resilience while supporting human and environmental needs in the face of natural and anthropogenic changes.
Nature – vital for ecological high structure	Connectivity in ecosystem or ecological functioning for a smoother transition from one habitat or ecosystem to another
Nature - recovery	Recolonisation of disturbed areas (natural or anthropogenic)
Nature - compensation	Habitat creation (dyke-realignments) or enhancements through interventions such as groins to reduce the flow velocity or facilitate sedimentation. Nourishments can also raise bed levels and expand the availability or size of dry habitats (Perkpolder, Hedwigepolder).
Nature – support conservation objectives	For reef formation, as specific bird sanctuaries- high water resting areas and/ or refuges, foraging areas during low tide, and nesting areas (dry land); and as bird foraging locations
Carbon storage	Tidal marsh restoration or (vegetation) development and habitat creation- can be nature-based and/or through human interventions

The list of 72 indicators (Table 7.1) may contribute to a future framework of indicators to assess characteristics of transitions of salinization interventions in coastal transition zones (Table 6.1). Many specific coastal indicators are yet in development or not well quantified, and thus not tailor made for salinization aspects. During the process it was identified that focus to address specific salinization and coastal land use was relevant. Therefore, a scientific paper: "Too salty to farm: Rethinking coastal land use in response to soil salinization" (Velilla et al., 2024, Under review) was submitted. This paper addressed conventional agriculture towards nature-based approaches as a more sustainable alternative, such as the restoration of intertidal and estuarine ecosystems. These nature-based approaches harness natural processes to provide key ecosystem services, including enhanced biodiversity, carbon sequestration, flood protection, and improved water quality, often surpassing the benefits of maintaining degraded farmland (Velilla et al., 2024, Under review). A single case study of Plan Tureluur was reported to show case assessment of the ES provided.

6.4 Conclusion and Recommendations

Although localized salinization challenges are acknowledged, large-scale salinization is not yet perceived as an urgent concern. Specific regions, particularly those well-documented, experience significant issues, prompting a policy focusing primarily on water management. Stakeholders consistently identified economic performance in agriculture as the dominant factor influencing interventions. Despite evidence to the contrary, efforts predominantly aim at preserving freshwater resources. Concerns are particularly pronounced in deeper peatlands, where soil subsidence due to oxidation exacerbates the issue.

Provincial authorities primarily address salinization from a water management perspective (note, water management stakeholders were consulted in the interviews), believing current conditions are sustainable if water extraction adheres to regulations. Nevertheless, deviations from the rules, such as excessive stress on freshwater lenses, pose a risk for future sustainable freshwater resources. Currently, individual or localised interests often take precedence over collective objectives, leading to emotionally charged and polarised debates that hinder effective policies targeting future climate-proof and resilient ecosystems.

Regarding identified and future land use transition options, proposals align with existing frameworks, with the addition of tourism as a potential opportunity. The stakeholders interviewed uniformly indicated that policy discussions would be fundamentally different if agricultural priorities were less dominant. The key recommendations, also based on stakeholder interviews are summarised in seven points below.

1. Prioritise intervention in areas most vulnerable to salinization, such as coastal regions, that often also have significant ecological value. Focus on the intrinsic strengths of these regions rather than current limitations.
2. Establish participatory processes to enhance stakeholder dialogue, foster mutual understanding, and co-develop solutions. Thus, emphasising adaptive processes over predefined regional goals.
3. Develop integrated, multidimensional solutions such as combining ecosystem services (e.g., ecotourism, nature-based grazing of cattle) with coastal defence mechanisms. Plan Tureluur serves as a prominent example of this approach (as reported in Velilla et al., 2024, Under review).
4. Expand the scope of analysis to include novel land-use functions and revenue models, such as extensive livestock farming or nature- and water-based economic activities.
5. Assess regional food productivity and food security to identify tipping points where traditional agricultural practices become economically unsustainable. These data may provide more actionable insights than current metrics, which are underutilised in policymaking.
6. Promote a transition to multifunctional landscapes with revised land-use patterns, such as shifting from intensive grassland farming to grazing systems or novel landscape configurations informed by future-oriented visions.
7. Explore alternative management measures such as sustainable water management practices driven by societal rather than purely economic considerations. To extend need for land transitions, explore ways to reduce reliance on heavy agricultural machinery to limit soil subsidence. Additionally, subsidy models linking nature conservation to agricultural production, and strategies such as de-poldering, should be coupled with restructured financing mechanisms to address societal challenges.

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7 Supplemental material

Table 7.1: Overview of indicators for ecosystem services applicable to land use transitions in saline areas (ANK, 2023 translated from Dutch language).

Section	**Division**	**Group**	**Class**
Regulatory services	Pollination		Current pollination by all types of pollinators
Manufacturing Services	Wood, fibres and genetic resources	Wood	Current wood production
Manufacturing services	Food	Expected efficiency (%) of agricultural crop production (from NK model)	Current production of arable crops
Manufacturing services	Food	Expected efficiency (%) of agricultural crop production (from NK model)	Current production of fruit
Manufacturing services	Food	Expected efficiency (%) of agricultural crop production (from NK model)	Current production of vegetables
Manufacturing services	Food	Expected efficiency (%) of agricultural crop production (from NK model)	Current production of maize
Manufacturing services	Food	Expected efficiency (%) of agricultural crop production (from NK model)	Current production of grass
Manufacturing services	Food	Indication of the economic value of ESD in food crops	Arable farming for food
Cultural services	Green recreation	Nature reserves and nature value	Amenity value of the landscape
Manufacturing services	Water for other uses	Sprinkling	Irrigation extractions: effect on groundwater seepage
Manufacturing services	Water for other uses	Sprinkling	Irrigation abstractions: from groundwater and surface water
Regulatory services	Coastal protection		Flood protection
Regulatory services	Pollination		Bee diversity in the Netherlands
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Soil carbon stock
Production Services and regulatory Services	Food, soil fertility	Soil supporting production services	Soil fertility for agriculture
Regulatory services	Carbon sequestration	Carbon sequestration by plants	CO_2 sequestration by plants in 2013
Regulatory services	Carbon sequestration	Carbon sequestration by plants	CO_2 sequestration by plants in July 2013
Regulatory services	Carbon sequestration	Carbon sequestration by plants	CO_2 sequestration by plants in March 2013
Regulatory services	Carbon sequestration	Carbon sequestration by plants	CO_2 sequestration by plants in May 2013

Regulatory services	Carbon sequestration	Carbon sequestration by plants	CO_2 sequestration by plants in September 2013
Regulatory services	Water storage	Water storage capacity	The subsoil
Abiotic sources	Mineral springs	Energy and raw materials factory	Mineral extraction at sea; Sand and gravel
Manufacturing services	Drinking water	Problematic substances in drinking water extraction	Drinking water extraction locations where chloride has been designated as a (potential) problem substance
Manufacturing services	Drinking water	Problematic substances in drinking water extraction	Drinking water extraction locations where emerging substances have been designated as (potential) problem substances
Manufacturing services	Drinking water	Problematic substances in drinking water extraction	Drinking water extraction locations where plant protection products have been designated as a (potential) problem substance
Manufacturing services	Drinking water	Problematic substances in drinking water extraction	Drinking water extraction locations where nitrate has been designated as a (potential) problem substance
Manufacturing services	Drinking water	Problematic substances in drinking water extraction	Drinking water extraction locations where old contaminants have been identified as (potential) problem substances
Manufacturing services	Drinking water	Drinking water extraction	Drinking water abstraction from groundwater
Regulatory services	Life cycle protection	Distribution maps	Large seagrass (*Zostera marina*) in 2011
Regulatory services	Life cycle protection	Distribution maps	Small seagrass (*Zostera noltii*) 2011
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Carbon sequestration in the soil when leaving crop residues behind
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Carbon sequestration in the soil in field edge management
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Carbon sequestration in the soil with green manure
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Carbon sequestration in the soil in non-inversion tillage
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Carbon sequestration in the soil when grassland is not torn
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Carbon sequestration in the soil when improving crop rotation
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Carbon sequestration in the soil without tillage
Regulatory services	Carbon sequestration	Carbon sequestration in the soil	Carbon sequestration in soil- total of all measures
Regulatory services	Pest suppression		Crops
Manufacturing services	Food	Opportunities for fisheries and aquaculture	Macro-algae production in the North Sea (*Laminaria digitata*)
Manufacturing services	Food	Opportunities for fisheries and aquaculture	Macro-algae production in the North Sea (*Saccharina latissima*)
Regulatory services	Pollination		Potential supply of pollination by all pollinators
Production services and	Food, pollination	Soil supporting production services	Potential supply of natural pollination

regulatory services			
Manufacturing Services	Biomass for energy	Potential biogas	Potential biogas from residual flows of arable farming (GJ/ha/ year)
Manufacturing Services	Biomass for energy	Potential biogas	Potential biogas from liquid manure (GJ/ha/ year)
Regulatory services	Cleaning soil, water, air	Air	Potential capture of particulate matter (PM10) by vegetation
Manufacturing services	Food	Soil supporting production services	Potential Natural Pest Regulation
Manufacturing services	Food	Soil suitability for agricultural crop production (from NK model)	Potential production of arable crops
Manufacturing services	Food	Soil suitability for agricultural crop production (from NK model)	Potential production of fruit
Manufacturing services	Food	Soil suitability for agricultural crop production (from NK model)	Potential production of vegetables
Manufacturing services	Food	Soil suitability for agricultural crop production (from NK model)	Potential production of maize
Manufacturing services	Food	Soil suitability for agricultural crop production (from NK model)	Potential production of grass
Regulatory services	Lifecycle protection	Distribution maps	Earthworms in the Netherlands (abundance)
Manufacturing services	Wood, fibres and genetic resources	Biomass	Reed and heather
Manufacturing services	Food	Opportunities for fisheries and aquaculture	Shellfish plots 2014
Regulatory services	Life cycle protection	Distribution maps	Beaked ruppia (*Ruppia maritma*)
Regulatory services	Life cycle protection	Distribution maps	Species diversity in the Netherlands
Manufacturing services	Wood, fibres and genetic resources	Biomass	Stem and leaf residues (not straw) from agriculture
Manufacturing services	Wood, fibres and genetic resources	Biomass	Straw from agriculture
Manufacturing services	Food	Indication of the economic value of ESD in food crops	Horticulture for food
Manufacturing services	Drinking water	Problematic substances in drinking water extraction	Change in nitrate concentration in groundwater (5-15 m deep)
Manufacturing services	Water for other uses	Sprinkling	Avoided reduction of crop evaporation as a result of irrigation
Manufacturing services	Drinking water	Problematic substances in drinking water extraction	Salinization of groundwater
Manufacturing services	Drinking water or water for other uses	Problematic substances in drinking water extraction or Shortage of freshwater	Salinization of surface water
Regulatory services	Water storage	Remainder	Moisture supply through the soil
Regulatory services	Cleaning soil, water, air	Bottom	Progress soil investigation and remediation

Manufacturing services	Food	Theoretical value of agricultural crop production with subsidies (from NK model)	Value of current production of arable crops with subsidies
Manufacturing services	Food	Theoretical value of agricultural crop production without subsidies (from NK model)	Value of current production of arable crops without subsidies
Manufacturing services	Food	Theoretical value of agricultural crop production with subsidies (from NK model)	Value of current production of fruit with subsidies
Manufacturing services	Food	Theoretical value of agricultural crop production without subsidies (from NK model)	Value of current production of fruit without subsidies
Manufacturing services	Food	Theoretical value of agricultural crop production with subsidies (from NK model)	Value of current production of vegetables with subsidies
Manufacturing services	Food	Theoretical value of agricultural crop production without subsidies (from NK model)	Value of current production of vegetables without subsidies
Manufacturing services	Food	Theoretical value of agricultural crop production with subsidies (from NK model)	Value of current production of maize with subsidies
Manufacturing services	Food	Theoretical value of agricultural crop production without subsidies (from NK model)	Value of current maize production without subsidies
Regulatory services	Water storage, cleaning capacity for soil, water and air	Other or water	Water regulation subsurface
Regulatory services	Cleaning soil, water, air	Water	Water-purifying effect of soil organisms in the Wadden Sea
Regulatory services	Cleaning soil, water, air	Bottom	Self-cleaning capacity in the top layer of the soil (relative)

Table 7.2: Interview template for discussion with stakeholders on dealing with transitions on salinized agricultural areas. Aim of the interviews was to identify how different stakeholders, such as freshwater farmers, saltwater farmers, water managers, spatial planners, water boards envision the future of salinizing agriculture areas. How stakeholders see the progress of salinization in their area of influence. These questions are aimed at understanding both the current and future landscape of salinization, and how various stakeholders are responding to this environmental challenge.

Name of interviewee:

Function :	
Role:	
Interviewer:	
Date:	
Estimated time	**60 minutes**

Interview Questions

1) **Current Perceptions of Salinization**

How do you perceive the current level of salinization in your area of influence (whether it be freshwater or saltwater agriculture, water management, or spatial planning)?

Have you noticed significant changes in salinity levels over time (seasonally or from year to year), and what factors do you believe are driving or influencing these changes?

2) **Impact on Agriculture**

How is salinization currently impacting agricultural productivity in your region?

For farmers and other users: In what way is salinization impacting agricultural productivity e.g., decrease in yield or quality per crop, land degradation?

For water managers and planners: How does salinization affect your approach to resource management and land-use planning?

3) **Current Mitigation/ Adaptation Strategies**

What strategies are currently being implemented to manage or mitigate the effects of salinization?

How effective have these strategies been so far, and what improvements or changes do you think are needed?

4) **Future Outlook on Salinization**

How do you foresee the progression of salinization in your region over the next 5-10 years?

What actions or policies do you believe are necessary to address salinization in the short or midterm?

5) **Alternative Land Use Options**

Under highly saline conditions, what other land use options do you see as feasible for the region (e.g., salt tolerant crops, aquaculture, wetland restoration, phytoremediation)?

What considerations (such as coastal defence, habitat restoration, etc) are taken into account when deciding on new land use functions in salinized areas?

6) **Transitioning to New Land Uses**

What are the key challenges you or your organization face when transitioning to alternative land uses in response to salinization?

How can these transitions be supported, either through policy, funding, or technology?

7) **Relevant Parameters for Land Use Decisions**

What parameters or factors are most important when considering land use transitions in salinized areas (e.g., ecosystem services, carbon sequestration, nitrogen regeneration, flood control, biodiversity)?

How do you (prioritise) the economic, environmental, and social impacts of potential land use changes in decision making?

8) **Collaboration and Support Needs**

What kind of collaboration is needed among stakeholders (farmers, water boards, planners, etc.) to address the challenges posed by salinization? (e.g. Collective collaborations, top-down approaches, or bottom-up processes).

How can governments, research institutions, or private sector players better support your efforts to adapt to salinization?

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