Stichting de Zilte Smaak

Study on the future agricultural possibilities for the polder of Terschelling

The suitability of animal feed and traditional crops for cultivation on saline soil and future salinization in the polder of Terschelling by the year 2100.

Research Report Bachelor Thesis

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Abstract

The salinization of soil is a major soil degradation process threatening ecosystems and is recognized on a global level as one of the most important problems regarding agricultural production, food security and sustainability in both arid and semi-arid regions. The salinization of soil is caused by factors such as climate change, rising sea levels, droughts and the use of traditional farming methods for fertilization and irrigation. In the Netherlands the salinization of soil can mainly be noticed along the coastal areas and is mostly caused by the entering of salt water into the system through surface water and the rising of brackish groundwater to the surface. With the soil becoming more saline and the food security jeopardized the traditional way of agriculture is looking at a transition to more saline agriculture. This study researched how the polder of Terschelling will be affected by salinization by the year 2100. The research studied which crops are able to be cultivated on saline soil, where specific crops are still able to grow by the year 2100 and which parts of the polder could possibly be saline by the year 2100 at three different depths. A literature research showed that eleven animal feed crops are salt-tolerant at a 100% yield and seven crops are salt-tolerant at a 10% yield loss. For the traditional crops there are eight crops salt-tolerant at a yield of 100% and ten crops at a 10% yield loss. Using QGIS and an intermediate model provided by Deltares the assumption can be made that the phreatic groundwater will still be mostly suitable for traditional agriculture. At -0.5 NAP and -6.5 NAP however, most of the soil will be unsuitable for traditional agriculture. For both animal feed and traditional crops could be seen that there will be more suitable soil in the polder at the threshold value of a 10% yield loss than there are at the threshold value of a 100% yield. Based on the results it could be concluded that traditional agriculture is still going to be possible in the polder of Terschelling by the year 2100. Nonetheless, if farmers want to use the full potential of the polder they will need to start with saline agriculture before the year 2100.

1. Introduction

Salinization of soil is a worldwide problem originating from a multitude of conditions such as climate change and the use of traditional farming methods for fertilization and irrigation (Saline Agriculture Worldwide Knowledge Centre, n.d.-b). The salinization of soil is a major soil degradation process, it threatens ecosystems and is recognized on a global level as one of the most important problems regarding agricultural production, food security and sustainability in both arid and semi-arid regions (Food and Agriculture Organization of the United Nations, n.d.-a). At the moment Australia, the Middle East, Eurasia and Africa are most affected by salinization, though all around the world salt-affected soils can already be found (Food and Agriculture Organization of the United Nations, n.d.-b). It is estimated that 50% of all arable land worldwide will be affected by salinization by 2050 (Snethlage et al., 2023). With this estimated future prospect, agriculture as we know it know might be looking at a transition instigated by the salinization of soil.

1.1 What is salinization

Salinization is the increase or accumulation of salts in soil (Saline Agriculture Worldwide Knowledge Centre, n.d.-b) and can be caused by a multitude of processes, both natural and human induced. Causes of salinization are sea level rise, irrigation with salt rich water, quick evaporation of water causing salt to remain at the surface (Cherlinka, 2021), drought and seepage of brackish groundwater or seawater through the soil from below (Saline Agriculture Worldwide Knowledge Centre, n.d.-b). The salts that accumulate in the soil consist mainly of magnesium, calcium, sodium, potassium, sulfate, chloride, carbonate and bicarbonate (Zamora Re et al., 2022). Of these eight salts, sodium is the main causative agent of salinization (Zia et al., 2021).

1.2 Salinization in the Netherlands

Located on the North side of the Netherlands lies the Wadden Sea and located on the West side of the Netherlands there is the North Sea (TU Delft, n.d.). The West and the North part of the Netherlands are also the regions most confronted with salinization as can be seen in figure 1 (Kenniscentrum InfoMil, n.d.). Figure 1 shows which areas in the Netherlands have a scarce amount of fresh water. The redder the area the more scarce fresh water is. Salinization in the Netherlands is mostly caused by two factors, namely: the rising of brackish groundwater to the surface and saltwater entering the system through surface water. The rising of brackish groundwater to the surface often happens in the lower parts of the Netherlands. As result, the brackish groundwater ends up in the groundwater or surface water causing the soil, surface water and groundwater to become more saline (see figure 2). It is expected that this process will speed up in the coastal areas as a result of the combination of the rising sea level and the subsidence of the soil, causing there to be more pressure from the sea on the groundwater (Helpdesk water, n.d.).

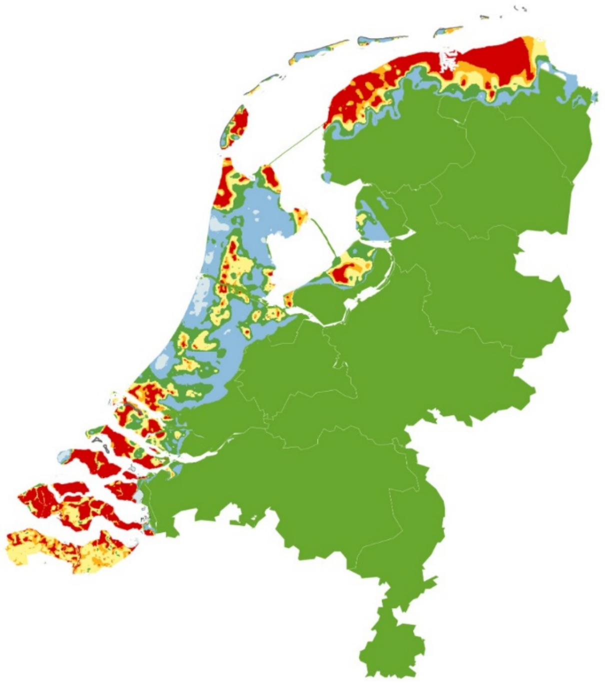


Figure 1. Map showing the salinization in the Netherlands. The redder an area, the more scarce fresh water is (Deltares, 2021).

The second way is by saltwater entering the system through the surface water at for example rivers or sluices. Especially when there is a drought and little river discharge, it allows for the saltwater to flow further inland (Helpdesk water, n.d.).

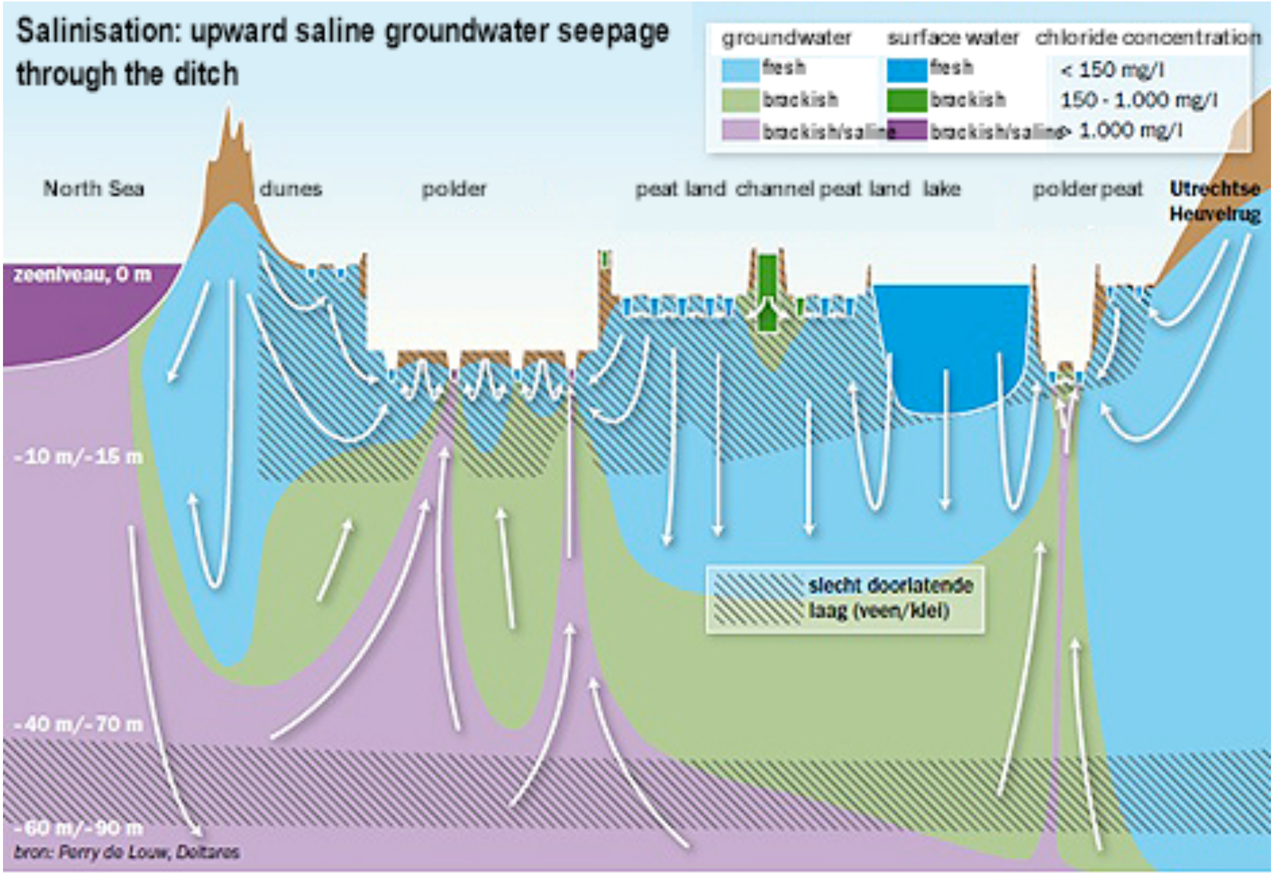


Figure 2. Figure showing the process of how brackish groundwater rises to the surface(Stowa, n.d.).

1.3 Effects of salinization

The salinization of water and soil has a multitude of consequences for the Netherlands. One of the consequences is that the availability of drinking water is threatened by salinization, this is due to salinization of drinking water having a negative impact on the taste and the quality of the water.

With the water getting more saline it can cause technical installations in both corporations and houses to erode and wear faster. Salinization can form a risk for ecosystems as well, this is because a large number of organisms can only deal with certain variations in salinity. When these organisms are exposed to a too high salinity for a period of time it could lead to both temporary as well as permanent damage to the organism (Informatiepunt Leefomgeving, n.d.).

Salinization also has an effect on agriculture which is often seen as a negative effect. With the traditional form of agriculture fresh water is needed for crops to grow well. One of the problems for the crops regarding salinization is in the way that crops take up water. Plants take up water through their roots by a process called osmosis. The process of osmosis is based on the level of salt maintained in the water inside the plant and the level of salt in the soil water. Water will go to the place with the highest salt level. This means that if the soil water gets too saline, the water from the plant can flow from the roots back into the soil, causing the plant to dehydrate which may result in a declining harvest or even for the plant to completely die off (Queensland Government, 2013). Another saline factor that can have an effect on crops is salt spray, salt water from the sea that is blown land inward by the wind. Salt spray can have multiple negative impacts on plants, namely: salt burn on leaves, small twigs and buds. The bud scales can also get dehydrated resulting in exposure of tender tissue such as developing flowers and leaves leaving them to dry out (Bayer & Njue, 2016).

Cattle farmers too experience negative effects of salinization, especially if they have dairy cattle. It appears that cattle such as sheep and beef do not immediately experience problems if the salinity value rises, however the advice for highly productive dairy cattle is to not give them water with a salinity percentage of more than 0.3% (Visscher, 2012). Most dairy farms located in the Netherlands use a roughage supply based on pasture production and a varying part of silage corn. Grass has quite a reasonable salt tolerance though there will be a declining pasture production if salinization were to strongly increase. A change in botanical composition of the pasture can also be the cause for a lower (net)pasture production. This change in botanical composition is also a result of salinization and rewetting of the soil and groundwater.

Grass species that have a moderate valuation like creeping bentgrass (*Agrostis stolonifera*) and rough bluegrass (*Poa trivialis*) repress higher valuated grass species like perennial ryegrass (*Lolium perenne*). The moderately valued grass species have a lower yield and feed quality than the higher evaluated grass species. To compensate for feeding dairy cows with the moderately valued grass species, the farmer needs to buy better roughage or higher concentrated feed to prevent a decline in dairy production. The mineral composition of roughage can also become less optimal due to salinization, this can for example be expressed in to high Na- or Cl-values (Visscher, 2012).

1.4 Solutions

Saline agriculture could be a possible solution regarding the salinization of agricultural grounds. Saline agriculture can consist of two things, either food or crops are produced on soil that has been salt-affected or the crops get irrigated with brackish or salt water. For a long time it was thought that it was impossible to culture crops on saline soil, however it appears there are crops that are more salt-tolerant. Growing salt-tolerant crops in combination with alternative techniques in fertilization, irrigation and water management makes agriculture on salt-affected soil possible (Saline Agriculture Worldwide Knowledge Centre, n.d.-a). The crops used or studied for saline agriculture consists of two types of crops. The first category are the traditional crops or cultivars that already have a higher salt tolerance or can be made more salt-tolerant. The second category are the halophytes, this are plants that are already salt-tolerant of themselves like samphire (*Crithmum maritimum*) (Bergkamp et al., 2018).

The salt-tolerance of crops are influenced by multiple factors, under which climate, soil type and way of irrigation. With climate, the focus is mainly on seasonality and amount of rainfall as the rain can leach the salts from the soil. The importance of soil type lies in the effect the type of soil has on the drainage characteristics in the rootzone, which on their part have an effect on the leaching and accumulation of salts in the soil. The frequency and method of irrigation used (overhead sprinkler, drip, flood or surface) influences the salt-tolerance as well (NSW Department of Primary Industries, 2017). Another matter to keep in consideration is that certain varieties, rootstalks or cultivars may be able to tolerate higher salt levels than others. Crops are most sensitive to higher salinity levels immediately after transplanting, when still in the seedling stages. Crops are also really sensitive to high salinity levels when undergoing stresses from for example insects, nutrients or disease (Amacher et al., 2000)

1.5 Stichting de Zilte Smaak

Established in 2017 Stichting de Zilte Smaak is a foundation that has as goal to cultivate saline and salt-resistant crops in a sustainable manner, to gather and share knowledge on the topic and to make these crops and their possibilities more known, using Terschelling as a demonstration plot. The island Terschelling is one of the five inhabited Wadden islands located on the North of the Dutch coast. It is the second largest island of the five with a length of 28,6km and a maximum width of 4,4km (Terschelling.org, n.d.).

On the moment there are only cattle farmers located on the island, there is no agriculture except for some vegetable gardens for personal use and one picking garden (Volunteers Stichting de Zilte Smaak, personal communication, September 6, 2023). The loss of agriculture on Terschelling happened after the second world war. The agricultural sector in the Netherlands scaled up and thereafter was the matter of land consolidation. After these two processes the agricultural sector completely disappeared from Terschelling (Gorter, n.d.).

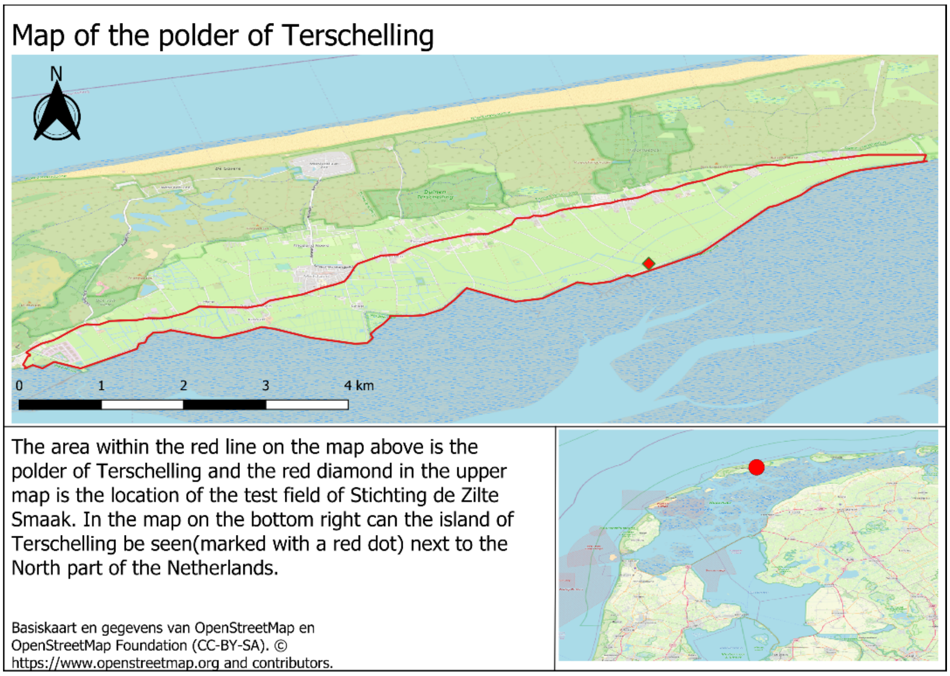


Figure 3. Map of the polder of Terschelling. The area within the red lines is the research area of this study.

The foundation set up a field on the most saline part of meadow in the polder of Terschelling to promote and develop saline agriculture (figure 2). Using the yield of the field they try to develop and manufacture consumer products (Stichting de Zilte Smaak!, n.d.; P. Vellinga personal communication, September 4, 2023). Deltares is currently also conducting a research on Terschelling and part of that research is making a model that shows the salinity of the soil in chloride concentration in grams per liter (g/l) for the whole island in the year 2050 and 2100. For this research they were kind enough to share the intermediate results of the year 2100, making it possible to study which areas of the polder of Terschelling are unsuitable for traditional agriculture by the year 2100 but suitable for saline agriculture. This research will look at the salinity of the phreatic groundwater and the groundwater at a depth of -0.5 NAP. Phreatic groundwater is groundwater that at the top is confined by the atmosphere, meaning it is the upper layer of groundwater. At the bottom phreatic groundwater can be confined by an impermeable layer such as clay (Ecopedia, n.d.)

1.6 Problem statement

The Netherlands are already affected by salinization and this will only increase in the future. This can have negative effects on the traditional way of agriculture and open opportunities for saline agriculture. This study focuses on the polder of the Dutch island Terschelling and wants to know in which areas traditional agriculture and cattle farming can continue there. For it is currently unknown which parts of the polder of Terschelling would be suitable for agriculture by the year 2100 and which animal feed crops and traditional crops can be cultured on saline soil.

1.7 Aim

The aim of this research is to give suggestions to Stichting de Zilte Smaak on which parts of the polder are unsuitable for the traditional way of agriculture and cattle farming in 2100 and are suitable for saline agriculture based on the model provided by Deltares. And to be able to inform Stichting de Zilte Smaak on which animal feed crops and traditional crops can be cultured on saline soil. Stichting de Zilte Smaak can pass along these results to the consortium[1] of the research project Handelingsperspectief Klimaatadaptatie Landbouw Terschelling.

1.8 Research questions

Main question:

Which parts of the polder on Terschelling are in 2100[2] less suitable for the traditional way of agriculture and cattle farming and are suitable for the cultivation of saline crops and which animal feed crops and traditional crops can be cultivated on saline soil?

Sub questions:

1. What is the salt-tolerance of perennial ryegrass[3] and are there animal feed crops that are more salt-tolerant and profitable?
2. Which traditional crops can potentially be used for saline agriculture?
3. Which parts of the polder are less suitable for the traditional way of agriculture and cattle farms based on the 2100 salinization scenario from Deltares?
4. Which parts of the polder are suitable for the cultivation of the salt-tolerant crops found at sub question 1&2 by the year 2100?

[1] The consortium consists of Van Hall Larenstein University of Applied Sciences, Deltares, Wetterskip Fryslân, the municipality of Terschelling, Provincie Fryslân, Netherlands Bird Protection, Staatsbosbeheer, LTO-Noord, Agrarisch Belang Terschelling, Agrarishe Natuurvereniging (ANV) Waddenvogels, DLF Seeds and Science, Dairyfarm C.G. Cupido, Terschellinger Campinghouders Vereniging, Stichting de Zilte Smaak, Vitens, Vogelwacht Terschelling, Acacia Water and Wageningen Economic Research (part of Wageningen University & Research) (H2O, 2022).

[2] According to the salinization model (intermediate results) by Deltares.

[3] Of all grass species perennial ryegrass was chosen as reference crop because it is the grass species most often used in the Dutch agricultural sector.

2. Materials & Methods

2.1 Materials

- QGIS 3.28.10
- Laptop/computer
- Search engines
- Models provided by Deltares on salinization of Terschelling of the phreatic groundwater and on -0.5 NAP and -6.5 NAP pf of the year 2100.

The intermediate models of Deltares were made using iMOD-WQ, version 5.4, which contains the often used software code SEAWAT for density driven sweet and salt groundwater modeling. The models were made up of multiple modflow-packages in which the physical components of the subsoil and (ground)water systems were schematized. After the models were put toghether they were further calibrated. After this they were calculated with the sealevel rise and climate change to be able to make calculations for the year 2100 (V. Kaandorp, personal communication, January 9, 2024)

2.2 Methods

A literature review was performed to answer sub question one on what the salt-tolerance of perennial ryegrass is and if there are animal feed crops that are more salt-tolerant and profitable and sub question two on which traditional crops could potentially be used for saline agriculture. This literature review consisted almost completely of searching online for information. This information consisted among others of: what is the salinity threshold of perennial ryegrass, which crops can be/are used as animal feed, the salinity level/threshold of crops and yield loss of crops cultivated on saline soil. The search engines google, google scholar and Greeni were used to search for online scientific articles, documents and reports. In case that information could not be found online, experts regarding agriculture, cattle farming and saline agriculture were asked for information. Down below is a list with search terms used to answer sub question one and two:

- Saline agriculture
- Salt-tolerant crops
- Salinity threshold for agricultural crops
- Salt-tolerance of perennial ryegrass
- Is saline agriculture profitable
- Salt-tolerant animal feed
- Animal feed crops

Based on the literature review two tables were made, one for animal feed crops and one for traditional crops. For both these tables the crop name and the salinity threshold value and salinity class at both a 100% yield and a 10% yield loss were noted down. For animal feed was also looked at and noted down whether or not the crop had a higher threshold value than perennial ryegrass. For the traditional crops was also looked at whether or not the crops could be used for saline agriculture.

In most research reports and articles the measure of salinity is reported in either electrical conductivity, EC or in deci-Siemens per meter, dS/m (Landscape South Australia - Murraylands and Riverland, 2015). EC can be written as EC_e as well, in which case it stands for estimated electrical conductivity. The unit dS/m is used for the soil salinity and mili-Siemens per metre, mS/m is used for the water salinity. The conversion of water salinity to soil salinity is 100mS/m = 1dS/m (Department of Primary Industries and Regional Development's - Agriculture and Food, 2022). Soil is considered saline once the EC_e reaches 4dS/m or higher (Negacz et al., 2022). In table 1 the salinity class and the corresponding EC_e range are shown.

Table 1. This table shows the soil salinity class and the corresponding EC_e range in dS/m (Department of Primary Industries and Regional Development's - Agriculture and Food, 2022).

Salinity class	***EC_e range (dS/m)***
Non-saline	0-2
Slightly saline	2-4
Moderately saline	4-8
Highly saline	8-16
Severely saline	16-32
Extremely saline	>32

Sub question three regarding which parts of the polder will be less suitable for the traditional way of agriculture and cattle farms based on the model from Deltares, together with sub question four, which parts of the polder are suitable for the cultivation of the salt-tolerant crops found at sub question 1&2 by the year 2100 were answered using QGIS version 3.28.10 and models provided by Deltares on the salinization of Terschelling by the year 2100. The models were opened in QGIS. In QGIS the chloride concentration in grams per liter (g/l) for each area of Terschelling could be seen.

Information gathered from these models was used to make an estimation on which parts of the polder of Terschelling will be less suitable for traditional agriculture and cattle farming by the year 2100 and will be suitable for saline agriculture. This was done for the phreatic groundwater and -0.5NAP and -6.5NAP. As agriculture is considered saline agriculture if the crops are cultivated on saline soil (EC_e of soil is 4dS/m or higher) areas were considered as less suitable for traditional agriculture and cattle farming once the EC_e dS/m was equal to or higher than 4dS/m. Areas above 4dS/m were considered suitable for saline agriculture. Once this information was gathered, a map of the polder of Terschelling was made in which the areas suitable for traditional and saline agriculture were mapped out.

- In this research the salt-tolerance is the threshold value of a crop: the soil salinity level at which yield-reducing effects could be noticed in crops (Amacher et al., 2000).
- Regarding sub question one, profitability was looked at by comparing the threshold value at which a 10% yield loss occurs. The higher the threshold value at 10% yield loss, the higher the profitability.
- Crops were considered saline crops if they had a salinity threshold of EC_e 4dS/m or higher.
- The term traditional agriculture in this research means agriculture on non-saline soil.
- For sub question three and four, in the model provided by Deltares, the variable salinization is expressed as chloride concentration in grams per liter (g/l).
- The abbreviation NAP stands for Normaal Amsterdams Peil which is the same as Amsterdam Ordnance Datum (AOD) (Stichting Normaal Amsterdams Peil, n.d.).
- For sub question three, suitability was when the soil salinity was below EC_e 4dS/m.
- For sub question four, suitability for the cultivation of saline crops was when the soil salinity was below the salinity value of the specific crop. EC_e values equal to or higher than the threshold value were considered unsuitable.

2.3 Data analysis

2.3.1 Sub question 1/2

- Sub question one was formulated to get more information on which animal feed crops could potentially be salt-tolerant and cultured on saline soil. Since perennial ryegrass is the grass species most often used in the Dutch agricultural sector it was decided to study if there would be other animal feed crops that could have a higher salt-tolerance than perennial ryegrass and might be more profitable to culture in the future than perennial ryegrass. However this question was also needed to answer sub question four.
- Sub question two was formulated to get an idea of which traditional crops could be cultured on saline soil and what the crops their salt-tolerance would be. Since traditional crops are often crops people consume and it would thus be important to know which crops can still be cultivated in a scenario where the soil has become saline. This information would also be needed to answer sub question four and the main question regarding the matter of which parts of the polder on Terschelling will be 2100 less suitable for the traditional way of agriculture
- The unit EC_e was used since this unit is most often used in research regarding the response of plants on salinity levels (Department of Primary Industries and Regional Development's - Agriculture and Food, 2022).
- The choice to take the value $EC_e >= 4$dS/m as the value at which crops are considered saline was made based on the fact that soil is considered saline at this value. This is stated in research of Yan and Marschner (2013) and Negacz et al. (2022). So if the soil is considered saline at this value or higher than crops that can grow on soil with a value of 4 dS/m or higher can be considered saline.
- The crops studied in this research were chosen based on the fact that this are crops that can be cultivated in the Netherlands.
- The decision to take a 10% yield loss as the baseline for profitability was made based on the idea that if this is the loss on a whole harvest the farmer might accept it, however if the loss is higher than 10% a farmer might not even want to sow this crop because the loss they will suffer is too big compared to the profits they make.

2.3.2 Sub question 3

- Sub question three was written down to see if the polder of Terschelling would be mostly consisting of saline soil or not. If almost no soil within the polder of Terschelling would be saline by the year 2100 than answering sub question four would be of little use since in that case all traditional crops could still be cultured in the polder of Terschelling.

2.3.3 Sub question 4

- Before answering sub question four, all threshold values needed to be transformed from (EC_e (dS/m)) to chloride concentration in gram per liter, since this was the unit used in the models provided by Deltares. To do this the following calculations were used:
  G/L = EC (dS/m) x 640 (EC from 0.1 to 5 dS/m):1000
  G/L = EC (dS/m) x 800 (EC > 5 dS/m):1000
  The answers were rounded to two decimal places. The new values can be found in tables 4 and 5 in the green columns.
- Sub question four was formulated based on the fact that the crops could each have different salt-tolerances, meaning that if the polder did get saline it would not guarantee that all saline crops could automatically be cultured throughout the whole polder. This made it interesting to study for each individual crop where exactly in the polder they could grow.

- Based on the results of sub question three, it was decided to only look at the groundwater at -0.5NAP for sub question four. -6.5NAP was too deep for roots to reach (Fan et al., 2016) so it was of no use to look at which crops could grow where at this depth. Since -0.5NAP is at a depth which the roots reach(Fan et al., 2016) and had more salinization than the phreatic groundwater based on the results of sub question three, it made sense to only look at -0.5NAP.
- For sub question four, it was decided to put foxtail millet and millet in one figure, since for both crops only the threshold value at a 100% yield was known and this was for both crops the same value, namely 6.0 EC_e .

4.Results

4.1 The salt-tolerance of perennial ryegrass and animal feed crops that are more salt-tolerant

This research did not look at more salt-tolerant grass species as this is already part of a running Deltares-WUR/VHL project (P. Vellinga personal communication, September 25, 2023). Instead this research focused on other salt-tolerant forage crops that could be cultured in the Netherlands.

Perennial ryegrass is the most used/cultured grass species in Dutch meadows (Feenstra, 2014) and is the most commonly used species to feed dairy cows with. The reason for this is that perennial ryegrass has a high productivity, digestibility and nutritive value (Taweel, 2004). Since perennial ryegrass is the most cultured and most used grass species for animal feed, it was decided to look at crops that could still be cultured on saline soil if the soil salinity were to become too high for perennial ryegrass. Looking at the threshold value of perennial ryegrass, it starts to show a decline in yield at a salinity level of 5.6 EC_e. Looking at table 2 it would mean that perennial ryegrass can endure moderately saline soil.

Table 2. The table shows the salinity threshold value together with the corresponding soil salinity class of all mentioned crops along with whether or not the threshold value is higher than that of perennial ryegrass. The EC_e (dS/m) value at which a 10% yield loss occurs and whether or not the threshold value is higher than that of perennial ryegrass is given for the crops of which this information could be found.

Crop	Threshold value at a 100% yield (EC_e (dS/m))	Soil salinity class at a 100% yield	Threshold value at a yield loss of 10% (EC_e(dS/m))	Soil salinity class at a 10% yield loss	Higher threshold value than perennial ryegrass at a 100% yield	Higher threshold value than perennial ryegrass at a 10% yield loss
Perennial ryegrass[1]	5.6	Moderately saline	6.9	Moderately saline	-	-
Alfalfa[1]	2.0	Non/slightly saline	3.4	Slightly saline	No	No
Barley[1]	5.3	Moderately saline	7.4	Moderately saline	No	Yes
Birdsfoot Tre-foil[1]	4.0	Slightly/mod-erately saline	6.0	Moderately saline	No	No
Clovers (Ber-seem)[1]	1.5	Non-saline	3.2	Slightly saline	No	No
Clovers (Straw-berry)[1]	5.0	Moderately saline	8.0	Moder-ately/highly saline	No	Yes
Clovers (Alsike, Ladino, Red)[1]	1.3	Non-saline	2.3	Slightly saline	No	No
Corn (silage)[1]	1.8	Non-saline	2.7	Slightly saline	No	No
Field Peas[1]	1.3	Non-saline	2.0	Non/slightly saline	No	No
Fodder beet[2]	15	Highly saline	-	-	Yes	-
Foxtail millet[3]	6.0	Moderately saline	-	-	Yes	-
Millet[3]	6.0	Moderately saline	-	-	Yes	-
Oats(forage)[1]	2.6	Slightly saline	3.2	Slightly saline	No	No
Rye (forage)[1]	2.5	Slightly saline	3.5	Slightly saline	No	No

Sorghum[1]	4.0	Slightly/moderately saline	5.1	Moderately saline	No	No
Soybeans[4]	5.0	Moderately saline	-	-	No	-
Sweet clover[1]	4.0	Slightly/moderately saline	6.0	Moderately saline	No	No
Triticale (forage)[1]	6.1	Moderately saline	8.1	Highly saline	Yes	Yes
Turnip[1]	0.9	Non-saline	1.9	Non-saline	No	No

*This data serves only as guideline since the salinity-tolerance of crops is influenced by soil type, climate, and irrigation and the salinity-tolerance can vary per specific crop variety.
*Sources: 1, (Amacher et al., 2000), 2, (Yolcu et al., 2021), 3, (Mushtaq et al., 2021), 4, (Phang et al., 2008)

Looking at table 2 it seems that only a four crops have a higher salinity threshold value than perennial ryegrass (5.6 EC_e) which are fodder beet (15 EC_e), foxtail millet (6.0 EC_e), millet (6.0 EC_e) and triticale (forage)(6.1 EC_e). Of these five crops (including perennial ryegrass) fodder beet has the highest threshold value of all with a threshold value of 15 EC_e. With this high threshold value, fodder beet is capable of growing on highly saline soil without experiencing yield loss. Two other crops are capable of growing on highly saline soil though with a 10% yield lose, those are clovers (strawberry) and tritacle (forage).

All crops which can be cultivated on saline soil are: perennial ryegrass, barley, birdsfoot trefoil, clovers (Strawberry), fodder beet, foxtail millet, millet, sorghum, soybeans, sweet clover and triticale (forage).

The salinity threshold value at which a 10% yield loss occurs could not be found for all crops. Of all the crops this value could be found for, only three have a higher salinity value than perennial ryegrass (6.9 EC_e), namely: barley (7.4 EC_e), clovers (strawberry)(8.0 EC_e) and triticale (forage)(8.1 EC_e). Of these three crops, triticale (forage) ends up having the highest salinity value with a value of 8.1 EC_e.

All crops that can be cultivated on saline soil with a 10% yield loss are perennial ryegrass, barley, birdsfoot trefoil, clovers (strawberry), sorghum, sweet clover and triticale (forage).

4.2 Traditional crops suitable for saline agriculture

In the Netherlands a vast variety of crops is cultivated, however not all of these crops can endure saline soil. In the table below, a list of crops cultivated outside on open ground in the Netherlands has been put together to see which crops can be used for saline agriculture (EC_e >= 4dS/m) and which not.

Table 3. This table shows a large portion of traditional crops cultivated in the Netherlands. For both a 100% yield and a 10% yield loss the threshold value per crop, with the accompanying soil salinity class is given as well as whether or not the crops can be used for saline agriculture.

Crop	Threshold value at a 100% yield (EC_e(dS/m))	Soil salinity class at a 100% yield	Threshold value at a yield loss of 10% (EC_e(dS/m))	Soil salinity class at a 10% yield loss	Can be used for saline agriculture at a 100% yield	Can be used for saline agriculture with a 10% yield loss
Asparagus	5.0	Moderately saline	8.0	Moderately /highly saline	Yes	Yes
Barley*	8.0	Moderately/highly saline	9.6	Highly saline	Yes	Yes
Beans	1.0	Non-saline	1.5	Non-saline	No	No
Beets	5.3	Moderately saline	8.0	Moderately /highly saline	Yes	Yes
Broccoli	2.7	Slightly saline	3.5	Slightly saline	No	No
Cabbage	1.8	Non-saline	2.8	Slightly saline	No	No
Corn (grain)*	2.7	Slightly saline	3.7	Slightly saline	No	No
Carrot	1.0	Non-saline	1.7	Non-saline	No	No
Couliflower	2.7	Slightly saline	3.5	Slightly saline	No	No
Celery	1.8	Non-saline	3.5	Slightly saline	No	No
Sweet corn	1.7	Non-saline	2.5	Slightly saline	No	No
Lettuce	1.3	Non-saline	2.1	Slightly saline	No	No
Oats (grain)*	5.2	Moderately saline	6.7	Moderately saline	Yes	Yes
Onion	1.2	Non-saline	1.8	Non-saline	No	No
Peas	0.9	Non-saline	2.0	Non/slightly saline	No	No
Potato	1.7	Non-saline	2.5	Slightly saline	No	No
Pumpkin	3.9	Slightly saline	4.9	Moderately saline	No	Yes
Radish	1.2	Non-saline	2.0	Non/slightly saline	No	No
Rye (grain)*	5.9	Moderately saline	7.7	Moderately saline	Yes	Yes
Sorghum*	4.0	Slightly/moder-ately saline	5.1	Moderately saline	Yes	Yes
Spinach	3.7	Slightly saline	5.5	Moderately saline	No	Yes
Sugar beets	6.7	Moderately saline	8.7	Highly saline	Yes	Yes
Sweet potato	1.5	Non-saline	2.4	Slightly saline	No	No
Turnips	0.9	Non-saline	1.9	Non-saline	No	No
Wheat*	4.7	Moderately saline	6.0	Moderately saline	Yes	Yes

Source: (Amacher et al., 2000)

*These crops are grains

**This data serves only as guideline since the salinity-tolerance of crops is influenced by soil type, climate, and irrigation and the salinity threshold value can vary per specific crop variety.

Table 3 shows that there are eight crops that are suitable for saline agriculture when looking at the threshold value, these crops are: asparagus (5.0 EC_e), barley (8.0 EC_e), beets (5.3 EC_e), oats (grain)(5.2 EC_e), rye (grain)(5.9 EC_e), sorghum (4.0 EC_e), sugar beets (6.7 EC_e) and wheat (4.7 EC_e). Of these eight crops barley has the highest salinity value with a value of 8.0 EC_e and can grow on highly saline soil.

There are two things that change when looking at the salinity value at which a 10% yield loss occurs. Firstly, the salinity value of the crops stated above rises. Secondly, there are two more additional crops that can be cultivated on saline soil, which are spinach and pumpkin. The list of crops suitable for saline agriculture with a 10% yield loss consists of: asparagus (8.0 EC_e), barley (9.6 EC_e), beets (8.0 EC_e), oats (grain)(6.7 EC_e), pumpkin (4.9 EC_e), rye (grain)(7.7), sorghum (grain)(5.1), spinach (5.5 EC_e), sugar beets (8.7 EC_e) and wheat (6.0 EC_e). Only asparagus, barley, beets and sugar beets are capable of growing on highly saline soil with a salinity value of 8.0 EC_e or higher.

4.3. Less suitable areas for traditional agriculture and cattle farming

Now that the animal feed crops and traditional crops suitable for saline agriculture are known it is time to look at which parts of the polder are still suitable for the traditional way of agriculture by the year 2100. This study will look at the salinity of the phreatic groundwater and of the water at -0.5 NAP and -6.5 NAP by the year 2100.

Looking at the phreatic groundwater by the year 2100 (figure 4), it appears that the corner in the North East and the West, along with the most Northern part of the research area would still be suitable for traditional agriculture without patches of unsuitable soil interrupting. The area in the middle would have quite some suitable soil, however these areas are interrupted by patches of unsuitable soil. The area with the most unsuitable soil for traditional agriculture will be located along the shore.

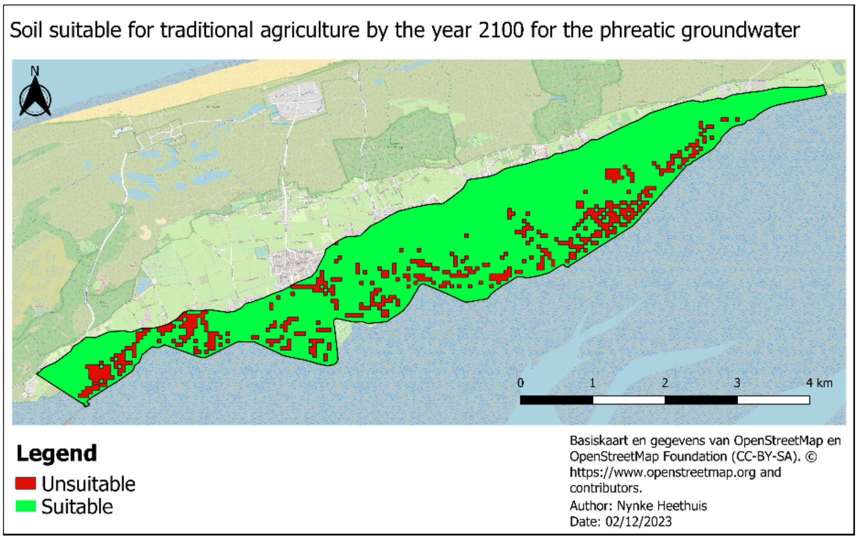


Figure 4. Map of the polder of Terschelling showing which areas are unsuitable for traditional agriculture by the year 2100 when studying the phreatic groundwater.

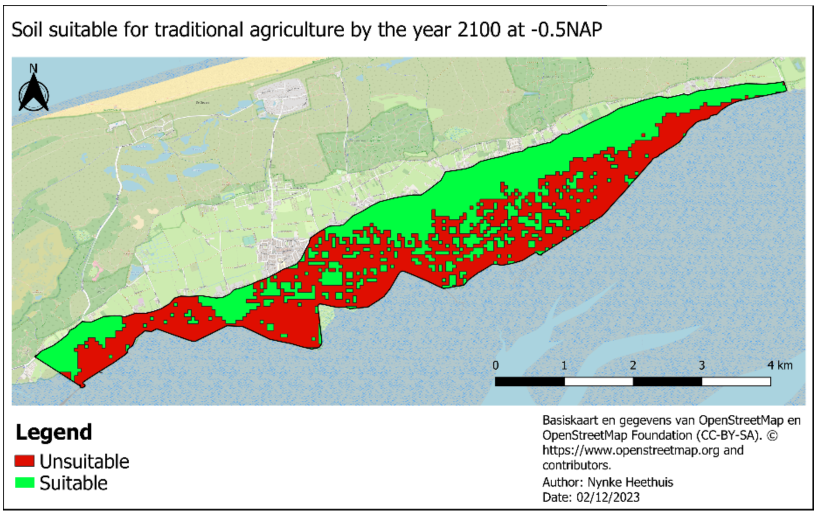


Figure 5. Map of the polder of Terschelling showing which areas are unsuitable for traditional agriculture by the year 2100 when studying the groundwater at -6.5NAP.

Focusing on the groundwater at -0.5NAP it can be seen that a large portion of the polder will be unsuitable for traditional agriculture by the year 2100 (figure 5).
The area in the North and North East of the polder will still be suitable for traditional agriculture without being interrupted by small patches of unsuitable soil by the year 2100, along with two small uninterrupted areas in the West. However, the majority of the polder will be unsuitable for traditional agriculture by the year 2100.

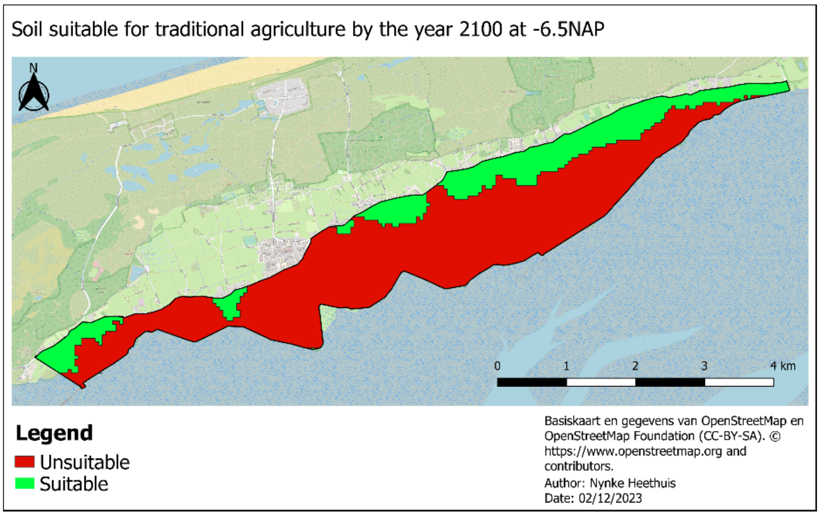


Figure 6. Map of the polder of Terschelling showing which areas are unsuitable for traditional agriculture by the year 2100 when studying the groundwater at -6.5NAP.

In figure 6 can clearly be seen that a majority of the polder will be unsuitable for traditional agriculture at the depth of -6.5NAP by the year 2100. The unsuitable soil starts at the coast and at some places spans the whole length of the research area. Two small areas in the West along with three areas in the North and East will still be suitable for traditional agriculture by the year 2100. Although most crop roots do not grow this deep (Fan et al., 2016), it might be a harbinger for future salinization of the polder.

4.4 Parts of the polder suitable for the cultivation of saline crops by 2100

Table 4 and 5 below show all 21 saline crops (EC_e >= 4dS/m) gathered from the results of sub question one and two.

Table 4. The table displays the threshold values for all animal feed crops with a threshold value equal to or higher than 4 and the threshold values transformed from EC_e to chloride concentration (g/l).

Crop (Animal feed)	Threshold value at 100% yield (EC_e (dS/m))	Threshold value at 100% yield (chloride concentration in g/l)	Threshold value at a yield loss of 10% (EC_e (dS/m))	Threshold value at a yield loss of 10% (chloride concentration in g/l)
Perennial ryegrass	5.6	4.48	6.9	5.52
Barley	5.3	4.24	7.4	5.92
Birdsfoot trefoil	4.0	2.56	6.0	4.80
Clovers (strawberry)	5.0	3.20	8.0	6.40
Fodder beet	15	12	-	-
Foxtail millet	6.0	4.80	-	-
Millet	6.0	4.80	-	-
Sorghum	4.0	2.56	5.1	4.08
Soybeans	5.0	3.20	-	-
Sweet clover	4.0	2.56	6.0	4.80
Tritacle (forage)	6.1	4.88	8.1	6.48

Table 5. This table displays the threshold values for all traditional crops with a threshold value equal to or higher than 4 and the threshold values transformed from EC_e to chloride concentration (g/l).

Crop (traditional	Threshold value at 100% yield (EC_e (dS/m))	Threshold value at 100% yield (chloride concentration in g/l)	Threshold value at a yield loss of 10% (EC_e (dS/m))	Threshold value at a yield loss of 10% (chloride concentration in g/l)
Asparagus	5.0	3.20	8.0	6.40
Barley	8.0	6.40	9.6	7.68
Beets	5.3	4.24	8.0	6.40
Oats (grain)	5.2	4.16	6.7	5.36
Pumpkin	-	-	4.9	3.14
Rye (grain)	5.9	4.72	7.7	6.16
Sorghum	4.0	2.56	5.1	4.08
Spinach	-	-	5.5	4.40
Sugar beets	6.7	5.36	8.7	6.96
Wheat	4.7	3.01	6.0	4.80

4.4.1 Animal feed crops

For the fodder beet, foxtail millet, millet and soybeans (figures 11, 12, 14) only the threshold value at a 100% yield was available, because of this no conclusion can be made on whether or not there would be more suitable soil for these crops with a 10% yield loss. Since only the 100% yield was known for foxtail millet and millet, and both crops have the same threshold value it was decided to combine them in one figure.

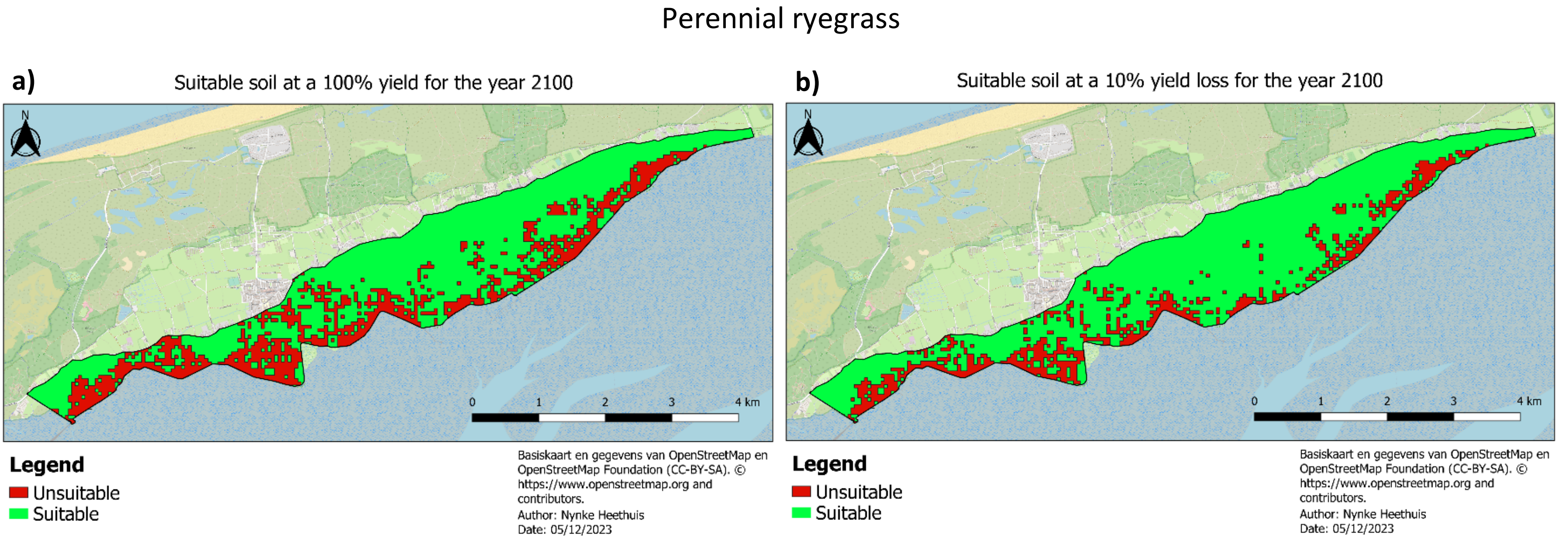
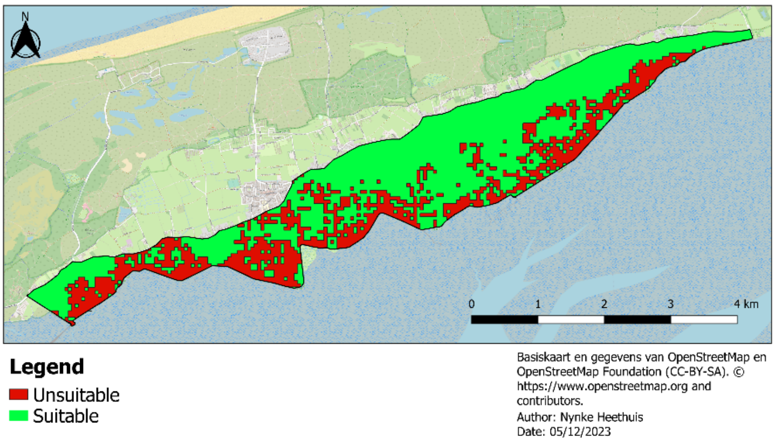


Figure 7a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of perennial ryegrass at a 100% yield (5.6 EC_e).
Figure 7b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of perennial ryegrass at a 10% yield loss (6.9 EC_e).

Barley

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

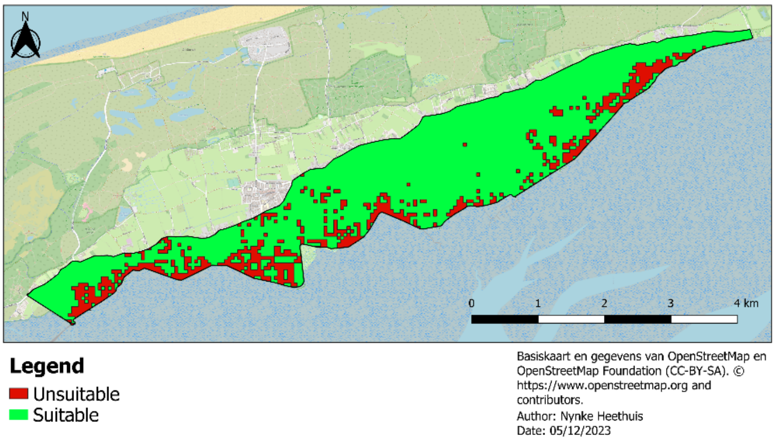
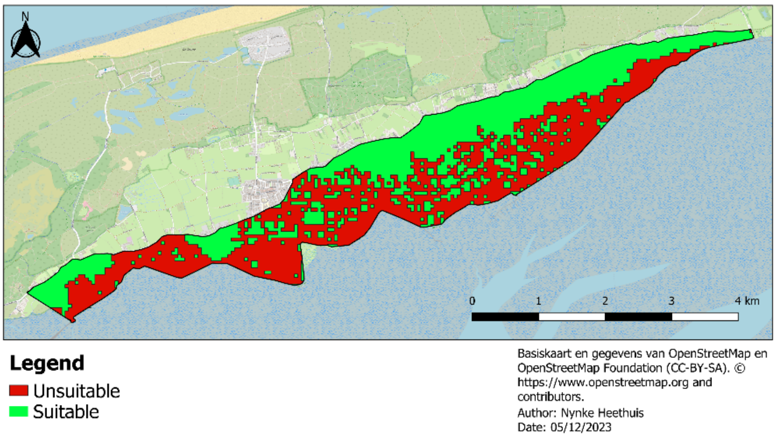


Figure 8a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of barley at a 100% yield (5.3 EC_e).
Figure 8b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of barley at a 10% yield loss (7.4 EC_e).

Birdsfoot trefoil

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

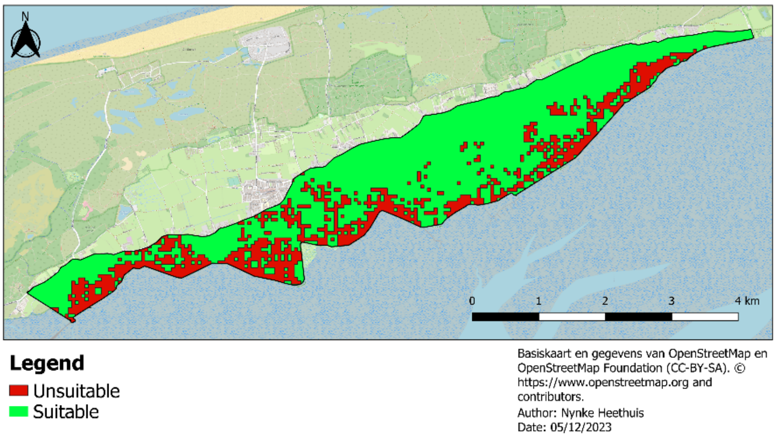
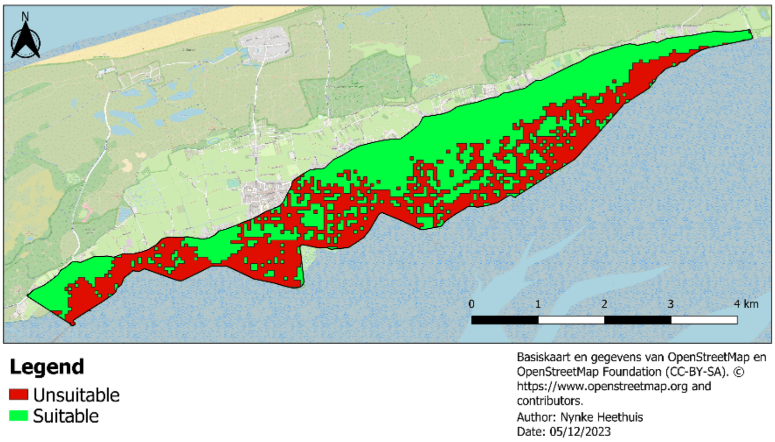


Figure 9a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of birdsfoot trefoil at a 100% yield (4.0 EC_e).
Figure 9b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of birdsfoot trefoil at a 10% yield loss (6.0 EC_e).

Clovers (strawberry)

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

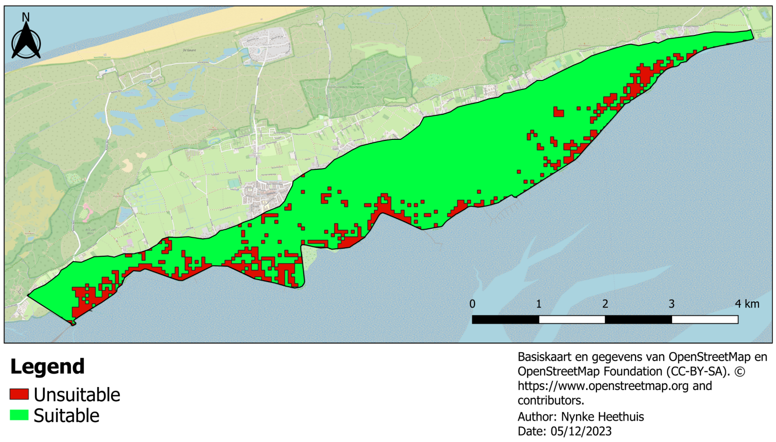


Figure 10a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of clovers (strawberry) at a 100% yield (5.0 EC_e).
Figure 10b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of clover (strawberry) at a 10% yield loss (8.0 EC_e).

Fodder beet

Suitable soil at a 100% yield for the year 2100

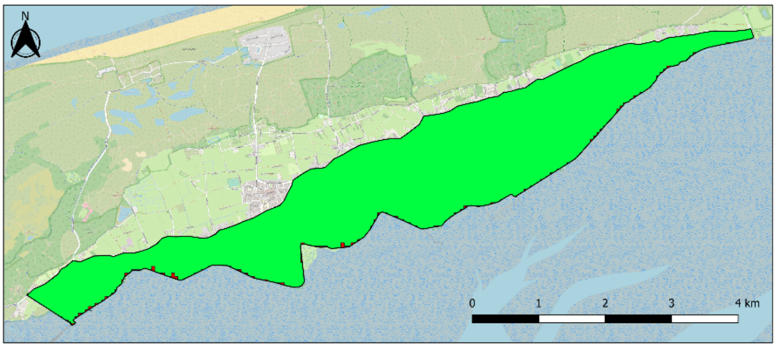


Figure 11. The map displays the areas suitable and unsuitable for the cultivation of fodder beet by the year 2100 at a 100% yield (15 EC_e).

Millet/Foxtail millet

Suitable soil at a 100% yield for the year 2100

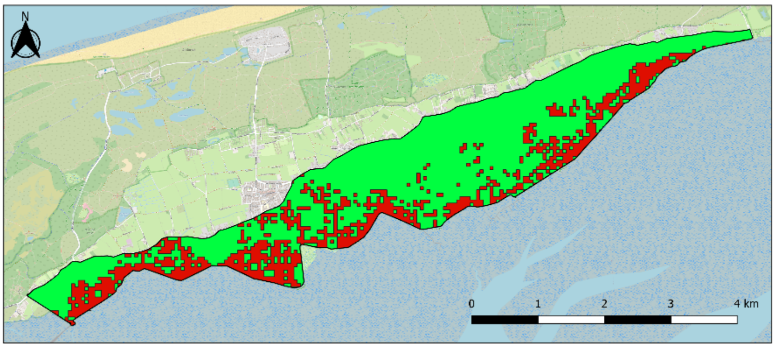
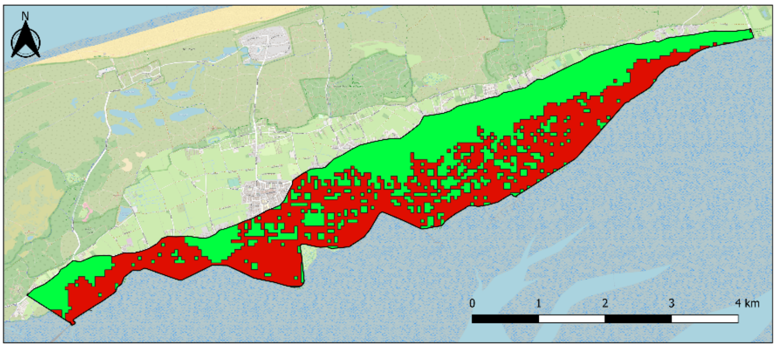


Figure 12. This map shows the areas suitable and unsuitable by the year 2100 for the cultivation of millet, foxtail millet at a 100% yield (6.0 EC_e).

Sorghum

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

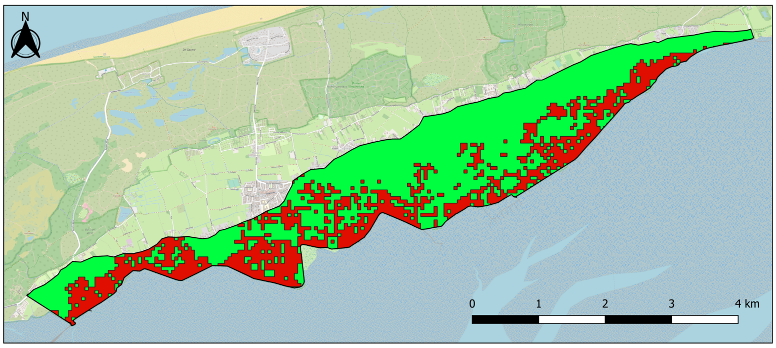


Figure 13a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of sorghum at a 100% yield (4.0 EC_e).
Figure 13b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of sorghum at a 10% yield loss (5.1 EC_e).

Soybeans

Suitable soil at a 100% yield for the year 2100

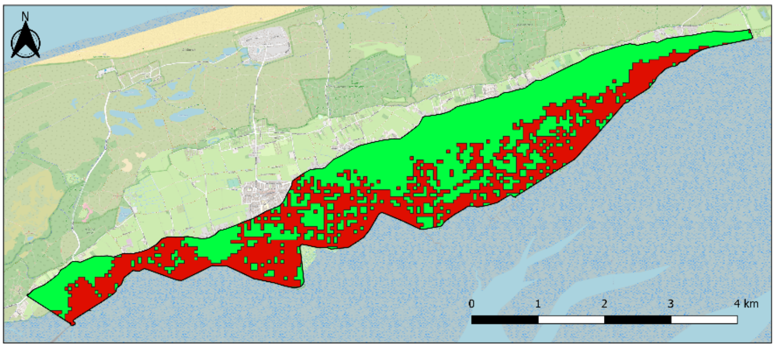
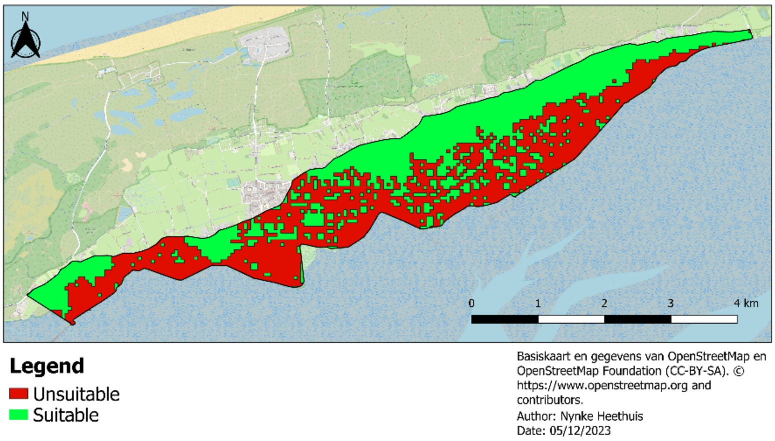


Figure 14. Displays the suitable and unsuitable areas at a 100% yield for the cultivation of soybeans (5.0 EC_e) by the year 2100.

Sweet clover

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

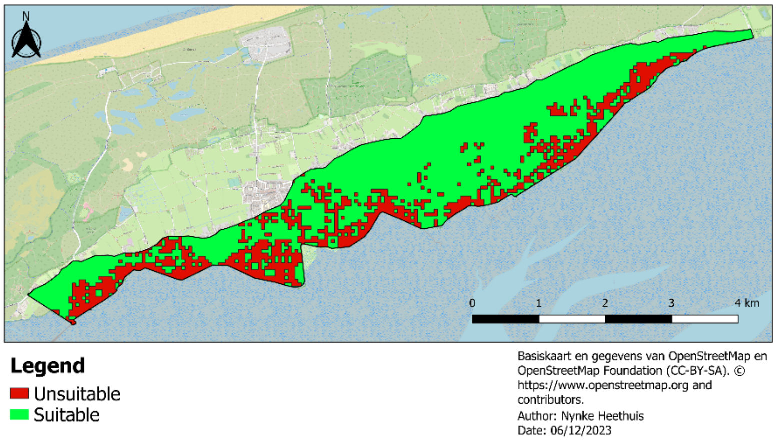
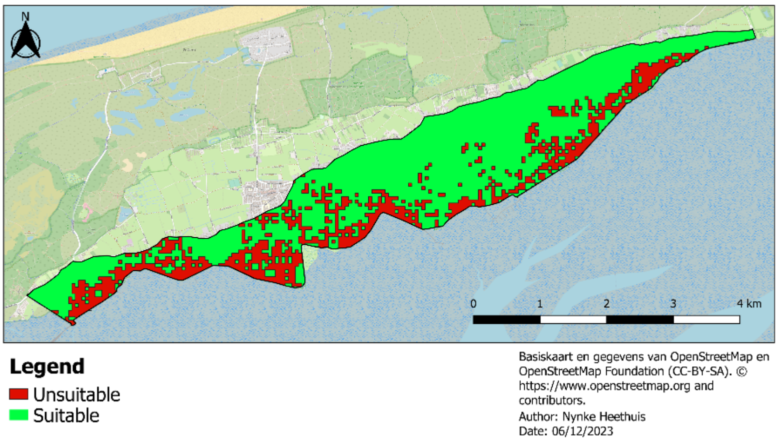


Figure 15a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of sweet clover at a 100% yield (4.0 EC_e).
Figure 15b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of sweet clover at a 10% yield loss (6.0 EC_e).

Tritacle (forage)

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

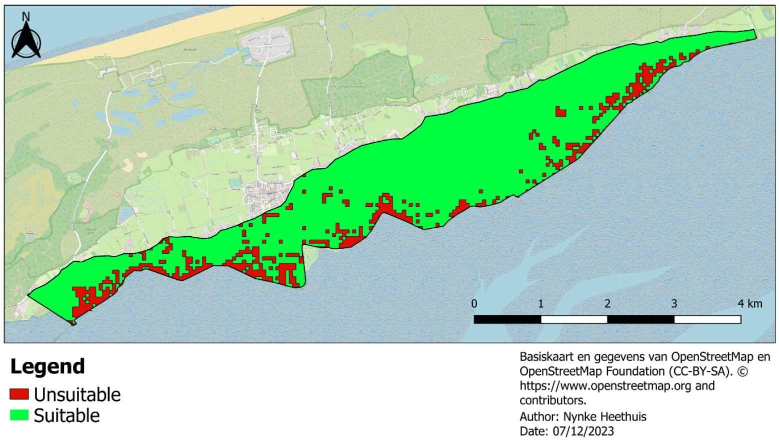


Figure 16a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of tritacle (forage) at a 100% yield (6.1 EC_e).
Figure 16b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of tritacle (forage) at a 10% yield loss (8.1 EC_e).

Table 6. The table shows the total number of pixels that represent unsuitable soil, per yield, per crop for the animal feed crops. The table also displays the difference in the amount of unsuitable soil between the 100% yield and 10% yield loss and how much this difference amounts to in percentage. For fodder beet, foxtail millet, millet and soybeans only the 100% yield was known and thus the difference between the 100% yield and 10% yield loss could not be calculated.

Crop (Animal feed)	100% yield, amount of unsuitable soil (pixels)	10% yield loss, amount of unsuitable soil (pixels)	Difference	Difference in percentage (rounded to 2 decimal places)
Perennial ryegrass	1324	890	434	32,8%
Barley	1436	747	689	48,0%
Birdsfoot trefoil	2381	1185	1196	50,2%
Clovers (strawberry)	1979	602	1377	69,6%
Fodder beet	23	-	23	-
Foxtail millet	1186	-	1186	-
Millet	1186	-	1186	-
Sorghum	2381	1512	869	36,5%
Soybeans	1979	-	1979	-
Sweet clover	2381	1185	1196	50,2%
Tritacle (forage)	1156	575	581	50,3%

For all animal feed crops can be seen that there will be more suitable soil at the threshold value of a 10% yield loss than there are at the threshold value of a 100% yield. Tabel 6 supports this as it can be seen that there is more unsuitable soil at a 100% yield than that there is at a 10% yield loss with at least a 32% or higher difference between the two yields. The map of clover (strawberry) with a 10% yield loss (figure 10b) and a threshold value of 8EC_e clearly shows that there will be areas of the polder that will be highly saline (8 EC_e -16 EC_e) by the year 2100.

Table 6 shows that clover (strawberry) has the biggest difference in the amount of unsuitable soil between the 100% yield and 10% yield loss with a difference of 69.6%. Birdsfoot trefoil and sweet clover have a difference of 50.2% followed by tritacle forage with a 50.3% difference and barley with a 48.0% difference. The smallest difference in the amount of unsuitable soil between yields is at perennial rye grass with a difference of 32.8% followed by sorghum with a 36.5% difference.
In all the figures (figures 7 t/m 16) can be seen that the area in the northeast corner of the research area as well as the west corner consists of suitable soil at both a 100% yield and a 10% yield loss.
In most cases the soil in the middle on the northern edge of the research area consists of suitable soil as well, and depending on the crop the suitable soil can go further down.
At a 100% yield birdsfoot trefoil, sorghum and sweet clover have the same threshold of 4.0 EC_e, clovers (strawberry) and soybeans both have a threshold value of 5.0 EC_e, and lastly foxtail millet and millet each have a threshold value of 6.0 EC_e (table 4). At a 10% yield loss only the crops birdsfoot trefoil and sweet clover have the same threshold value of 6.0 EC_e.

Fodder beet (figure 11) can be grown throughout almost all of the polder by the year 2100 except for a couple of small spots along the coast where the soil is too saline.
For birdsfoot trefoil, clovers (strawberry), sorghum, soybeans and sweet clover (figures 9a, 10a, 13a, 14 and 15a) most of the soil will be unsuitable at a 100% yield.

4.4.2 Traditional crops

For pumpkin and spinach (figures 21 and 24) only the suitable soil at the threshold value at a 10% yield loss has been mapped out since the threshold value at a 100% was below 4 EC_e.

Asparagus

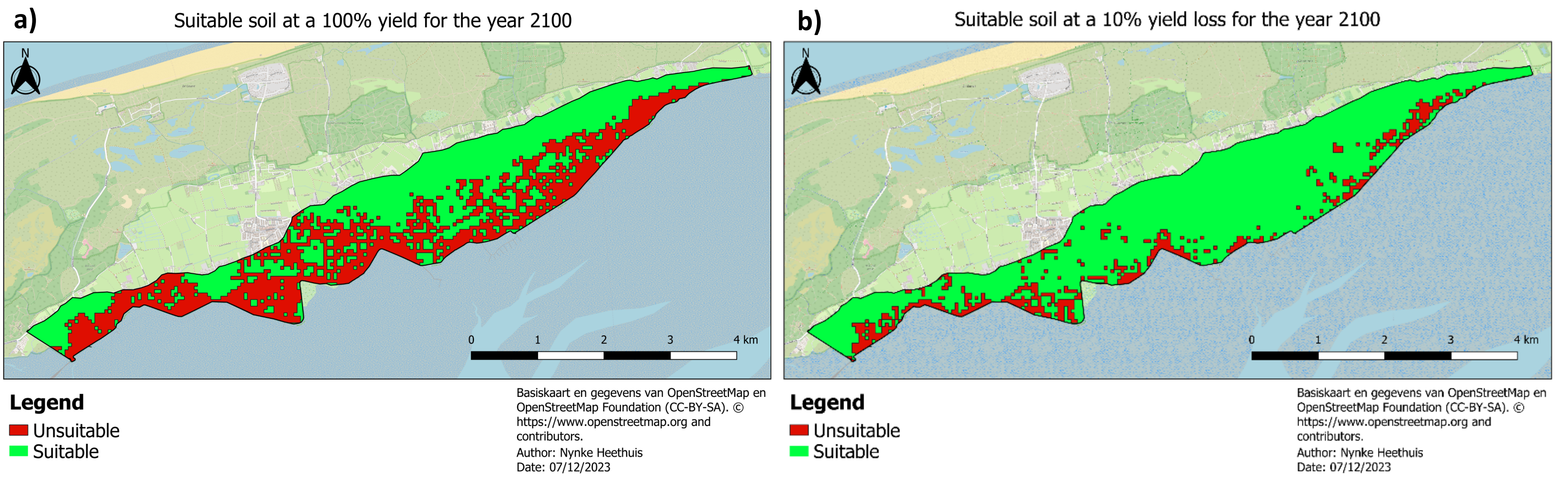


Figure 17a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of asparagus at a 100% yield (5.0 EC_e).
Figure 17b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of asparagus at a 10% yield loss (8.0 EC_e).

Barley

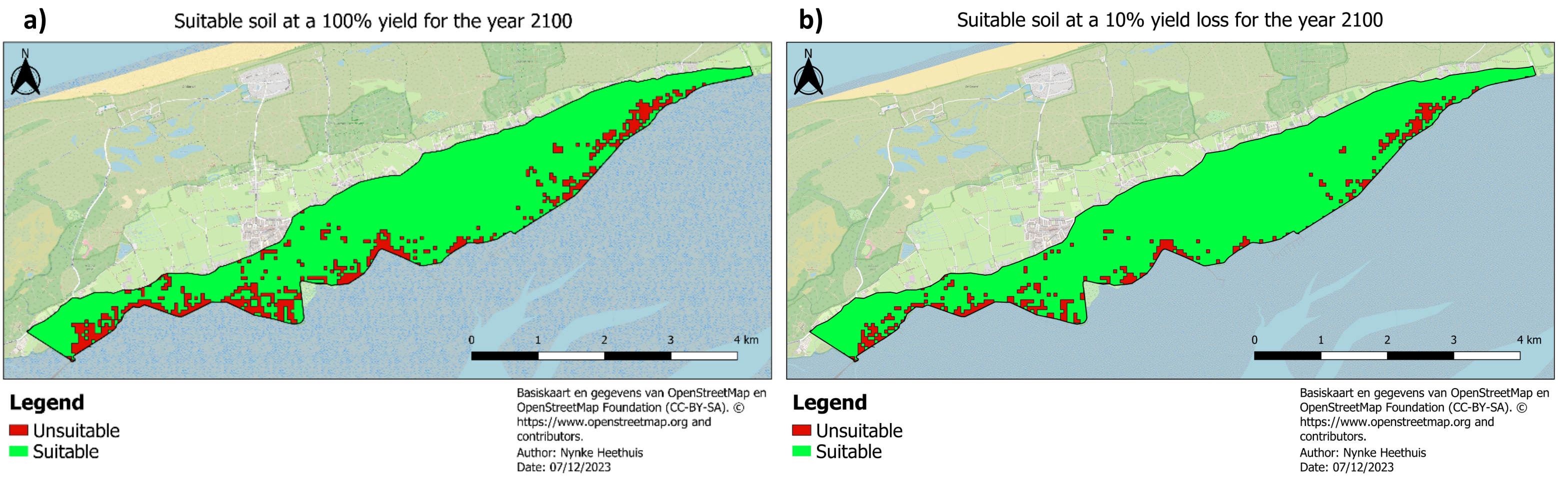
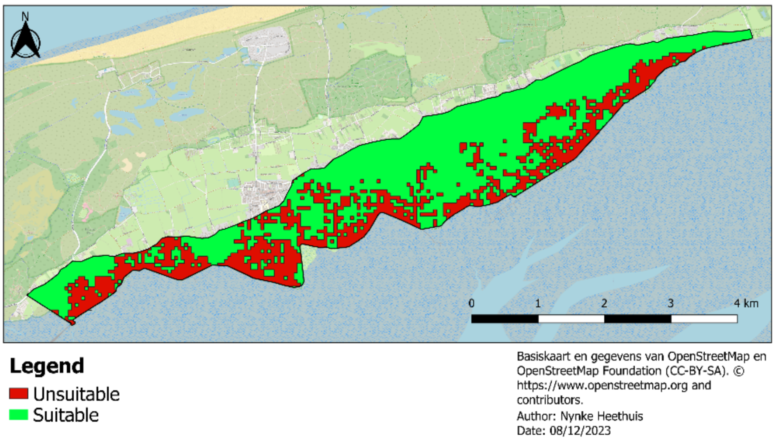


Figure 18a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of barley at a 100% yield (8.0 EC_e).
Figure 18b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of barley at a 10% yield loss (9.6 EC_e).

Beets

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

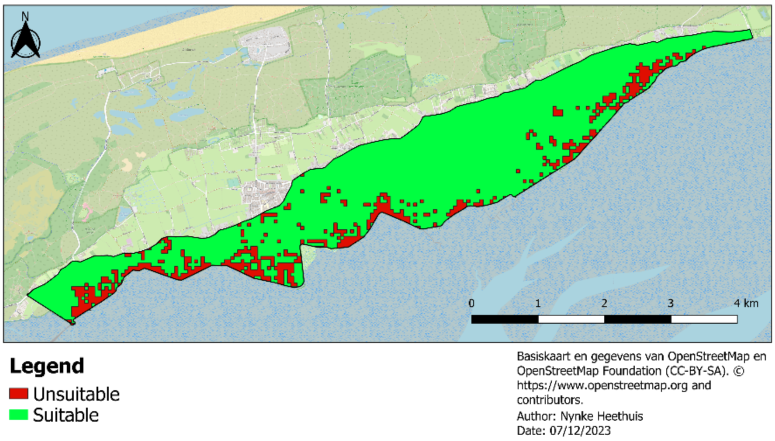
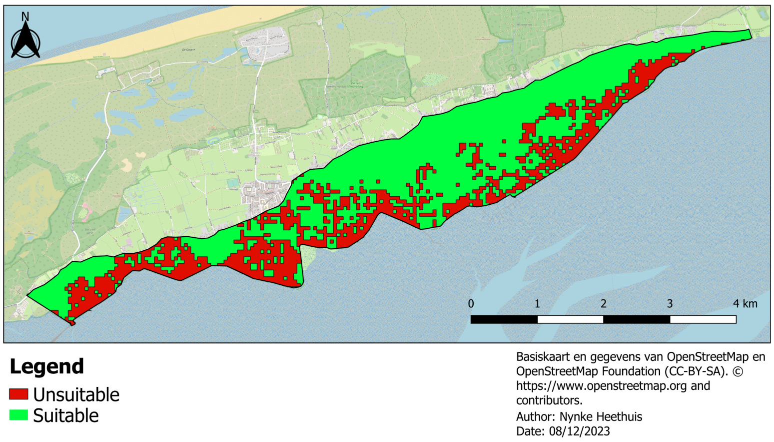


Figure 19a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of beets at a 100% yield (5.3 EC_e).
Figure 19b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of beets at a 10% yield loss (8.0 EC_e).

Oats (grain)

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

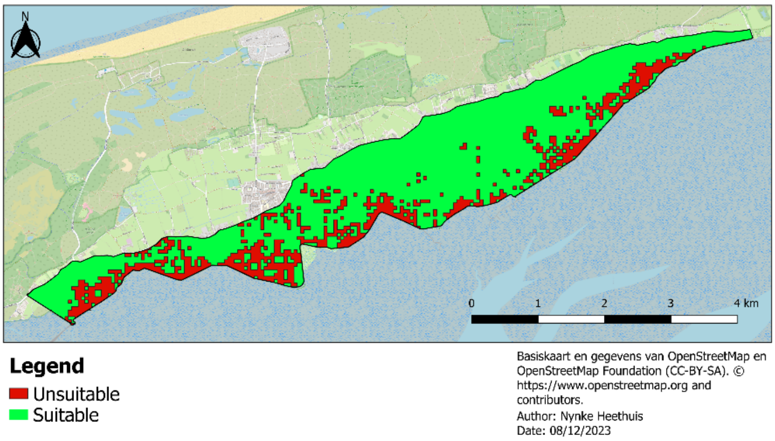


Figure 20a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of oats (grain) at a 100% yield (5.2 EC_e).
Figure 20b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of oats (grain) at a 10% yield loss (6.7 EC_e).

Pumpkin

Suitable soil at a 10% yield loss for the year 2100

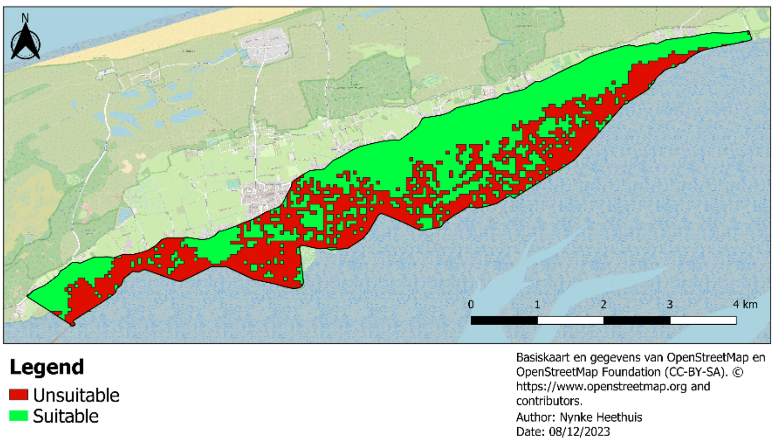


Figure 21. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of pumpkin at a 10% yield loss (4.9 EC_e).

Rye (grain)

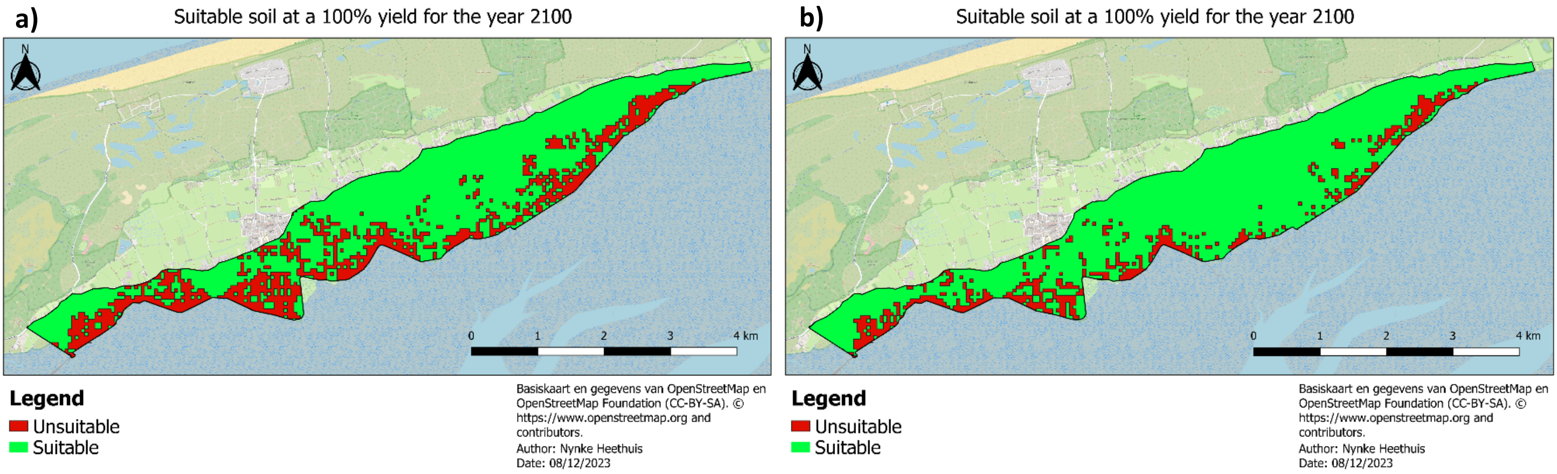


Figure 22a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of rye (grain) at a 100% yield (5.9 EC_e).
Figure 22b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of rye (grain) at a 10% yield loss (7.7 EC_e).

Sorghum

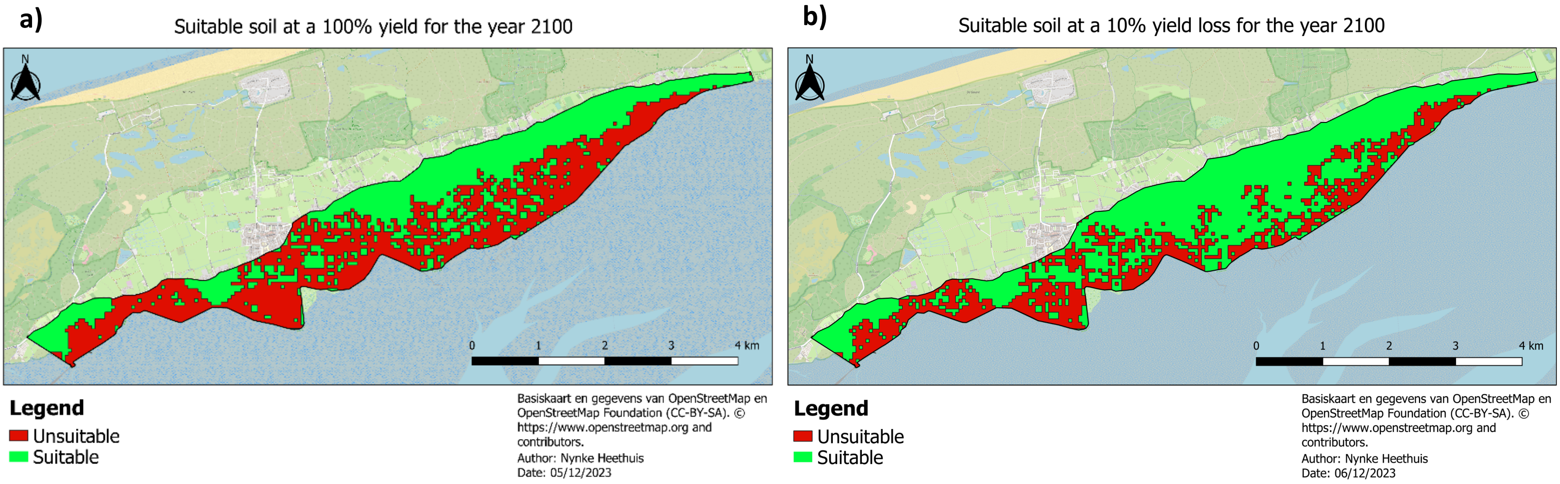


Figure 23a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of sorghum at a 100% yield(4.0 EC_e).
Figure 23b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of sorghum at a 10% yield loss (5.1 EC_e).

Spinach

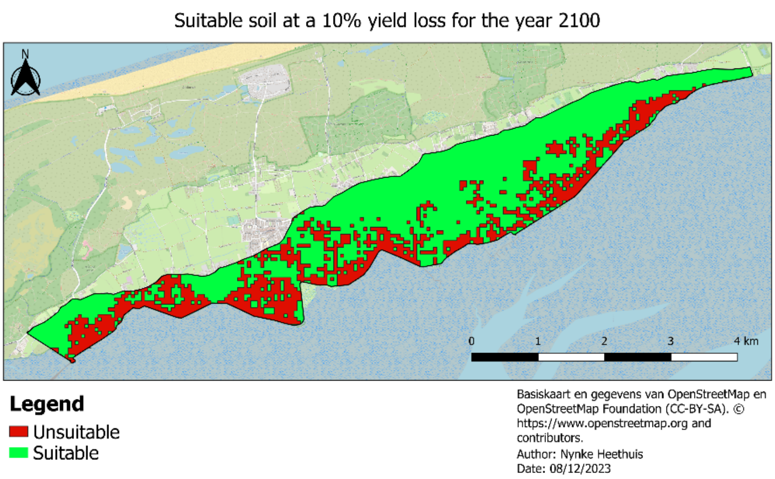
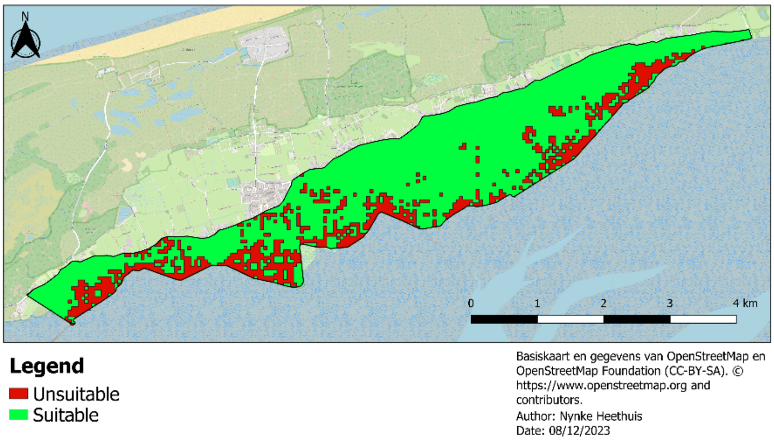


Figure 24. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of spinach) at a 10% yield loss (5.5 EC_e).

Sugar beets

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

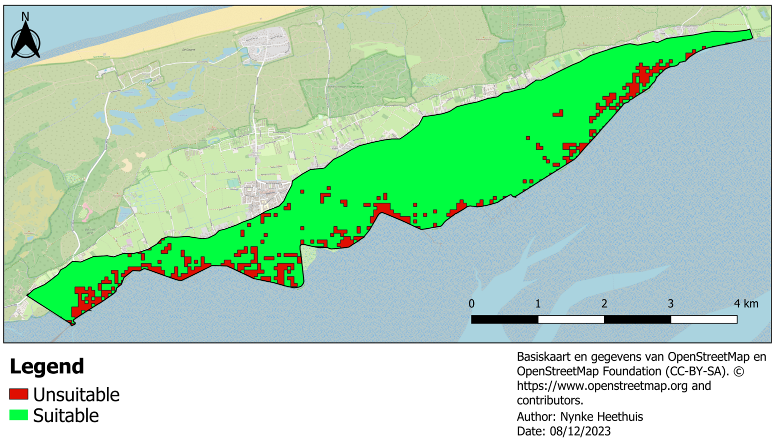
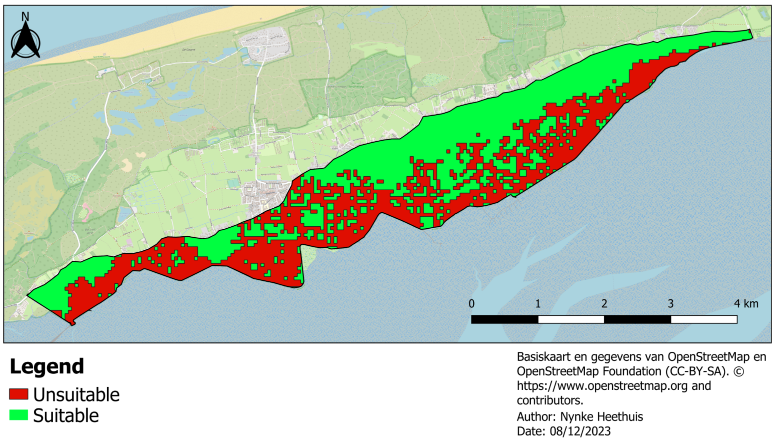


Figure 25a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of sugar beets at a 100% yield (6.7 EC_e).
Figure 25b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of sugar beets at a 10% yield loss (8.7 EC_e).

Wheat

a) Suitable soil at a 100% yield for the year 2100



b) Suitable soil at a 10% yield loss for the year 2100

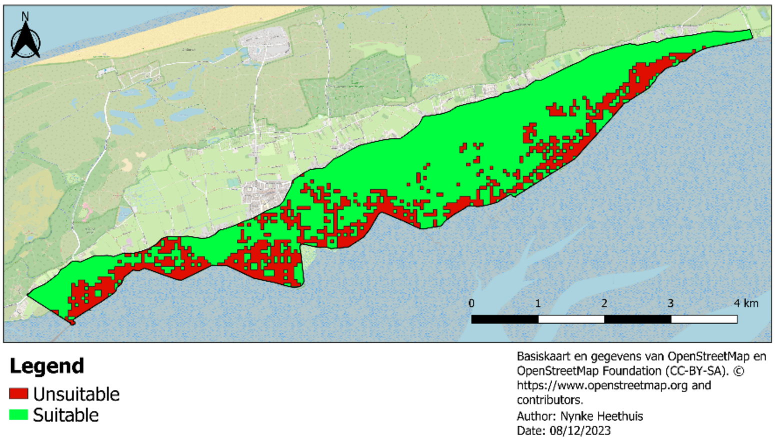


Figure 26a. The map shows the areas suitable and unsuitable by the year 2100 for the cultivation of wheat at a 100% yield (4.7 EC_e).
Figure 26b. This map displays the areas suitable and unsuitable by the year 2100 for the cultivation of wheat) at a 10% yield loss (6.0 EC_e).

Tabel 7. The table shows the total number of pixels that represent unsuitable soil, per yield, per crop for the traditional crops. The table also displays the difference in the amount of unsuitable soil between the 100% yield and 10% yield loss and how much this difference amounts to in percentage. For pumpkin and spinach the difference could not be calculated as only the 10% yield is known as for both crops the threshold value of the 100% yield was below 4 EC_e.

Crop (Traditional)	100% yield, amount of unsuitable soil (pixels)	10% yield loss, amount of unsuitable soil (pix-els)	Difference	Difference in percentage (rounded to 2 decimal places)
Asparagus	1979	602	1377	69,6%
Barley	602	348	254	42,2%
Beets	1436	602	834	58,1%
Oats (grain)	1473	947	526	35,7%
Pumpkin	-	2008	2008	-
Rye (grain)	1218	674	544	44,7%
Sorghum	2381	1512	869	36,5%
Spinach	-	1372	1372	-
Sugar beets	947	469	478	50,5%
Wheat	2089	1186	903	43,2%

For all traditional crops can be seen that there will be more suitable soil at the threshold value of a 10% yield loss than there are at the threshold value of a 100% yield. Table 7 confirms this as there is more unsuitable soil at a 100% yield than at a 10% yield loss with at least a 35% or higher difference between the two yields. It can also be seen that for all crops the unsuitable areas start at the seaside and depending on the specific crop go further inland.

Table 7 shows that asparagus has the biggest difference in the amount of unsuitable soil between the 100% yield and 10% yield loss with a difference of 69.6%. Beets have a difference of 58.1% between yields followed by sugar beets with a difference of 50.5%. Oats (grain) has the smallest difference between yields with 35.7%, closely followed by sorghum with 36.5%. Three crops fall between the highest and lowest percentage of difference, these are rye (grain) with 44.7% difference, wheat with 43.2% difference and barley with 42.2% difference between the 100% yield and 10% yield loss.

In all the figures (figures 17 t/m 26) can be seen that the area in the northeast of the research area as well as the west corner consists of suitable soil at both a 100% yield and a 10% yield loss. In most cases the soil in the middle on the northern edge of the research area consists of suitable soil as well, and depending on the crop the suitable soil can go further down to in some cases even all the way down to the coast. At a 100% yield there are no crops with the same threshold value. At a 10% yield loss only the crops asparagus and beets have the same threshold value 8.0 EC_e (table t5).

Barley (figure 18) can be cultivated in a large part of the polder at both a 100% yield and a 10% yield loss. It is mostly along the coast where the salinity is too high for barley with some small patches unsuitable soil more inland. At a 10% yield loss asparagus, beets and sugar beets (figures 17b, 19b, 25b) can be cultivated throughout most of the polder except for along the coast.

For asparagus, sorghum and wheat (figures 17a, 23a, and 26a) most of the soil at the 100% yield will be unsuitable. For pumpkin (figure 21) most of the soil will be unsuitable at a 10% yield loss.

5. Discussion

This research showed that when looking at the salinity of the phreatic groundwater by the year 2100, with exception of some small parts, most land in the polder of Terschelling will still be suitable for traditional agriculture. However when looking at -0.5NAP a large part of the polder, going from the sea side up will be unsuitable by the year 2100. Of all 44 crops studied, 21 turned out to be salt-tolerant, with the highest salinity threshold value going up to 15 $EC_{e.}$

5.1 Animal feed crops

Of the nineteen studied animal feed crops (including perennial ryegrass) there are eleven crops that are salt-tolerant at a 100% yield, of which four crops (fodder beet (15 EC_e), foxtail millet (6.0 EC_e), millet (6.0 EC_e) and triticale (forage)(6.1 EC_e) have a higher salinity tolerance than perennial ryegrass. Of these eleven salt-tolerant crops, fodder beet is the most salt-tolerant animal feed crop with a threshold value of 15 EC_e. There are seven animal feed crops that are salt-tolerant at a yield loss of 10%. This number is lower than that of the 100% yield because the salt-tolerance at a 10% yield loss could not be found for four of the crops. By the year 2100 it would thus be possible to cultivate animal feed in the polder of Terschelling even if the soil were to become saline, though the farmers might need to switch to a different feed then they originally used. In the scenario of this research there will be highly saline soil (8-16 ECe) in the polder of Terschelling. This can be seen in figure 10b where sweet clover has an EC_e value of 8.0 EC_e and there are still areas of unsuitable soil visible in the polder. As perennial ryegrass cannot be cultivated in areas where the soil has become highly saline, farmers would then need to switch to fodder beet or clovers (strawberry) and tritacle (forage) as this are animal feed crops that can tolerate highly saline soil. The farmers would however suffer a 10% yield loss with the last two crops. It is difficult to say how this would influence the profit as the price of crops can vary strongly depending on the costs of the seeds and what the crops need regarding fertilization, crop protection products and the amount of labor that goes into cultivating the crop. The cultivation method a farmer uses as well as the soil type all have an effect on the cost price of the crops (Nederlandse Akkerbouw, n.d.) This amount of yield loss might not be acceptable for farmers, however, with only three crops able to grow on highly saline soil there is not much choice left. Dairy farmers keeping highly productive dairy cattle would however need to monitor whether or not the salt-tolerant crops cultivated on saline soil contain more salt or not. As too much salt can have a negative effect on dairy cattle (Visscher, 2012).

5.2 Traditional crops

Of the 25 traditional crops there are eight salt-tolerant crops at a yield of 100%. It is interesting to note that of these traditional crops it appears that all grains except for corn are salt-tolerant and make up five of the total eight salt-tolerant traditional crops. These five grains can all be cultivated on moderately saline soil at both a 100% yield and a 10% yield loss, with barley even being able to be cultivated on highly saline soil. Ten of the 25 traditional crops are suitable for saline agriculture at a 10% yield loss. At both a 100% yield and a 10% yield loss barley has the highest salinity threshold of all crops. It is also the only crop that can be cultivated on highly saline soil with a 100% yield. At a 10% yield loss asparagus, barley, beets and sugar beets can be cultivated on a highly saline soil as well. Even if the polder of Terschelling were to become saline ($EC_e >= 4.0$) it would thus still be possible for farmers to cultivate traditional crops there. The only thing is that the selection of crops based on this research is limited to ten different kinds of crops of which five are grains and two (pumpkin and spinach) will have a 10% yield loss.

What is extremely important to keep in mind for both the threshold values of the animal feed and traditional crops is that the threshold values of the crops are not absolute. Factors such as climate, soil type and irrigation can have an influence on the salinity threshold values of the crops (NSW Department of Primary Industries, 2017). Regarding the reliability of the threshold values, not all threshold values are from recent studies or articles as some of the crops are barely studied in regard of the effects of salinization. Nevertheless the threshold value of the crops is unlikely to change drastically over the years.

The results regarding which animal feed and traditional crops could possibly be cultured on saline soil are not only useful to the farmers of Terschelling, but can be extrapolated to other areas of the Netherlands as well. This is because all the crops on this list can be and are cultivated throughout the whole Netherlands.

5.3 Future prospect for the soil salinity of the polder of Terschelling

Looking at figure 4, it is clear that there is going to be some salinization of the phreatic groundwater by the year 2100. However there will still be a lot of suitable soil left, making that traditional agriculture is still going to be possible in the polder as long as the crop roots do not grow past the phreatic groundwater. At -0.5NAP (figure 5) half of the polder of Terschelling will be dealing with salinization by the year 2100. Along the upper border of the research area and a little down from there, traditional agriculture might still be possible at some places. Nonetheless, to make full use of all the land available in the polder, farmers should already have started with cultivating saline crops before the year 2100. At -6.5 NAP most of the soil will be saline by the year 2100. Though there are still some areas along the upper border of the research area that are suitable for traditional agriculture. What is noticeable is that the area of unsuitable soil is a completely covered area, there are no longer small gaps of suitable soil visible. Fortunately for farmers, almost no crops have roots that grow that deep (Fan et al., 2016). For farmers the phreatic groundwater and -0.5NAP will be most interesting as most crops will likely have roots that grow somewhere along this depth (Fan et al., 2016).

The reliability of the models is not a 100%. There are two reasons for this. The first reason being that the models used were intermediate models of Deltares. At the time of this research Deltares was still improving these models. This means that if the maps regarding the suitable soil per depth and per crop were made again with the finished models the results might differ slightly. The second reason these models are not a 100% reliable is because it is a prediction for the future. With the year 2100 still being 76 years from now a lot of things can happen that have a direct or indirect effect on the salinity of the soil of the polder of Terschelling. An event could happen that causes the sea level to rise (Cherlinka, 2021), or serious droughts could occur allowing the seawater to flow further inland (Helpdesk water, n.d.; Saline Agriculture Worldwide Knowledge Centre, n.d.-b). This are only two examples of many factors that can have an influence on the soil salinity.

The results of this research might be useful to the Netherlands Bird Protection, Staatsbosbeheer, Vogelwacht Terschelling and Terschellinger Campinghouders Vereniging. The salinity maps of the phreatic groundwater and the groundwater at -0.5 NAP and -6.5 NAP can be useful to these stakeholders as a reference on how the salinization will develop on the remainder of Terschelling. For Vitens the information might be useful since one third of the drinking water of Terschelling comes from the island itself (Peters, 2013). If the groundwater becomes saline this might give problems with the drinking water supply. Based on the results of this research they could possibly start thinking if solutions are needed and if yes what solutions might be possible.

5.4 Availability of suitable soil

What is clear is that fodder beet (figure 11), except for some small areas along the coast, can still be cultivated at a 100% yield throughout almost the entire polder by the year 2100. It is the only crop of all 25 crops for which this is the case. Cultivating birdsfoot trefoil, sorghum (animal feed and traditional) and sweet clover is on large parts of the polder not possible at a 100% yield. If farmers are willing to accept a 10% yield loss a majority of all 25 crops can still be cultivated throughout the polder of Terschelling by the year 2100. Only the part along the coast is for a lot of crops too saline. In these areas along the coast farmers could choose to plant the following crops: fodder beet, clovers (strawberry, 10% yield loss), tritacle (forage), asparagus (10% yield loss), barley (traditional), beets

(10% yield loss), oats (grain, 10% yield loss) and rye (grain, 10% yield loss). This are crops that can still be cultivated on a large part of the polder, including the coastal area, by the year 2100. Using a combination of different crops farmers should be able to still use almost the entire polder by the year 2100. However farmers might have to make some concessions on the amount of yield they can harvest depending on the salinity of their soil and the crops they want to cultivate. The crops they can cultivate will also depend on where the farmland they own is located and how saline the soil there will be. If a farmer were to only own farmland along the coast then they would have a significantly more limited choice of crops than a farmer on the upper border of the research area would have. The fact that most of the soil along the coast has a higher salinity than other areas might be caused by brackish groundwater rising to the surface. Due to the combination of the rising sea level and the subsidence of soil, it is expected that the salinization of soil will go faster in the coastal areas. This combination causes the pressure from the seawater on the groundwater to increase (Helpdesk water, n.d.).

The entirety of this research can be of use for Van Hall Larenstein, Deltares, Wageningen Economic Research (Member of the WUR) and DLF Seeds and Science as it provides them with information which they can either use for their own research, or they can build further on the results of this research. DLF Seeds and Science can use the results of this research to see what the expected salinization in the polder of Terschelling will be and which crops are already salt-resistant and which not. This information might help them to develop seeds that are more salt-resistant and how high the salinity threshold value of crops should be in the future for the crops to be able to grow.

The entire research can be of value to ABT (Agrarisch Belang Terschelling), LTO-Noord and Dairyfarm C.G. Cupido as it informs them of which crops can be cultivated on saline soil, where specific crops should be able to grow in the polder by the year 2100 and how much salinization can be expected by the year 2100 in the polder. All this information can possibly help them making decisions for the future, whether they can continue as they are doing now, or if they already want to slowly start making changes.

The municipality of Terschelling, Provincie Fryslân, Wetterskip Fryslân, ANV Waddenvogels, and Acacia Water can use this research to get informed on the possibilities regarding saline and traditional agriculture in the future and how they might be able to help the farmers cope with the future salinization of the polder of Terschelling.

What might be interesting for following studies is to look if there are differences in salt-tolerance between different varieties of the traditional crops. This is because this research only studied one crop in the broad sense while most of the crops have multiple varieties. Is one potato variation more salt-tolerant than the other for example. This would give information on whether different variations of a crop have a different salt-tolerance or not and a better insight in which specific crop variations could be used for saline agriculture.

6. Conclusion

Traditional methods of fertilization and irrigation as well as climate change all have an impact on the soil salinity. Based on the results it can be concluded that traditional agriculture is still going to be possible in the polder of Terschelling by the year 2100. There are some areas along the northern border of the polder where traditional agriculture can still be practiced by the year 2100. Yet the future of agriculture in the polder lies with saline agriculture, as most of the soil from the coast up will become saline based on the intermediate models of Deltares and this might be the case for other places in the Netherlands as well. To ensure food security, the agricultural sector will need to transition to cultivating more salt-tolerant crops that will be able to endure the saline conditions of the polder of Terschelling. Farmers would need to experiment a little with which crops will grow where exactly based on the results of this research, as the salinity tolerance of the crops may vary depending on abiotic factors. Both animal feed and traditional crops can be cultured on saline soil, though the choice in crops will be limited to 25 different crops. Depending on the salinity level of the soil the choice might be even more limited. If the soil were to become highly saline there will only be seven crops (fodder beet, clovers (strawberry), tritacle (forage), asparagus, barley, beets and sugar beets) that can still be cultivated.

Farmers might not be waiting for this information on the moment, however if their land becomes saline they may need this information to keep their business going. Except for possibly new seeds, farmers would not have to buy new or additional equipment for the cultivation of saline crops. It would be wise of the farmers to test their land to know how saline the soil is and what crops can grow on their land. Farmers will likely need to learn some new information with the focus on which crops can be cultivated on saline soil and how abiotic factors like climate and soil type can affect the salt-tolerance of crops.

It has to be kept in mind however that all the results and maps produced at sub question three and four are estimations, based on an intermediate model, of how the salinization of the polder of Terschelling might develop. There are no guarantees that the salinization of the polder will turn out as the results of this research predict. The salinization of the polder would need to be kept monitored and new models need to be made to keep making more accurate estimations on how the salinization of the polder will develop.

A possible way to keep monitoring the salinization of the polder might be through gathering data from the same spots every five years using a monitoring well and putting this data into a model. As well as keeping the models used in this research up to date with the latest information and data. Based on this model maps can be made much like the ones showing the amount of salinization by the year 2100 at multiple depths. These types of maps would be made for the salinization of the time the data was gathered and to make predictions for the future. This way it can be seen how much the salinity of the soil changes over time and predictions for the future can be made.

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