Work Package 3:

Baseline Study Final Report

Chapter 2: Economic impacts of salinity induced soil degradation

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1 Introduction

Soil salinity is a global problem and one of the major causes of land degradation. A major UNEP project, GLASOD (Global Assessment of Soil Degradation), which was a first attempt to produce a world map on the status of human-induced soil degradation, identified soil salinization as one of the major types of soil degradation (Oldeman, et al. 1991). Soil salinization is defined as the accumulation of water-soluble salts in the soil to a level that impacts on agricultural production, environmental health, and economic welfare (FAO, 2011).

The drivers or types of soil salinization has generally been characterised as either primary or secondary (Daliakopoulos et al. 2016). Primary salinization is the long term accumulation of salts in the soil profile through natural processes. Secondary salinization (or human-induced salinization), on the other hand, is driven by human interventions; mainly irrigation with saline water often coupled with poor drainage systems, over-exploitation of ground water, and a lack of or inadequate coastal protection measures to prevent sea water ingress into coastal land. The focus of this chapter is on the impacts of human-induced salinization.

Salinization is a significant constraint to agricultural production globally. For example, FAO and ITPS (2015) estimates that increasing soil salinity problems are taking up to 1.5 million ha of farmland out of production each year and decreasing the production potential of another 20 to 46 million ha. Furthermore, projected changes associated with climate change are likely to exacerbate the risks associated with salinization (Koutroulis et al., 2013). In particular, climate change is generally expected to lead to a reduction in potential yields of major crops (such as wheat) around the world. Hence, the expansion of the level of agricultural output will require greater use of inputs at an increasing cost and innovations in "climate-smart" agricultural practices (Lipper et al., 2014) such as saline farming. This has implications for a number of societal policy areas such as food security and the sustainability of farm enterprises and the global food system.

Despite the significance of salinization, there is sparse information on its impact to agriculture (and economy) in Europe. This is partly because of unavailability of data on the extent and severity of salinization ("salinization map"). This hinders biophysical modelling of impacts of salinization which is a pre-requisite to any assessment of the concomitant economic impacts. For example, the industry and policy makers need information on the economic costs of salinization to guide investment decisions on amelioration to minimise productivity loses and to set priorities for innovative adaptation strategies such as the development of saline agriculture.

The overall aim of Work Package 3 is to develop essential baseline environmental information, data and available knowledge to ensure a consistent integration of methods, tools and information flows across work packages and to ascertain the scope for the development of salt-tolerant agriculture. This chapter addresses one specific objective of the Work Package: an assessment of the economic impacts of salinity-induced land degradation.

The rest of the chapter is structured as follows. Section 2 further reviews key literature on economic impacts of soil salinity. Section 3 presents our conceptual and methodological framework for assessing the economic costs of salinization. This leads to section 4 in which we present empirical results of farm level, regional (case study) and wider economy impact of salinity, structured around a typology of salinization processes (irrigation, seepage and flooding salinization). Section 5 concludes the chapter.

2 A review of studies on economic impacts of soil salinity

The biophysical effects (e.g. yield loses) of soil salinization is relatively well documented. Although there is a wide variation between and within crop types, farm level studies show crop yield loses on salt affected lands of 40 – 63% in India, 36 – 69% in Pakistan and 71 – 86% in Kazakhstan (Qadir et al., 2014). However the social and economic impacts of salinity induced land degradation has received little attention in the literature.

One of the first studies on global costs of salinity was conducted by Ghassemi et al. (1995), who assessed that the global income loss due to salinity as about 11. 4 billion USD per year in irrigated areas and 1.2 billion USD per year in non-irrigated areas. Building on Ghassemi et al. (1995), a comprehensive meta-analysis conducted by Qadir et al. (2014) estimated the annual (inflation adjusted) income losses from salt-affected irrigated areas as US$ 27.3 billion, based mainly on crop yield losses. The authors based their calculations on FAO estimated globally irrigated area of 310 Mha (FAO, 2011) and an estimated 20% of this area being salt affected (62 Mha). Based on this estimates, the annual cost of salt related land degradation was approximated as US$ 441 per ha in 2013. It is noted, however, that these estimates on the global cost of salinized land degradation are mainly based on crop yield losses. These costs are expected to be even higher when other cost components are taken into consideration, such as the environmental costs associated with salt affected lands and the potential social cost on farm businesses. On the other hand, adaptation measures such the use of salt-tolerant crops may be expected to ameliorate the impact of salinization.

Economic studies on the impact of soil salinization in Europe are limited. One of the early studies in Europe is Zekri and Albisu (1993) who studied the economic effect of salinity at the farm level in Berdenas, an area of 56,760 ha of irrigated land situated north of Zaragoza and south of Navarra in Spain. The objectives of the research were to assess soil salinity levels, to simulate the future situation without the effects of salinity and to estimate soil reclamation costs and benefits. They employed an interactive multi-objective mathematical programming methodology, optimizing four different objectives: (a) maximizing total farm gross margin, (b) maximizing labour used and, (c) minimizing labour seasonality in order to avoid periods of unemployment during the year and minimizing risk. The study showed considerable benefits from soil reclamation at a level equivalent to 69 Million Euro, with 799 jobs generated. More recently, Montanarella (2007) study in three European countries (Spain, Hungary and Bulgaria) estimated annual costs of soil salinization mainly as a result agricultural yield losses, but also damages to infrastructure and the environment in the range of 158 – 321 M€.

Most studies focus on the cost of salinity in irrigation systems. A majority of these studies estimate the cost of salinization from biophysical output losses (mainly crop yield losses) for a range of salt-affected irrigation lands (Qadir et al. 2014). Some economic studies take account of additional costs (e.g. remediation of salt degraded land) or additional inputs (and costs) used to mitigate some of the impacts of salt related land degradation, which would otherwise not be used under non-degraded land. The general consensus is that preventing salinization would result in considerable savings, coming from avoidance of yield loss, mitigation and opportunity costs. For example, the cost analysis conducted by Qadir et al (2014) provides values related to the area affected, which allowed for the calculation of an average cost per ha of 148 USD. It may also be considered as an extra income that would be earned if the soils were not saline.

Table 1 summarises estimates of economic costs (yield loss & additional costs) of salinity in different parts of the world. As may be expected, most studies on the economic impact of salt-induced land degradation have been conducted in countries where salinity is a major problem, notably Australia, India, the United States, Iraq, Pakistan, Kazakhstan, Uzbekistan, and Spain. Salinity-related economic analyses particularly have a long history in Australia, where salinity is a prominent problem.

Table 1: Economic costs of salt-induced land degradation in different parts of the world

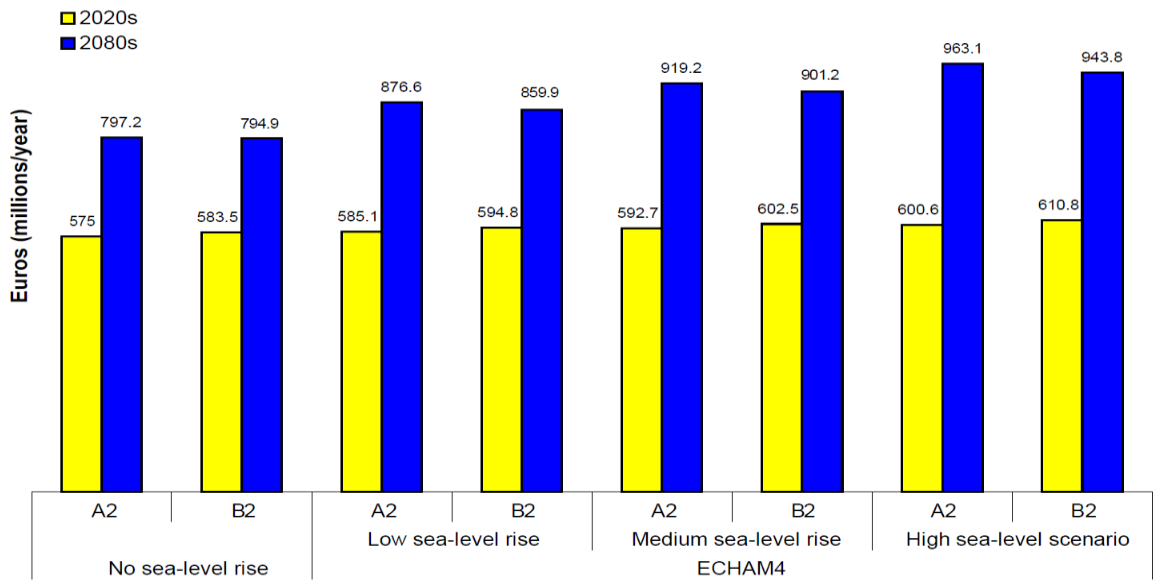
Study authors	**Country**	**Methodology**	**Equivalent in million USD per year**
Marshall and Jones (1997)	Australia	Opportunity costs based on dose response method and mitigation costs	0.83
Janmaat (2004)	India	Opportunity costs (forgone agricultural income)	46
Marshall (2004)	Australia	Transaction costs	20.03
John et al. (2005)	Australia	Opportunity costs	0.09
Aslam and Prathapar (2006)	Pakistan	Opportunity costs	267
McCann and Hafdahl (2007)	Australia	Transaction costs	102
Winpenny et al. (2010)	Spain	Mitigation costs	810

Source: Negacz (2018)

Studies on economic costs of salinization attributable to climate change are limited. One exception is PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis) a major EC-funded project on the impacts of climate change in Europe covering 25 countries (Richards and Nicholls, 2009; Bosello et al. 2012). The study examined all the key direct bio-physical impacts of climate change and sea-level rise: (i) increased erosion, (ii) increased flood risk and inundation, (iii) coastal wetland loss and change, and (iv) (surface) salinization costs. The higher order costs of these impacts were then assessed using a computable general equilibrium (CGE) modelling framework for the EU with country level detail to assess the wider economic implications. Focusing on salinization part of the study, the results show that salinity intrusion costs are substantial and increase with sea-level rise and over time and across all scenarios investigated in the study.

Figure 1 displays salinity intrusion costs under a combination of various climate change/sea level rise scenarios (labelled EHAM4) and socio-economic scenarios (labelled A2 and B2) defined in the PESETA study (for details, see Richards and Nicholls, 2009; Bosello et al. 2012). According to the study, salinity costs range from € 577 – 610 million per year and this is expected to increase significantly rise by 2080s. The study further notes that adaptation is crucial to keep the negative impacts of sea-level rise at an “acceptable” level. We argue that saline agriculture may be part of an adaptation strategy.

Figure 1: Annual costs of damages due to salinity intrusion (millions €/year; 1995 values)



Source: Bosello et al. (2012)

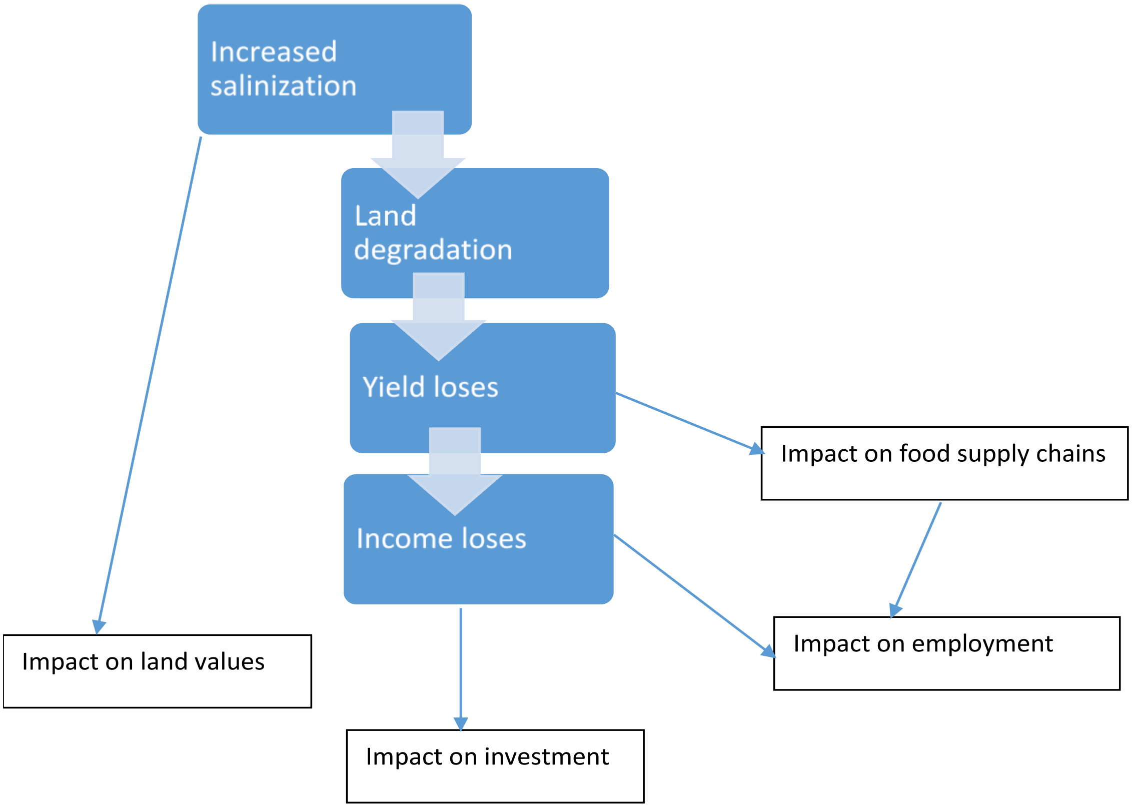
3 Methodological framework to assessing economic impact of salinization

3.1 Overall approach and conceptual framework

The impact of salinization on agriculture depend a complex range of related factors. This includes the ***type*** of salinization (the process that causes salinization), the ***degree*** of salinization (the present state of salinization), the types of crops grown in the affected region, the value of those crops, shocks (such as climate change induced sea-level rise) and farm-level decisions to ameliorate the impacts of salinization (which may include the planting of salt-tolerant crops).

This section develops a modelling framework that attempts to incorporate these variables to allow farm-level and wider level evaluations of the economic risks of soil salinization. The chain of causes and effects that must be appraised is represented diagrammatically in Figure 2 below. As depicted in the figure, the economic analysis calculate the scale of impact along each bold arrow. The wider economic impacts can also be estimated at the regional levels by using appropriate multiplier and other local evidence.

Figure 2: Stylized framework for assessing farm scale and wider impact of salinization



To operationalize the framework, we employ multistage empirical modelling and scenario analysis to represent the chain of causes and effects of salinization on crop yields and "downstream" economic impacts at the farm and regional or wider scales. As alluded to earlier, these impacts critically depend on the *type* and *degree* of salinization, among other factors. In our approach, the type of salinization is defined following the "SalFar framework on salinization processes" (De Waegemaeker, 2019) while the degree of salinization is developed from detailed scenario analysis informed by a critical review of the literature and analysis of data from a survey of SaLFar project partners. Our approach encompasses a series of logical steps, bringing together data from a number of sources (Table 2).

Table 2: A summary of methodology and data sources used to assess economic impacts of salinization.

<u>Farm scale impacts</u>
Step 1: Develop a typology of salinization process based on the "SalFar framework on salinization processes" (De Waegemaeker, 2019)
Step 2: For each type of salinization process, develop a range of salinity scenarios informed by a critical review of the literature (e.g. van Straten et al., 2019) and data from SalFar project partners.
Step 3: Collate a representative list of crops grown in the North sea region (NSR), using information from the survey of SalFar project partners.
Step 4: Conduct a yield gap analysis to estimate production penalties (relative yield) of specific crops under each type of salinization process and salinity scenarios, using crop salt tolerance (threshold and slope) parameters provided by Salt Farm Texel (De Vos et al., 2016)
Step 5: Estimate the yield loss (tons/ha) of specific crops under each type of salinization process and salinity scenarios, using EUROSTAT (https://ec.europa.eu/eurostat) country level data on average yield per ha for each crop.
Step 6: Based on the estimated yield gaps per ha, calculate the gross value of production attributable to these estimated yield gaps, under each type of salinization process and salinity scenarios, using EUROSTAT (https://ec.europa.eu/eurostat) data on average prices of specific crops.
<u>Regional/economy-wide scale impacts</u>
Step 7: Estimate the area affected or at risk of each type of salinization process, using GIS mapping of areas at risk (where available) or expert opinion, combined with typical crop composition using satellite remote sensing data, where available.
Step 8: Extrapolate crop yield loss to areas at risk of salinity under each type of salinization process, using EUROSTAT (https://ec.europa.eu/eurostat) data on average yield per ha for the regionally representative crop composition.
Step 9: Estimate expected financial losses, extrapolated to areas affected or at risk of salinization, under each type of salinization process, using EUROSTAT (https://ec.europa.eu/eurostat) data on average prices of the regionally representative crop composition.
Step 10: Finally, scale up output losses to calculate impacts to the wider economy, using appropriate multipliers where data is available.

3.2 Salinity processes and scenarios

Soil salinity measurement is based on electrical conductivity (EC, in dS/m) and chloride concentrations (de Vos et al. 2016). The soil is considered saline when salt concentration is 4 dS/m or higher (Table 3). Depending on the level, salinity may have a profound influence on plant productivity, as shown in the table below and described in detail in de Vos et al. (2016).

Table 3: Soil salinity classes and effect on crop growth

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

Source: Adapted from Van Orshoven et al. (2014)

To facilitate comparability and compatibility, we employ a typology of salinization developed by De Waegemaeker (2019) as a basis of our economic analysis: irrigation salinization, flood salinization and seepage salinization and aerosol salinization. It may be noted that this typology categorizes the processes that create saline soil conditions and not the resulting saline soil conditions. Due to unavailability of data on the actual degree of salinity, we use scenario analysis to estimate potential economic impact of salinization. To calibrate the analysis of economic impacts, we developed a range salinity scenarios, ranging from slightly saline to strongly saline (Table 3). This was informed by a critical review of the literature (e.g. van Straten et al., 2019) and data from a survey of SalFar project partners. Table 4 summarises salinity scenarios used in the analysis.

Table 4: Salinity scenarios employed in economic analysis

Salinization process	Description	Salinity scenario levels (EC ds/m)
Irrigation salinization (IS)	Salinization that results from irrigation of non-saline agricultural soils with salt or brackish water.	4, 8, 12, 16
Seepage salinization (SS)	Salinization that results from the rise of salt rich groundwater. The salt rich groundwater may be hydrologically linked to nearby seawater.	0.02, 0.09, 0.2, 0.7 (or 6, 26, 64 and 215 mg/l Chloride)
Flood salinization (FS)	Salinization that occurs as soils are flooded by brackish or salt-rich water. Flood risk may be exacerbated by climate change	7.1, 6.08, 5.06, 4.04, 3.03 (dS/m)

Notes: We do not include aerosol salinization in our analyses because SalFar partners did not identify it as a major process of salinization in their regions.

For irrigation salinization, we used four different salinity levels of irrigation water. The salinity levels of irrigation water were chosen based on the study by Van Straten et al. (2019). It may be noted, however, that there was no change in the yield results for salinity levels above EC 4 dS/m.

For seepage salinization we used two levels of ground water salinity scenarios. The calibration of the levels of ground water salinity scenarios was based on data on actual salinity of ground water obtained from the province of Groningen (measured in chloride (Cl) concentrations). Looking at the Cl groundwater concentrations across the province of Groningen we chose the concentrations corresponding to four percentiles 0%, 25%, 50% and 75% (corresponding to 6, 26, 64 and 215 mg/l respectively) of the Cl distribution (or 0.02, 0.09, 0.2, 0.7 EC ds/m equivalent). However, in the empirical analysis we focus only on the salinity scenario level that had a significant impact on yields (i.e. 215 mg/l). The result of the other salinity levels had only a marginal or no impact one crop yield.

Finally, for flooding salinization, we considered that seawater flooding impacts on yield can occur over many years. Therefore, to assess total yield loss (current and future years) as the soil recovers, we firstly calculate the response of different crop types (relative yields) to salt-affected land. We do this by predicting salt soil levels in recovery years. However, for farm-scale assessments, this method could be adapted by basing on known, or historic salt levels. We assumed the complete loss of the standing crop during the flood (zero yield in flood year) followed by a sliding recovery approach during the following years, where the rate of recovery was a function of the salt tolerance per crop type based on predicted salt soil levels.

Thus, the model considers that highly tolerant crops recover yield on inundated fields at a faster rate than sensitive crops. Salt recovery time depends on soil type; for example, a well-drained sandy soil may recover back to post-flood production in 2 years, whereas a heavier, poorly drained soil may take up to 7 years. As such, without knowledge of site specific drainage regimes, we modelled 6 recovery scenarios on a scale of 2 to 7 year soil recovery.

To evaluate the impact of soil salinity and facilitate comparisons, where appropriate, we converted irrigation water salinity (i.e. electrical conductivity of irrigation water, EC_w) into corresponding soil salinity (EC_e) using a leaching factor (LF) of 15 – 20% and procedures outlined in Ayers and Westcot (1985). Where soil salinity was measured in chloride, we converted chloride (Cl) concentrations (in mg/l) into equivalent EC (in ds/m) using established correlations between Cl and EC in the literature (de Vos et al. 2016). Table 4: presents harmonised salinity scenarios employed in analysis and Box 1 below documents established correlations for converting irrigation water salinity into soil salinity and for converting soil salinity EC (in ds/m) into equivalent chloride concentration (mg/l).

Box 1: Established correlations for converting (a) irrigation water salinity into soil salinity (EC) (b) soil salinity EC (in ds/m) into equivalent chloride concentration (mg/l)

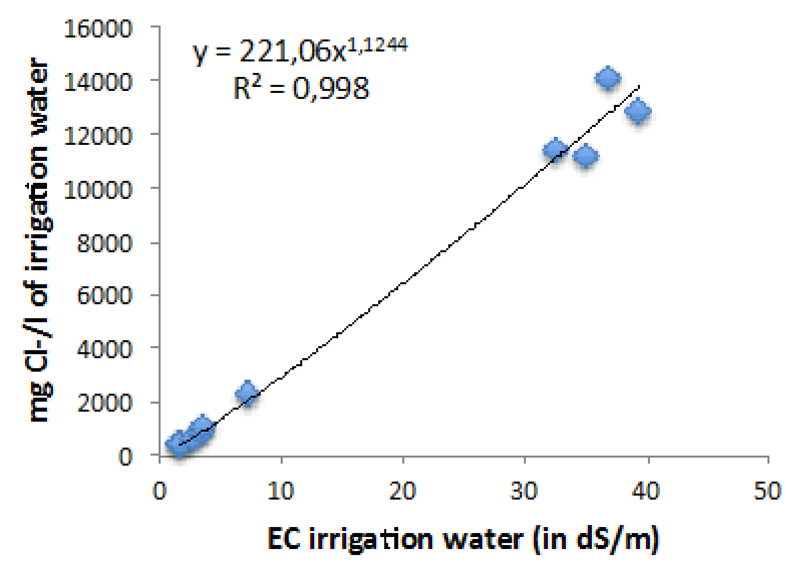
This Box documents procedures for converting (a) irrigation water salinity into soil salinity (EC) (b) soil salinity EC (in ds/m) into equivalent chloride concentration (mg/l). We start with the relationships between the salinity in irrigation water (electrical conductivity of irrigation water, EC_w) and the average root zone or soil salinity (EC_e). When sufficient irrigation water is applied to cause 15% of the water to percolate through the root zone (referred to as leaching factor, LF), then the ECe is approximately equal to 1.5*ECw. This deep percolation of water through the root zone is necessary to continue leaching of accumulated salts out of the active root areas. For example, if the ECw is 5 dS/m, then the ECe would be approximately 7.5 dS/m if we assume that 15% of the applied water moves down through the root zone as deep percolation will leach salts out (Grattan, 2002).

LF 10% leads to ECw x 2.1 = ECe

LF 15-20% leads to ECw x 1.5 = ECe

LF 30% leads to ECw = ECe

Turning to converting soil salinity EC (in ds/m) into equivalent chloride concentration (mg/l), we use established correlation presented in the figure below (de Vos et al. 2016).



3.3 Economic model: Impact of salinity on crop yield and output

Crop salt tolerance can be measured on the basis of two parameters: (a) the threshold salinity that is expected to cause the initial significant reduction in the maximum expected yield and (b) the percentage of yield expected to be reduced for each unit of added salinity above the threshold value (i.e. slope) (Shannon and Grieve, 1998). Using these parameters, the first step in economic analysis is to estimate the crop relative yields based on the following model (Maas & Hoffman, 1977; Tanji & Kielen, 2002):

$$Yr = 100 - b(ECe - a) \quad (1)$$

Where *Yr* is the relative crop yield relative to the potential (under no salinity); *a* is the crop salinity threshold in dS/m; *b* is the slope expressed in percent per dS/m; and *ECe* is the predicted (or measured) salinity level (dS/m) of the soil. Values for *a* and *b* for each crop are traditionally based on FAO salt tolerance data which covers a comprehensive list of crops, albeit rather dated and were based on experiments mainly conducted in non-temperate environments (Maas & Hoffman, 1977; Tanji & Kielen, 2002). However, in our analysis we used updated set of parameters provided in de Vos et al. (2016) which were derived from experiments in Europe (Salt Farm Texel), albeit covering a limited range of crops. Finally in our analysis, values for *ECe* were based on soil salinity scenarios discussed in the previous section (Table 4).

To assess impacts to yields and crop tonnage, reference data for yield per hectare were obtained from EUROSTAT for the year 2018 (https://ec.europa.eu/eurostat). Total tonnage lost of each crop in each year was calculated using the following formula:

$$LY_x = (\mathrm{h} \times Y_{FM}) \times (\frac{100 - Yr_x}{100}) \quad (2)$$

Where LY_x is the loss in yield (tons); *h* is the hectare coverage of each crop; Y_{FM} is the yield per hectare values for each crop; and Yr_x is the relative yield, based on salinity and crop tolerance derived in Equation 1. These were converted to financial losses using data for prices per ton of each crop obtained from EUROSTAT (https://ec.europa.eu/eurostat). Crops were chosen based on a review of economic importance of various crops in Europe, information on the most commonly grown crops in the North Sea Region of Europe and information from the survey of SalFar project partners. A refined list of crops for analysis included potato, barley, sugar beet, wheat, maize, ryegrass, carrot, onion, lettuce, and cabbage.

Finally, the farm level impacts (yield and financial losses) were scaled up to a wider (regional) level, where data was available. This depended on the availability of reliable data on the extent and severity of salinization (or areas at risk of salinization) as well as detailed data on crop composition and distribution.

4 Results: economic impacts of salinization

Economic impacts of salinity can be assessed at different scales or levels: farm, regional and economy-wide scales. We begin with farm level impacts by estimating relative (and absolute) yield and financial losses of specific crops under different salinization processes and salinity scenarios.

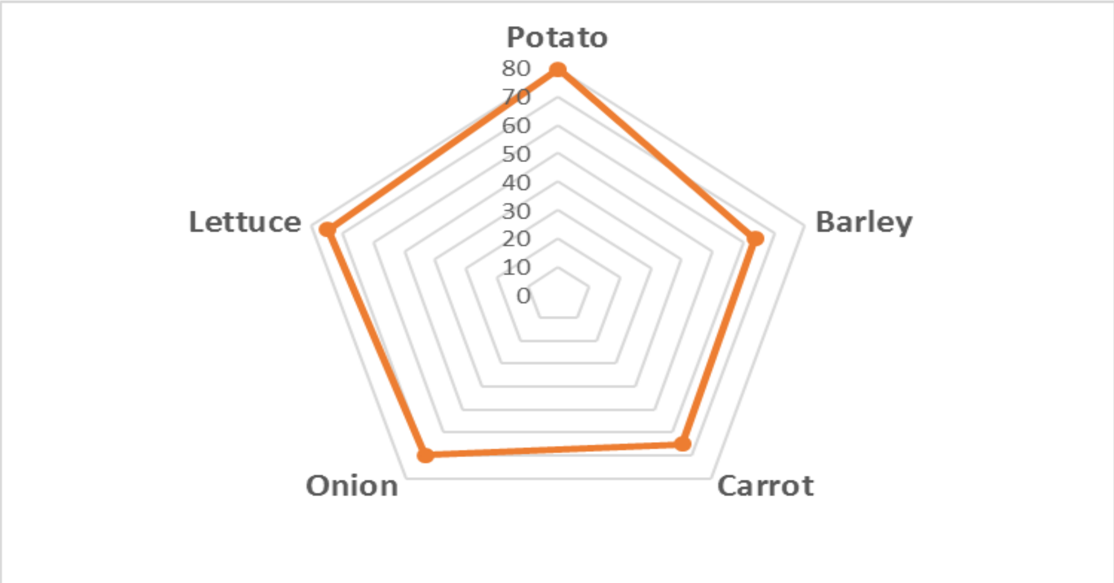
The analysis will show the potential economic impact of different salinization processes on crop yields. This can inform an assessment of crops that would be more affected by soil salinity and the countries that would undergo larger financial losses depending on the economic importance of the crops grown. We then extrapolate the impacts to the regional level (i.e. beyond the farm level). Because of limited availability of data, we present three case studies on regional economic impact of the main types of salinization: (a) Irrigation salinization – Netherlands (Groningen) (b) Seepage salinization – Belgium (Oudlandpolder), and (c) Flood salinization – UK (Lincolnshire)

4.1 Farm level economic impacts of salinization

4.1.1 Impacts of irrigation salinization

To assess the impact of irrigation salinization, we estimated the relative yields of key crops under saline irrigation water of EC 4 ds/m and crop salt tolerance parameters given in de Vos et al. (2016). Relative yields range from 64% (Barley) to 80% (Potatoes), indicating potatoes are comparatively more salt tolerant and barley is the least salt tolerance (Figure 3)

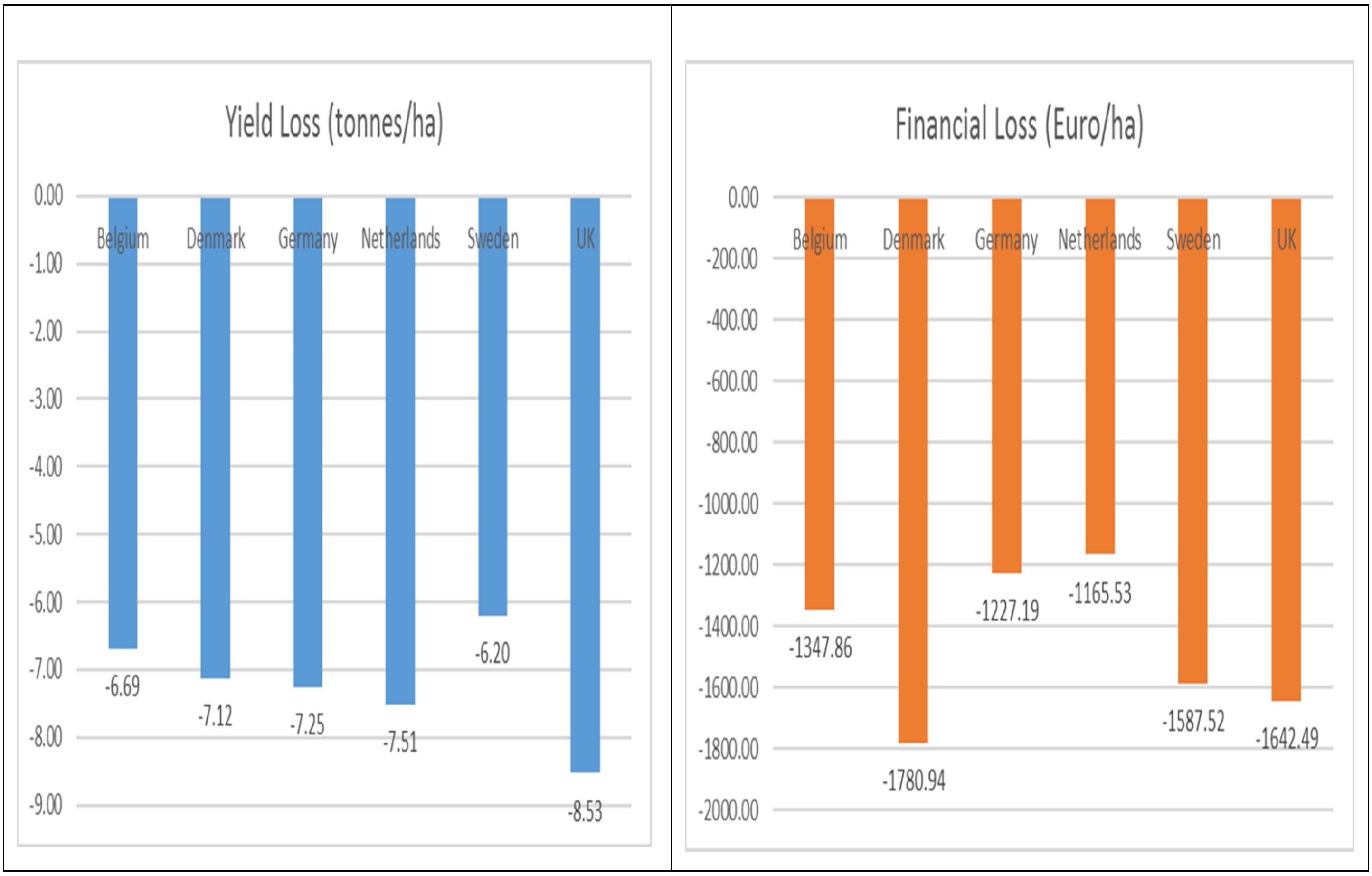
Figure 3: Relative yield of key crops under irrigation salinity



In relation to yield and financial losses, we used salinity effect on potato and barley as an example and compared yield and financial penalties across NSR countries (Figure 4). For instance, if potato was irrigated with EC 4 dS/m, the yield losses range from 6.2 tons/ha (Sweden) to 8.3 tons/ha (UK). We then converted yield loses into financial penalties using crop price data from EUROSTAT (https://ec.europa.eu/eurostat).

The results range from Euro 1478 to Euro 2259; Denmark incur the highest financial loss followed by the UK while the Netherlands would be the least financially affected but would incur the second largest yield loss per ha after the UK. For Norway prices were not available in EUROSTAT, hence we could only say that it would incur the least potential yield losses per ha. Similarly, comparing the financial losses under the other three irrigation levels across the countries, Denmark followed by the UK are the most affected by potato yield losses.

Figure 4: Irrigation salinization: Yield and financial losses of potato



Estimating the impact of irrigation salinity (EC 4 ds/m) on barley show yield penalties ranging from 1.1 tons/ha (Sweden) to 2.8 tons/ha (Belgium) and financial losses ranging from 141 Euro /ha (Sweden) to 483.60 Euro /ha (Netherlands). The results are summarised in Table 5. Belgium followed by the Netherlands, would undergo the highest yield losses among the countries, while the largest financial losses would occur in the Netherlands. Comparing these figures with those of potato further confirms that barley is relatively more salt tolerant.

Table 5: Irrigation salinization: Yield and financial losses of barley across countries

Country	**Yield loss (tons/ha)**	**Financial loss (€/ton)**
Belgium	2.8	391.67
Denmark	1.6	230.72
Germany	2.1	416.00
Netherlands	2.5	483.60
Sweden	1.1	141.00
The UK	2.0	240.55
Norway	1.4	-

4.1.2 Impacts of seepage salinization

To assess the impact of seepage salinization, we used salinity (chloride concentration of 215 mg/l) scenarios of groundwater, assuming that ground water reaches the root zone of the crops. However, the results show that all salinity scenarios have no impact on yield of all the crops investigated as shown in Table 6. Further investigation using FAO salinity tolerance data shows that the only crops that would be affected are carrot and onion. For this type of salinization, we were not able to estimate potential yield losses for each country for carrot and onion because Eurostat does not provide data for the prices and yields of vegetables.

Table 6: Seepage salinization: relative yields for all crops

Crops	Relative yield (%) (Based on Texel Salt Farm salinity tolerance parameters (de Vos et al., 2016)	Relative yield (%) (Based on FAO salinity tolerance parameters (Tanji & Kielen, 2002)
Potato	100	100
Barley	100	100
Sugar beet	*	100
Wheat	*	100
Maize	*	100
Ryegrass	*	100
Carrot	100	95.83
Onion	100	98.44
Lettuce	100	100
Cabbage	100	100

*Note: Texel Salt Farm salinity tolerance parameters were unavailable for these crops.

4.1.3 Impacts of flooding salinization

In the case of flooding salinization, we estimated the relative yields and potential yield losses assuming a flooding event. Hence, the first year after the flood we assume zero yields while the second recovery year we assume soil salinity with EC 7.1 dS/m. Taking as an example potato yields grown the second recovery year after a potential flood, we compare the results across the North Sea Region (NSR) countries. As shown in Figure 5, Yield losses for potato range from 7.86 tons/ha (Sweden) to 10.81 tons/ha (UK) while financial losses range from Euro 1,478 (Netherlands) to Euro 2,259 (Denmark). Similar to the case of irrigation salinization, results showed that Denmark would incur the largest financial losses if potato was grown in a field two years after a flood event and the UK would incur the highest yield losses per ha.

Figure 5: Yield and financial losses for potato under flood salinization across all countries

Results for barley (Table 7), showed that Belgium would incur the highest yield losses per ha, losing 460.05 €/ton and the Netherlands would lose 608.4 €/t. Comparing potato and barley financial losses per ton, it is apparent that countries or/and regions where potato is the principal crop will undergo severe financial losses in a case of flooding than areas which primarily grow barley.

Table 7: Yield and financial losses for barley under flood salinization across all countries

Country	Yield loss (tons/ha)	Financial loss (€/ton)
Belgium	3.48	460.056
Denmark	1.96	289.8
Germany	2.61	522
The Netherlands	3.12	608.4
Sweden	1.37	177.27
The UK	2.55	302.17
Norway	1.77	-

4.2 Regional economic impact of salinization

In this section, we scale up salinity impacts to the wider (regional) level, using case study areas where data was available. For flooding salinization, we draw from a recent study in Lincolnshire UK which evaluated the economic impact of coastal flooding to agriculture (Gould et al 2020), incorporating existing flood models, satellite acquired crop data, soil salinity and crop sensitivity to give a detailed assessment of salt damage to agricultural productivity over time. To illustrate economic impact of irrigation salinization, we chose the Province of Groningen as a case study informed by our research, which suggest that irrigation with brackish water has been identified in parts of the Province of Groningen. Our research also reveal that parts of Belgium (Oudlandpolder) has experienced the risk of seepage salinization. Applying a similar risk-modelling approach to the Lincolnshire flooding example, we analyse the extent of economic risk by applying factors of yield impacts and price levels relating to the climate and economy of the respective regions (Groningen and Oudlandpolder).

Therefore, we present the analysis of three case studies on regional economic impact of the main types of salinization: irrigation salinization – Netherlands (Groningen), Seepage salinization – Belgium (Oudlandpolder), and Flooding salinization – UK (Lincolnshire). Table 8 below summarises the economic impacts across the case study areas and the following sections discusses the individual case studies in more detail. Though not strictly comparable, the results suggest that flooding salinization potentially has the greatest economic impact (as indicated by the financial loss per ha), followed by seepage salinization and irrigation salinization in that order. It should be noted, however, that these losses are limited to direct farm impact in terms of yield losses i.e. excludes wider economy "multiplier" or supplier chain costs that can be substantial. For example, as will be discussed later in the case of flooding salinization in Lincolnshire (UK) in section 4.2.3, these wider economy impacts amounts to approximately Euro 115 million in GVA (Gross Value added) losses.

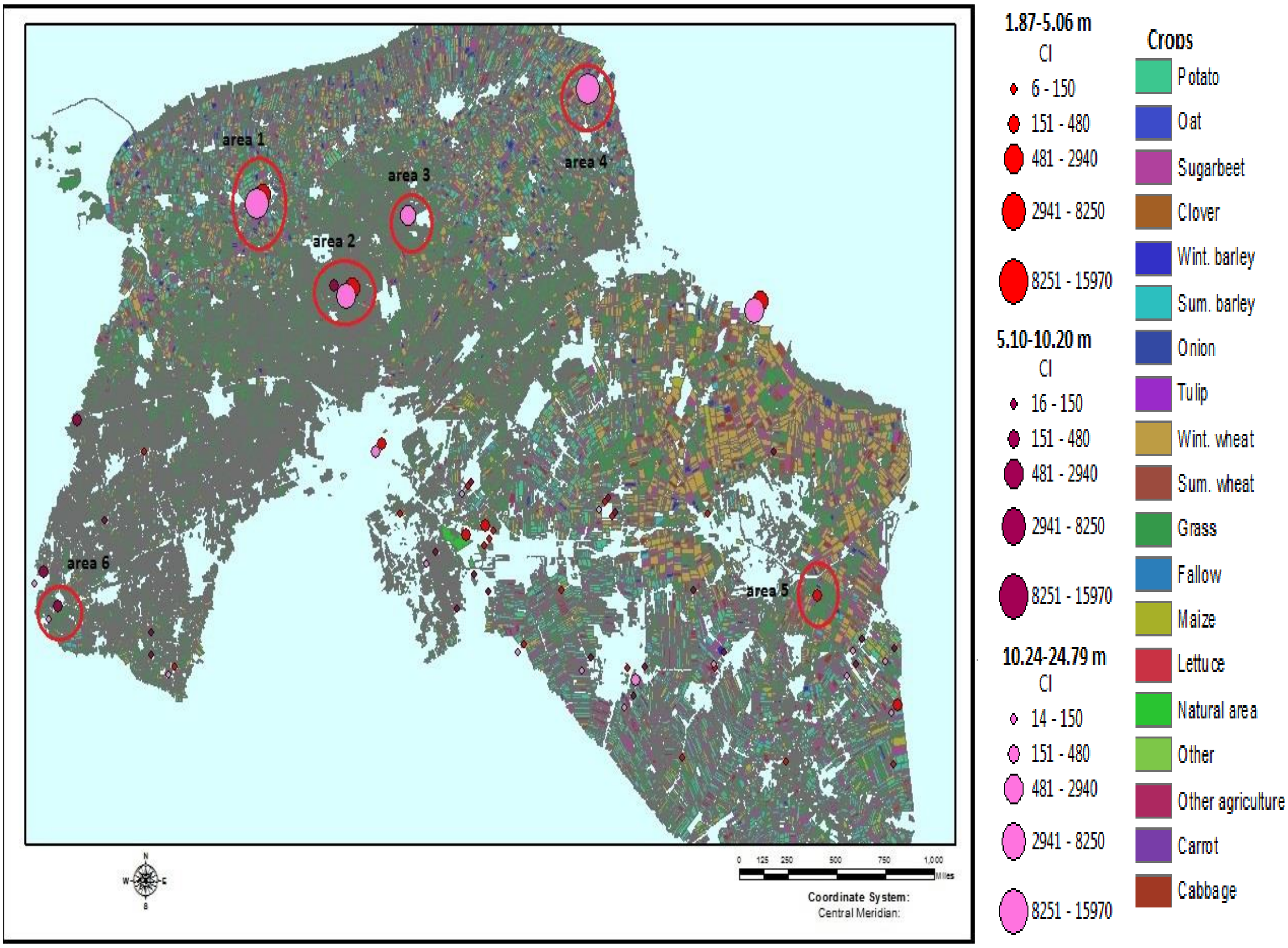
Table 8: Regional economic impact of salinization: North Sea Region case studies

Salinization process	Case study	Area at risk (ha)	Methods	Estimated Loss in yield (tons)	Estimated Financial loss (Euro)	Financial Loss per ha (Euro/ha)
Irrigation salinization	Holland (Groningen)	17,526	GIS mapping of affected areas and analysis of cropping composition and distribution. Groundwater salinity data (Cl) provided by the Province of Groningen	147,992	34,947,861	1,994.06
Seepage salinization	Belgium (Oudlandpolder)	11,938	Mapping of affected areas and analysis of cropping composition and distribution. Groundwater salinity data (EC) provided by Belgium	147,663	27,381,670	2,293.66
Flooding salinization	UK (Lincolnshire)	108,238	Climate (flood modelling) and salinization impact mapping based on GIS and satellite data analysis of cropping composition.	2,022,385	279,548,899	2,582.72

4.2.1 Regional economic impact of irrigation salinization: Province of Groningen

In this section, we estimate the potential yield losses in the province of Groningen assuming that farmers will irrigate with groundwater at different salinity levels. We use a combination of mapping of affected area (i.e. saline ground water irrigated area) and data on cropping composition and distribution. Figure 6 shows the crop map of the province of Groningen and the groundwater salinity levels in different depths as measured from the Province Groningen in 2018 (https://www.provinciegroningen.nl/). The circled areas on the map indicate the areas close to the boreholes that we postulate will be the source of (groundwater) water used for irrigation. Different colours show the different depths at which salinity (chloride concentration in mg/l) was measured, while different sized circles show the various salinity levels. For instance, in “area 4” chloride (Cl) concentration in groundwater at depth 10.24 – 24.79m, is between 8,025-15,970 mg/l.

Figure 6: Crop map in the province of Groningen, with groundwater salinity (Cl mg/l) measurements in different ground depths.



Using the methodology discussed in section 3, we first estimate the relative yields for each crop grown in the six areas shown on the map. In each area relative yield was estimated for each crop grown assuming that it was irrigated with groundwater abstracted at different depths below the ground surface. To estimate the financial impact of irrigating with saline water, reference data for yield per hectare was obtained from the CBS open data source online (CBS, 2019). Assuming high productivity and good land quality of the region, we based our modelling on higher yielding scenarios provided within CBS and conservative salinity tolerance and crop yield penalties.

Table 9 presents the hectares at risk of salinity, the total tonnage loss of each crop and finally the potential financial losses considering the salinity of groundwater at only one depth. We assumed that farmers will irrigate with groundwater closer to the surface rather than deeper. Summing up the potential yield loss for each area we predict that the yield loss (in tons and in equivalent monetary loss in parentheses) will be as follow: maize 3,118 tons (or €469,352), wheat yield loss will be 1,134 tons (or €224,570), sugar beet 20,650,094 tons (€7,367,954,003), barley 1,871,424 tons (or € 362,120,562), and potato 9,120,207 tons

(€1,511,586,940 €). Prices for each crop were obtained from Wageningen University & Research (2019).

Table 9: Crop yield and financial losses due to irrigation salinization in the Province of Groningen, Netherlands.

Areas	EC (ds/m)	Crops	Hectares at risk	Yield (tons per ha)	Loss in yield(ton)	Current yield(ton)	Financial loss (euro)
AREA1	5.31	Maize	257	10.6	1200	2,724	180,614
		Sugarbeet	1057	75.1	34959	79,380	12,473,453
		Barley	1461	7.65	1229	11,176	237,960
		Wheat	2243	8.7	0	19,514.	0
		Potato	3313	33.0	19684	109,329	3,267,657
AREA2	11.46	Wheat	179	8.7	608	1,557	120,456
		Sugarbeet	162	75.1	3173	12,166.20	1,132,327
AREA3	10.86	Maize	643	10.6	6,815	6,815.80	10,257
AREA4	53.10	Wheat	6044	8.7	52,582	52,582.80	104,114
		Onion	657	36.55	24,013	24,013.35	54,991
AREA5	2.17	Sugarbeet	2036	75.1	0	152,903	0
		Wheat	5764	8.7	0	50,146	0
		Barley	1145	7.65	350	8,759	67,726
AREA6	2.65	Potato	1154	33.0	1523	38,082	252,957
		Maize	1454	10.6	1850	15,412	278,482

4.2.2 Regional economic impact of seepage salinization: Oudlandpolder, Belgium

To investigate the regional impact of seepage salinization, we focus on the case of the region of Oudlandpolder, Belgium. The study area was chosen because of the high ground water salinity levels that were observed in recent summers and because of the data availability in these regions. The estimation of crop yield impacts is based on assumed ground water salinity scenarios (i.e. EC 10, 20, 30, 40) and the modelling framework discussed in section 3. The definition of these salinity scenarios were informed by surface water salinity measurements by the Flemish Environment Agency between January-August of 2018.

Table 10 provides the relative crop yields estimated assuming that groundwater of different salinity levels reaches the crops' root zone. We appreciate that this is a big assumption. Results showed that if saline groundwater reaches the root zone, the relative crop yields will be zero in most cases where salinity is greater than EC 20 dS/m. The zero relative yield indicates the upper bound soil salinity level (EC) at which crop growth ceases. In other words, groundwater with EC higher than 20 dS/m will result in all crops stop growing. Given the risk of climate change and extreme drought conditions such as that witnessed in the summer of 2018, farmers in the regions with high groundwater salinity levels should consistently measure their groundwater and soil salinity on their fields, as a risk preparedness strategy.

Table 10: Crop yield losses due to seepage salinization: Oudlandpolder, Belgium.

Crop	Varieties	EC (dS/m) for Leaching Factor (LF) 15-20%	Salinity threshold for groundwater (dS/m)	Slope Percent per dS/m	Yield potential (%)
Potato	Miss Mignonne	15	4.1	6.6	28.06
	Achilles	15	2.9	5.6	32.24
	Foc	15	2.1	5.2	32.92
	Met	15	1.9	5	34.5
	927	15	3.4	5.2	39.68
Barley	Que seed 2014	15	3.3	5.3	37.99
	Que shoot 2015	15	1.7	8.4	0

The regional (Oudlandpolder) impact of seepage salinization was based on a mapping of affected areas and an analysis cropping composition and distribution in the region and groundwater salinity scenarios defined earlier. We assume that the area of crops affected by salinized groundwater in the future will be the green area shown in Figure 7.

Figure 7: Mapping of area at risk of seepage salinization: Oudlandpolder, Belgium

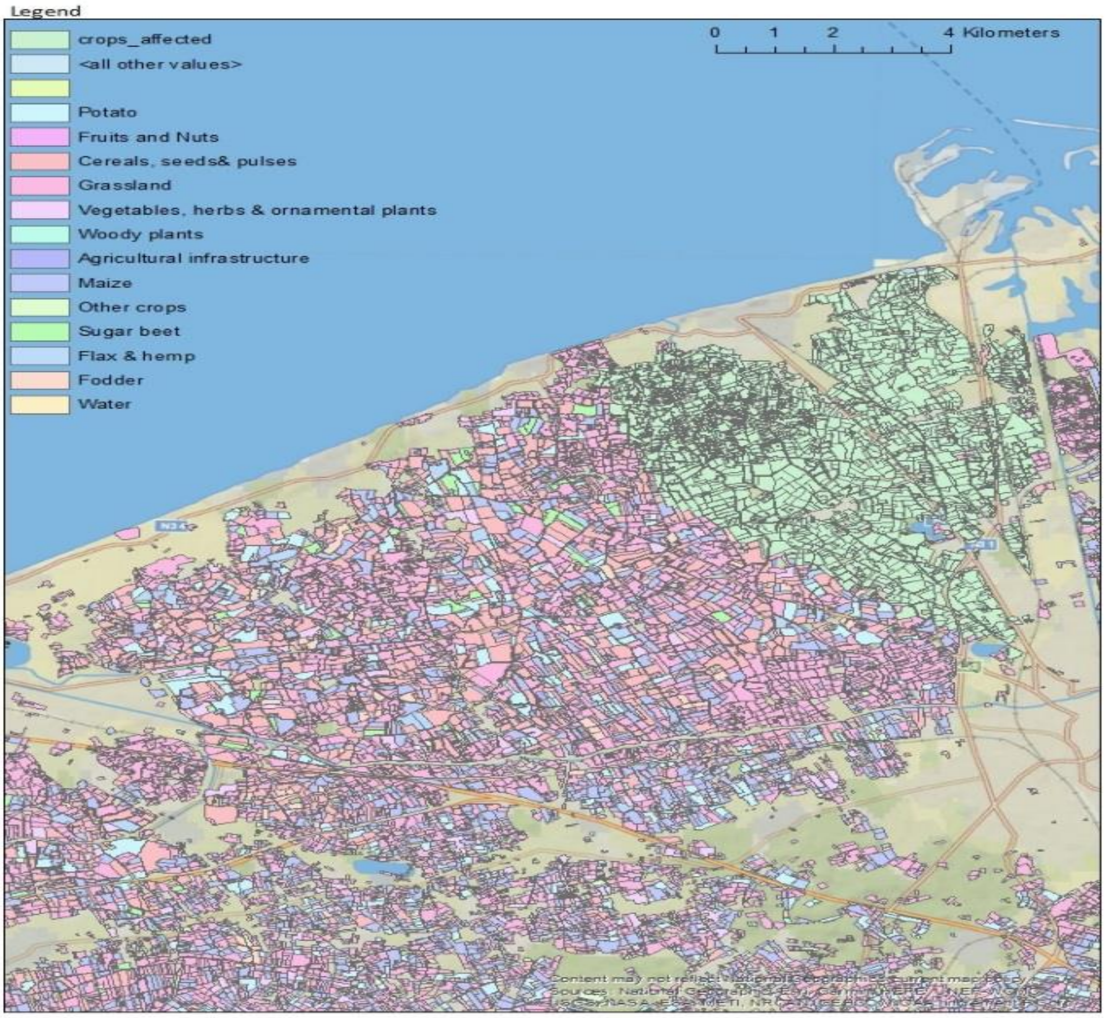


Table 11 presents the potential yield losses for the most commonly grown crops in the area of Oudlandpolder at risk of seepage salinization, assuming that saline groundwater of EC 10 dS/m (equivalent soil salinity of EC 15 dS/m) reaching the root zone. The results show that under seepage salinization, potato yields will be reduced by up to 62,923 tons, wheat by 46,144 tons, barley by 4,044 and sugar beet will be reduced by 34,552. It is noteworthy that sugar beet will incur the highest yield reduction (approximately 53%). The corresponding financial losses for each crop are presented in the last column of Table 11. Financial losses are calculated using EUROSTAT data on annual market prices of crops in Belgium.

Table 11: Regional economic impact of seepage salinization: Oudlandpolder, Belgium

Crops	Variety	Hectares at risk	Yield (tons per ha)	Yield loss (tons)	Current yield (tons)	Financial loss (euro)
Potato	Miss Mignonne	2,389	36.6	62,923	87,437	12,678,984
	Achilles			59,267		11,942,300
	Foc			58,672		11,822,408
	Met			57,290		11,543,935
	927			52,759		10,630,938
Wheat	FAO	7849.28	9.2	46,144	72,213	6,524,761
Barley	Que seed 2014	776.47	8.4	4,044	6,522	535,021
Sugar beet		923.13	79.3	34,552	73,204	7,642,902

Note: Crop yields are taken from Belgian Statistical Office (https://statbel.fgov.be/en)

4.2.3 Regional impact of flooding salinization: Lincolnshire, UK.

Coastal flooding risks are significant within Greater Lincolnshire. The region contributes 10% of the country's agricultural output by value (Collison, 2014), and accounts for a quarter of the UK's Grade 1 Agricultural Land (MAFF, 1988). In this section, we estimate economic and yield losses in Lincolnshire in the case of a flooding event. We use a combination of flood models and GIS/satellite data on cropping composition and distribution.

To assess crop composition within flood scenario regions, we used 2016 Land Cover Plus satellite data ESRI shapefiles from the NERC Centre for Ecology and Hydrology (NERC, 2016). The 2016 data included 11 field categories: 'winter wheat'; 'spring wheat'; 'winter barley'; 'spring barley'; 'beet'; 'field beans'; 'maize'; 'oilseed rape'; 'potatoes'; 'grass' and 'other' (brassica vegetables). These satellite crop data were overlain with selected flood scenarios in ARCGIS.

We then defined three flood scenarios reflecting (i) current breach risk; (ii) future breach risk and (iii) 'big' flood event. However, the primary focus of this chapter is on the current breach risk. For all breaches we assume the post-breach regime is to repair the breach and continue the existing defence strategy. To assess current areas exposed to sea bank breach risk, we used breach scenarios obtained from the UK Environment Agency. These flood scenarios are used to inform the UK flood defence strategy. They model the ingress of flood water for a 1 in 200 year breach (72 hour duration) of sea defences under 2006 climate conditions. 2006 are the most recent breach scenarios data released by the Environment Agency, and as such we describe as 'current'. We used breach scenarios from 67 individual locations spanning a 105km stretch of Lincolnshire coastline (Figure 8). To account for localised differences in tidal behaviour, we grouped these 67 model scenarios into 4 Coastal Zones (CZs) as shown in Figure 8. Using the Land Cover Plus data, average crop composition per breach area was calculated for each of the 4 coastal zones, giving a typical breach crop composition for each stretch of coastline.

Figure 8: Location of the case study area and location of each analysed breach scenario

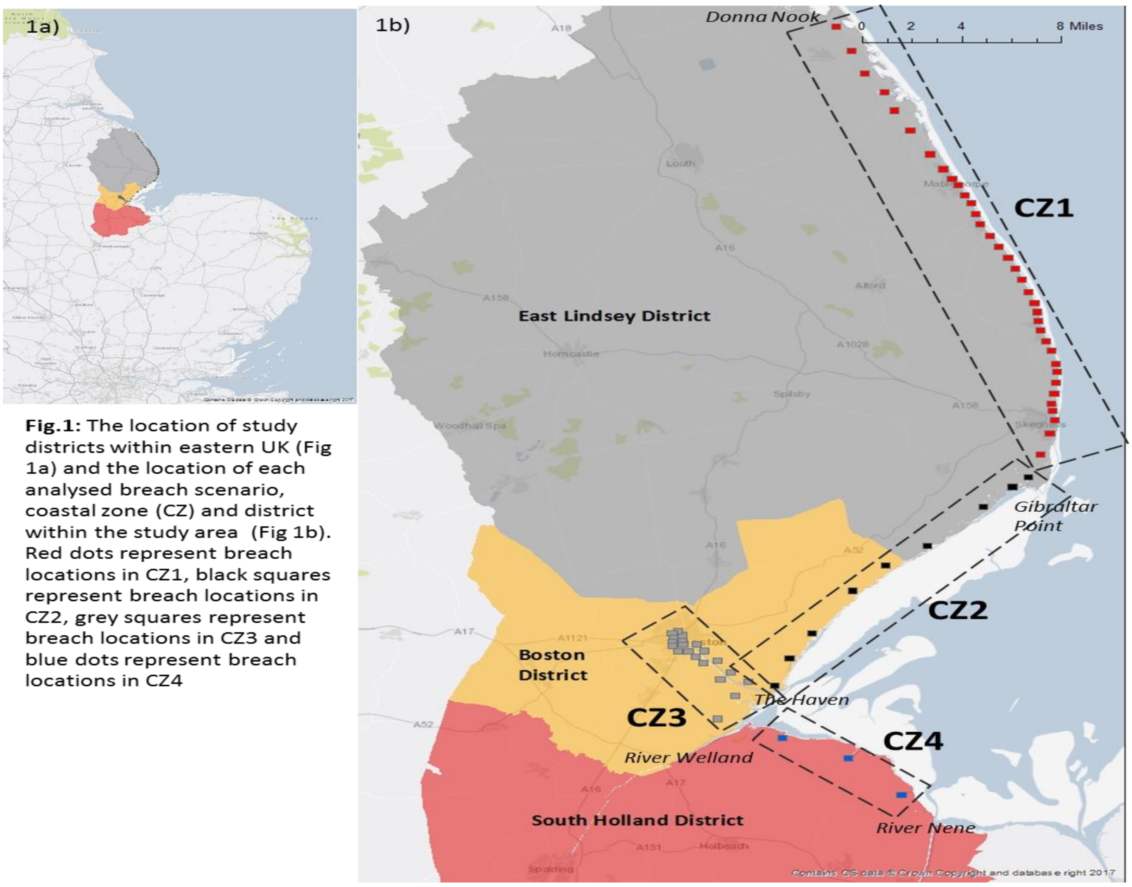


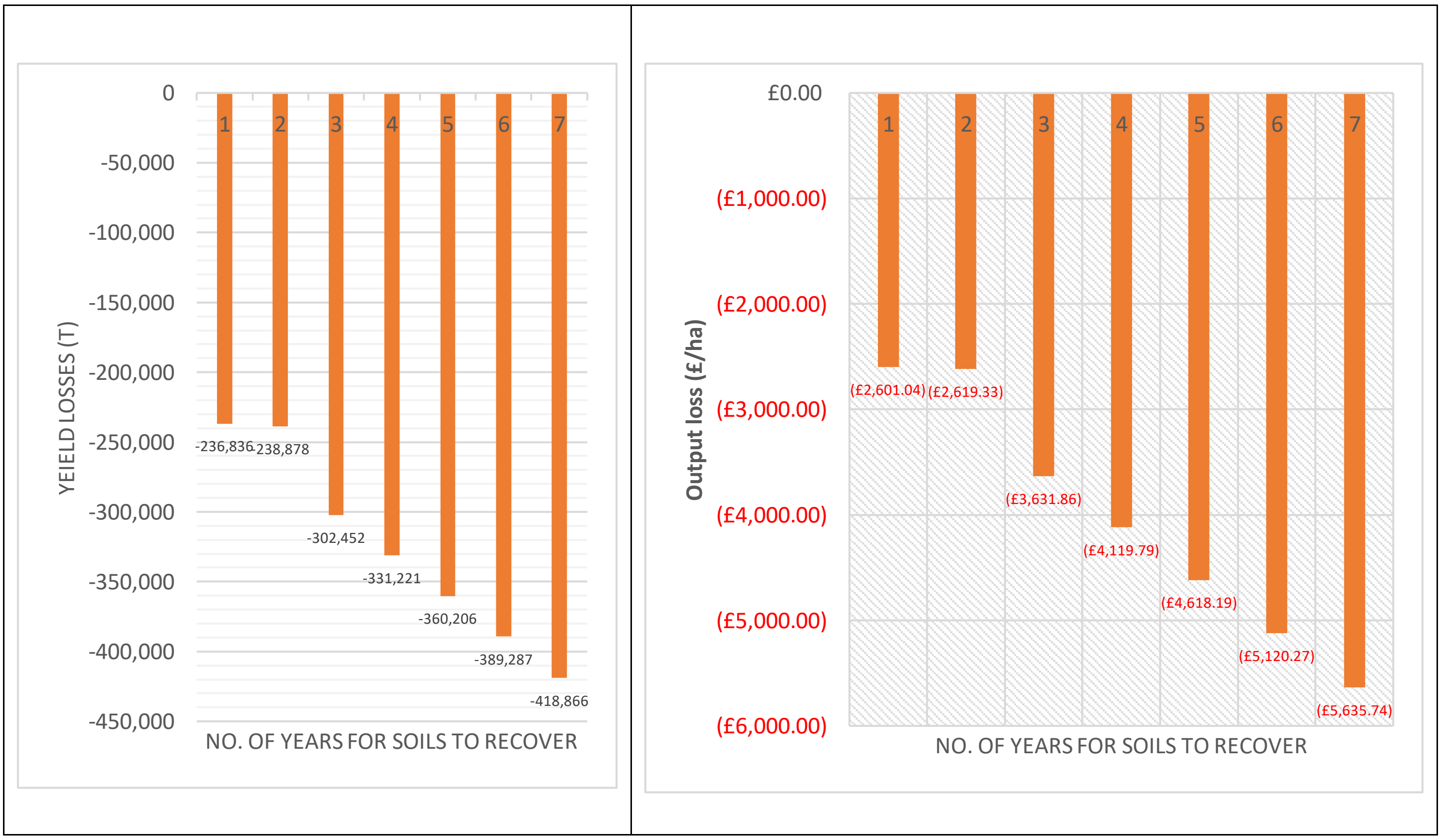
Fig.1: The location of study districts within eastern UK (Fig 1a) and the location of each analysed breach scenario, coastal zone (CZ) and district within the study area (Fig 1b). Red dots represent breach locations in CZ1, black squares represent breach locations in CZ2, grey squares represent breach locations in CZ3 and blue dots represent breach locations in CZ4

To assess total yield loss (current and future years) as the soil recovers, we firstly calculate the response of different crop types (relative yields) to salt-affected land. In this chapter, we do this by predicting salt soil levels in recovery years. However, for farm-scale assessments, this method could be adapted by basing on known or historic salt levels. We assumed the complete loss of the standing crop during the flood (zero yield in flood year) followed by a sliding recovery approach during the following years, where the rate of recovery was defined as a function of the salt tolerance per crop type based on predicted salt soil levels. Thus, the modelling approach captures the fact that highly tolerant crops recover yield on inundated fields at a faster rate than sensitive crops.

To assess impact, reference data for yield per hectare were obtained from the John Nix Farm Management Pocketbook (Redman, 2016), an information source for financial assessments of UK farmland. These were readily converted into output losses in monetary terms using crop price data obtained from EUROSTAT.

Figure 9 diagrammatically shows the yield and financial losses, aggregated across all the coastal zones over the full soil recovery time for all 1-7 year salt recovery time scenarios (1-7 years). Total yield loses over the recovery period is estimated to be up to £418,866 tons while the output loses per ha averages £5,636 over the recovery period.

Figure 9. Regional economic impact of flooding salinization: total yield and output losses per ha over full soil recovery time for all 1-7 year salt recovery time scenarios in Lincolnshire, UK



To investigate heterogeneity in yield and output losses across coastal zones (CZs), we turn to disaggregated analysis of impacts. Figure 10 displays total yield loses (tons) across CZs. The results reveal spatial heterogeneity in yield recovery across and hence yield loses across regions (CZs) due to differences in salt tolerance and crop composition across zones. For example, CZs where salt sensitive crops are dominant would be worst hit by flooding salinization. For example it was found that CZs where salt sensitive crops are dominant suffer 88% yield loss compared to 27% yield loss in more "tolerant" CZs. This implies greater potential for salt tolerant crops in these areas, particularly in early recover phases as a remediation or adaptation option for salt degraded land.

Figure 10: Regional economic impact of flooding salinization; total yield losses across coastal zones in Lincolnshire, UK

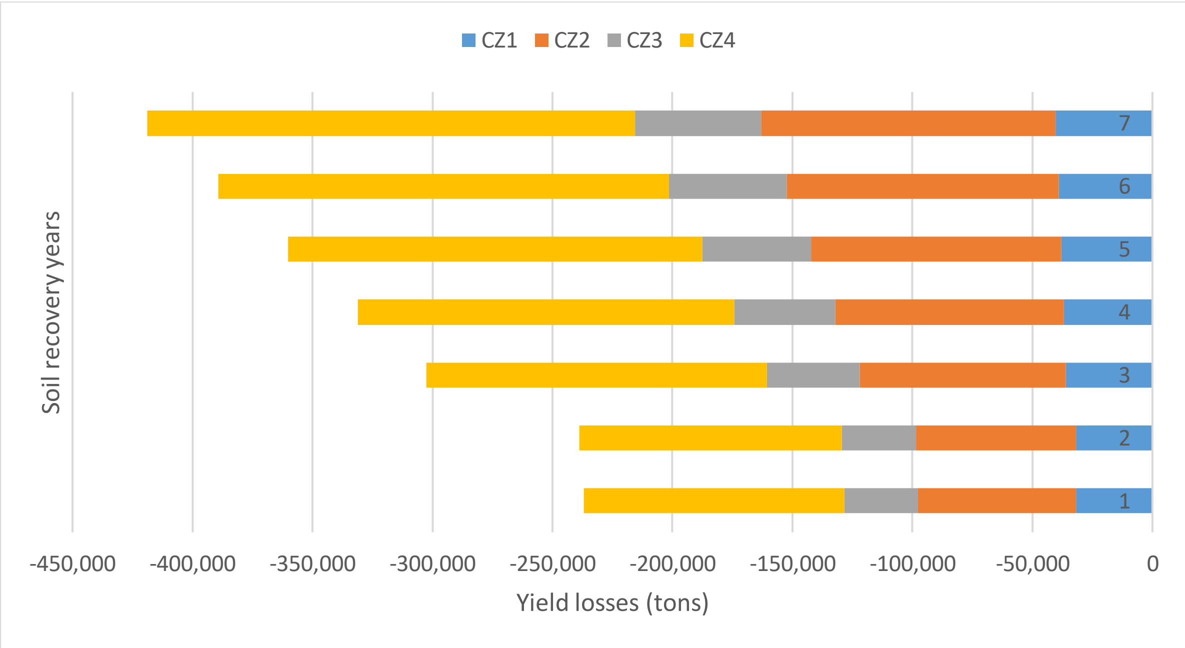


Table 12 reports the total yield losses, output losses and output losses per ha over full soil recovery time for all 1-7 year salt recovery time scenarios (1-7 years) for each coastal zone. This is based on the average breach crop composition in each coastal zone (CZ1-CZ4). The results show that in the first (flood) year alone, a single breach could deprive farms of a total yield of 31,778 tons in CZ1, 66,051 tons in CZ2, 30,671 tons in CZ3 and 108,336 tons in CZ4. When yield losses were converted into potential losses in monetary terms, this translates to £2,684,625 per breach in CZ1, £9,608,181 in CZ2, £4,183,383 in CZ3 and £15,264,116 in CZ4.

The results in Table 12 further shows a non-linear yield recovery (i.e. differences in yield and output losses between years are not uniform) which may be related to the salt tolerance of the typical crop composition. Within 2-3 years, beet, wheat, grass and barley will return to

100% yields, whilst yield losses remain in potatoes and vegetables for longer. As such, in the earlier recovery years (e.g. years 2-3) of coastal zones dominated with more salt tolerant crops, gains in yield recovery may appear more rapid than later years. This is true for CZ1, where the greatest yield losses were for more salt tolerant crops, whereas in the other 3 zones, the greatest losses were for more salt sensitive crops.

The more salt sensitive crops typical of our study region tend to have higher commercial value. As such, such crops suffer more damage and have greater financial loss, exacerbating the financial flood impact. When total output losses were converted to pounds sterling per hectare of agricultural land flooded (over the entire recovery duration), the highest values were found in CZ2 (£3,257.44 to £7,509.73 per ha), followed by CZ4 (£2,911.97 to £6,533.34 per ha), then CZ3 (£2,866.58 to £6380.43 per ha), with CZ1 having the lowest (£1,368.18 to £2,119.46) (Table 2). This suggests CZ1, where grazing is more commonplace and there is less vegetable and potato production, is a more resilient coastal zone to the long term impacts of flooding.

Table 12. Total yield losses, output losses and output losses per ha over full soil recovery time for all 1-7 year salt recovery time scenarios (1-7 years).

			No. of Years for Soils to Recover					
		Flood Year	**2**	**3**	**4**	**5**	**6**	**7**
Yield Losses (t)	**CZ1**	31,778	31,825	36,095	36,959	37,863	38,985	40,225
	CZ2	66,051	66,659	85,991	95,112	104,271	113,442	122,702
	CZ3	30,671	30,879	38,691	42,109	45,550	49,041	52,589
	CZ4	108,336	109,515	141,675	157,041	172,522	187,819	203,350
Output Losses (£)	**CZ1**	£ 2,684,625	£ 2,689,932	£ 3,236,549	£ 3,458,680	£ 3,690,058	£ 3,916,679	£ 4,158,767
	CZ2	£ 9,608,181	£ 9,680,736	£ 13,823,189	£ 15,853,098	£ 17,921,588	£ 20,013,414	£ 22,150,743
	CZ3	£ 4,183,383	£ 4,209,929	£ 5,919,917	£ 6,746,154	£ 7,589,012	£ 8,439,952	£ 9,311,382
	CZ4	£ 15,264,116	£ 15,409,027	£ 21,675,166	£ 24,737,134	£ 27,865,800	£ 31,013,861	£ 34,246,798
Output Losses per ha (£/ha)	**CZ1**	£ 1,368.18	£ 1,370.89	£ 1,649.47	£ 1,762.67	£ 1,880.59	£ 1,996.09	£ 2,119.46
	CZ2	£ 3,257.44	£ 3,282.04	£ 4,686.45	£ 5,374.65	£ 6,075.92	£ 6,785.11	£ 7,509.73
	CZ3	£ 2,866.58	£ 2,884.77	£ 4,056.50	£ 4,622.66	£ 5,200.21	£ 5,783.30	£ 6,380.43
	CZ4	£ 2,911.97	£ 2,939.62	£ 4,135.02	£ 4,719.16	£ 5,316.02	£ 5,916.58	£ 6,533.34

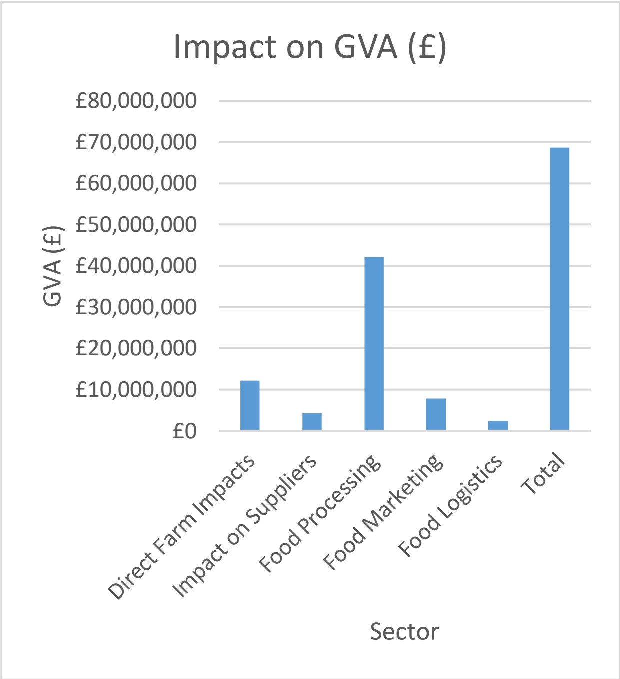
Finally, we turn to the impacts of coastal flooding salinization on the wider agri-food economy. It is acknowledged that bio-physical impact of flooding salinization is not limited to farmland (crop yields), but will have cascading negative consequences both backward (e.g. fertiliser, machinery suppliers) and forward (e.g. processing, distribution) along the supply chain. Based on the outputs of our model, Table 13 reports the results of a broader assessment of the impacts of a coastal flood salinization to the wider agri-food economy based on the flood year data alone.

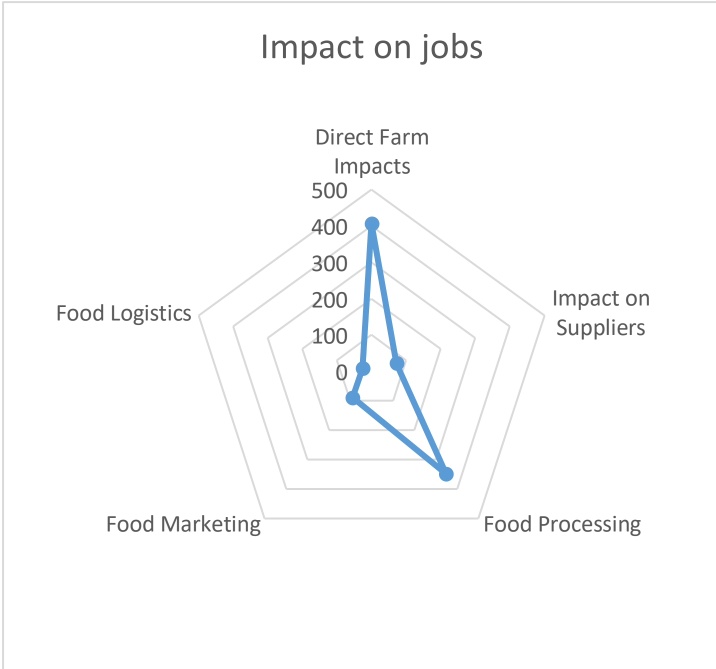
Table 13: Wider economy impacts of flooding salinization in Lincolnshire, UK: jobs and costs to Gross Margins (GM) or Gross Value Added (GVA) throughout the food value chain.

	At Risk	**CZ1**	**CZ2**	**CZ3**	**CZ4**	***Total***
Direct Farm Impacts	Jobs	45	111	49	202	*407*
	GM	£ 1,341,985	£ 3,339,480	£ 1,482,514	£ 6,058,340	*£12,222,319*
Impact on Suppliers	Jobs	5	23	10	34	*72*
	GVA	£ 287,134	£ 1,340,610	£ 577,601	£ 1,968,726	*£4,174,071*
Food Processing	Jobs	38	95	42	173	*348*
	GVA	£ 4,615,120	£11,484,552	£ 5,098,403	£ 20,834,779	*£42,032,854*
Food Marketing	Jobs	10	24	11	44	*89*
	GVA	£ 859,198	£ 2,138,082	£ 949,171	£ 3,878,815	*£7,825,266*
Food Logistics	Jobs	3	7	3	13	*26*
	GVA	£ 256,614	£ 638,574	£ 283,486	£ 1,158,473	*£2,337,147.00*
Total	Jobs	101	261	116	466	*944*
	Jobs per ha	0.07	0.09	0.08	0.09	*0.08*
	Direct Losses	£ 7,360,050	£ 18,941,297	£ 8,391,175	£ 33,899,133	*£68,591,655*
Multipliers	*Jobs*	*145*	*376*	*167*	*671*	*1359*
	GVA	*£10,598,472*	*£ 27,275,468*	*£ 12,083,292*	*£ 48,814,752*	*£98,771,984*

The results suggest significant economic losses; total job losses loss and Gross Value Added (GVA) across CZs is, respectively, approximately 944 and £69 million. Figure 11 summarises disaggregated impacts by sector, displaying total impacts across coastal zones. As shown in the figure, the greatest comparative losses are borne by food processing (£42 Million) followed by direct farm impacts in terms of loss in total Gross Margins (GM). These sectors similarly suffer higher losses in jobs; food processing job and direct farm losses amount to 348 and 407 respectively.

Figure 11: Wider economy impacts of flooding salinization in Lincolnshire, UK:





These costs are expected to be even higher when other cost components are added, e.g. environmental costs associated with salt affected lands; potential social cost of farm businesses. Saline agriculture, as an adaptation strategy, has the potential to ameliorate these impacts. Future studies could assess the magnitude of the benefits afforded by saline agriculture adaptation. For example, increasing drought combined with projected sea level rises will lead to more sustained threats from salinization and create a sustained, long-term opportunity for salt tolerant crop varieties

5 Conclusions

This chapter first reviewed the key literature on economic impacts of salinization and presented a conceptual methodological framework that may be applied to assessing such impacts, focusing on three typologies of salinization: irrigation salinization, seepage salinization and flooding salinization. We conceptualized impact on difference scales; farm level, regional and wider economy scales. We then applied the framework, first to estimate crop yield and financial losses due to each salinity process. Subsequently we scaled up the impact to regional or wider levels using data on affected areas and information on crop composition and distribution, where available. The analysis shows that there is significant economic impact of salinization.

Further, we find that the magnitude of the impact of salinization critically depend on a range of factors which include; the type of salinization process, degree/severity of salinity, types (and value) of crops grown, farm level decisions/choices such as the use of salt tolerant crops and other adaptation mechanisms as well as external shocks such as sea level rise due to climate change. These factors may also be linked to spatial differences. For example, in flooding salinization case study of Lincolnshire, we find marked differences in flood resilience and the concomitant economic impact of salinity across coastal zones.

The framework may provide a platform for risk assessment in regions where salinity poses a significant threat to agricultural production and the local/national economy. Furthermore, the analysis provides a "baseline" for economic costs of salinization and may inform assessment of adaptation (or mitigation) measures such as the adoption of salt tolerant crops.

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