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# Simulating the effects of sea level rise and soil salinization on adaptation and migration decisions in Mozambique

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**Abstract.** Coastal flooding and sea level rise (SLR) will affect farmers in coastal areas, as increasing salinity levels will reduce crop yields, leading to a loss of net annual income for farming communities. In response, farmers can take various actions. In order to assess such a response under SLR, we applied an agent-based model (ABM) to simulate the adaptation and migration decisions of farmers in coastal Mozambique. The ABM is coupled with a salinization module to simulate the relationship between soil salinity and SLR. The decision rules in the model (DYNAMO-M) are based on the economic theory of subjective expected utility. This theory posits that households can maximize their welfare by deciding whether to (a) stay and face losses from salinization and flooding, (b) stay and adapt (switching to salt-tolerant crops and enhancing physical resilience such as elevating houses), or (c) migrate to safer inland areas. The results show that coastal farmers in Mozambique face total losses of up to US$12.5 million per year from salt intrusion and up to US$800 million per year from flooding of buildings (RCP8.5 in the year 2080). Sorghum farmers may experience little damage from salt intrusion, while rice farmers may experience losses of up to US$15,000 per year. We show that medium-sized farmers (1–20 ha) are most at risk. This is because their farm size means that adaptation costs are substantial, while their incomes are too low to cover these costs. The number of households adapting varies between different districts (6%–50%), with salt adaptation being the most common, as costs are lowest. Despite adaptation measures, about 13%–20% of the total 300,000 farmers in coastal flood zones will migrate to safer areas under different settings of adaptive behaviour and different climatic and socioeconomic scenarios.

## 1 Introduction

With climate change and rising sea levels, coastal communities will increasingly face the risk of flooding, affecting their livelihoods. In addition, sea level rise (SLR) will further increase the salinization of coastal agricultural lands, affecting the fertility of coastal soils and crop yields (Materechera, 2011; Montcho et al., 2021). With an economy that is 70% dependent on agriculture (World Bank, 2017) and two-thirds of the population living in coastal areas, Mozambique already suffers from flooding and salinization in coastal zones. Given the projected trends, Mozambique is investigating adaptation options for coastal farmers to reduce the risk associated with SLR. Measures such as switching to salt-tolerant crop varieties may help

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farmers who have the resources and capacity to implement adaptation measures. For others, however, migration to safer locations may become inevitable (Nicholls and Cazenave, 2010).

Several studies have been conducted on the impact of salinity on crop production in Mozambique and other regions. For example, the Instituto de Investigação Agrária de Moçambique (IIAM) conducted an initial study that identified salinity as a problem, with $EC_e$ values exceeding 16 dS $m^{-1}$ in coastal areas. Additional data were published in subsequent studies at the national level (e.g. FAO & ISRIC, 2012) and at the global level (e.g. Ivushkin et al., 2019; Hassani et al., 2020; Hassani et al., 2021). Hassani et al. (2020) simulated salinity maps in agricultural areas and estimated 85,350 ha of salt-affected area in Mozambique. In addition, several studies have assessed how increased salinity levels may affect crop yields at different scales. For example, estimates based on remote sensing show that salt stress in plants limits their ability to take up water (Ivushkin et al., 2019; Madrigal et al., 2003). As a result, saline soils can reduce the fertility of arable land and reduce yields by more than 50% (Anami et al., 2020; Ivushkin et al., 2019). FAO (2021) published a map showing the spatial distribution of salt-affected areas in Mozambique as highly saline. Furthermore, Hasegawa et al. (2022) project the impact of climate change on crop yields in a global dataset reviewing 202 studies from 1984 to 2020 in 91 countries. They also consider the adaptation options of fertilizers, irrigation, cultivars, soil, organic matter management, planting time, tillage with irrigation, and fertilizers as the most important adaptation options. Adaptation by changing crop type can increase crop yield by 7%–15% (Challinor et al., 2014).

While SLR-induced migration in coastal areas has received attention in recent years (Reimann et al., 2023; Hauer, M. E. et al., 2020), these studies mostly focus on migration-related to flood risk. There are currently only a few studies on the effects of salinization and SLR on migration. For example, Chen and Mueller (2018) studied coastal Bangladesh and used a regression approach to observe migration to inland areas. Duc Tran et al. (2023) interviewed farmers in coastal provinces of Vietnam's Mekong Delta and assessed the perspectives of 120 farmers on rural out-migration. They found that rural out-migration is closely related to household vulnerability to natural disasters such as drought and salt intrusion in the Mekong region. In addition, the dynamic interactive vulnerability assessment (DIVA) model (Vafeidis et al., 2008; Hinkel and Klein, 2009) is a widely used modelling framework for studying coastal systems and studies coastal erosion, coastal flooding, and salt intrusion in deltas and estuaries (Wolff et al., 2016; Fang, Jiayi, et al. 2020). However, DIVA does not account for salinity intrusion into coastal aquifers. No studies have assessed the combined effects of flooding and salinization on both adaptation and migration responses in coastal areas.

In order to simulate the effects of SLR and salinization on the migration of coastal farmers, a model is needed that can simulate adaptation and migration decisions (and the trade-offs between them) under different scenarios of future salinization. Several methods could be used to address this challenge. For example, statistical models (e.g., Chen and Muller, 2018) can be useful but often require large amounts of data to produce significant results and may therefore be less suitable for a data-poor region such as Mozambique. Furthermore, a popular simulation model for migration and climate change is the gravity model (Cameron, 2018; Mallick & Siddiqui, 2015; Robinson et al., 2020; Simini et al., 2012). This model uses distance and population size (in the origin and destination of migrants) as the main drivers of migration (Lee, 1966). Gravity models are useful tools

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for exploring larger migration flows. Both statistical and gravity models are less suitable for assessing individual migration decisions and how these relate to other adaptation measures, where individual decisions are highly dependent on household characteristics, assets and the environment.

As we focus here on individual farmers' decisions on adaptation and migration, agent-based models (ABMs) have emerged as promising tools (Thober et al. 2018). ABMs allow us to assess how individual farmers' decisions are influenced not only by their environmental context (flooding, salinization, etc.) but also by other agents, such as the government. For example, Cai and Oppenheimer (2013) used an ABM to simulate climate-induced agricultural labour migration in the United States. Another recent example is the DYNAMO-M model built for France. This model simulates household decisions in response to coastal flooding by evaluating trade-offs between adaptation and migration. Such decisions are made under different scenarios of SLR, flooding and government intervention for flood protection (Tierolf et al., 2023). However, this model focuses only on the flood adaptation of households in urban areas and does not include salinization processes or the impact on crop yields for rural farmers.

The main goal of this paper is to investigate the interlinked migration and adaptation responses to both flood risk and salinization. This study is the first to develop a model to simulate both the adaptation and migration decisions of farmers in Mozambique under different SLR and salinization scenarios. We further improve the model by adding a novel database of household characteristics. We run the model with an annual time step from the current year to 2080 and also include flood risk as a second environmental driver alongside salinization.

The remainder of this paper is organized as follows: Chapter 2 discusses the case study; Chapter 3 describes the methods, including the ABM and data; and Chapter 4 presents the modelling results. Chapters 5 and 6 discuss the results, limitations and conclusions, respectively.

## 2 Case Study: Mozambique

Mozambique is a coastal country in southeastern Africa with a population of 33 million, almost 70% of whom work in agriculture. With a 2470 km coastline on the Indian Ocean and tens of thousands of people living in coastal floodplains, the country faces a high risk of coastal flooding from tropical cyclones (Neumann et al., 2015).

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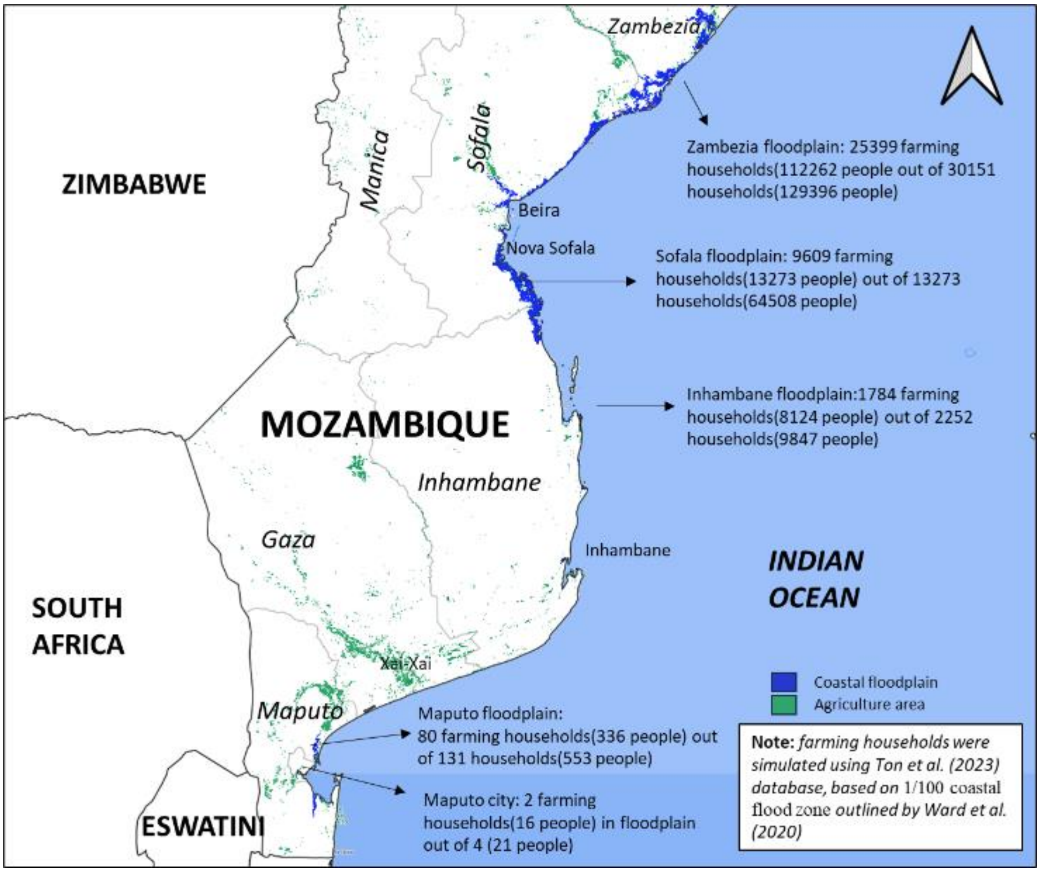


**Figure 1** Map of the coastal flood zones in Mozambique and number of households (source: Ton, Marijn,., 2023).

Mozambique has experienced several floods in the last decade. For example, the recent cyclone Idai flood in 2019 affected 3 million people, with 1.85 million in Mozambique (Relief web 2019). The impact was huge, with 905 fatalities and an estimated economic loss of US$3 billion (Nhundu, 2021). Figure 1 shows the flood zones affected by coastal flooding only, based on Ward et al. (2020). Figure 1 also shows the number of households involved in farming in the flood zone using a database from Ton, Marijn, (2023). In total, 48,651 farming households (219,194 farmers) live in coastal floodplains. In addition to the direct effects of flooding on buildings and infrastructure, agriculture will increasingly be affected by salt intrusion and lower yields. These impacts may affect the entire economy since 64% of Mozambique's total land area is agricultural, and 27% of the GDP comes from agricultural exports (The World Bank, 2017). The harvested area includes 47% rice, 26% maize, 16% cassava, and 11% legumes (see Supplementary annex S1.2).

Mozambique's dependence on agricultural exports also makes it one of the most vulnerable and least prepared countries for climate change-related risks (UND, 2015). For example, salt intrusion reduces yields, as most farmers in Mozambique grow rice, which is not a salt-tolerant crop. The relatively low GDP per capita of $514.5 in the year 2022 (World Bank 2022) makes

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it difficult for households to adapt. As a result, Mozambique is also the third-largest recipient of climate finance, receiving around $147.3 million in 2016 (HBS, 2016).

There are several adaptive responses to reduce climate risk: (1) At the farm level, farmers can reduce excess salt levels in the soil by applying irrigation, using manure or compost (Chen et al., 2020; Islam et al., 2017), adding gypsum, or applying topsoil replacement (Ibrahim et al., 2012; Sarwar et al., 2011; Tahir & Sarwar, 2013). In addition, a generally accepted and sustainable adaptation measure is the use of a salt-tolerant crop variety (Atzori, 2022; Bourhim et al., 2022; Negacz et al., 2022). (2) In order to reduce the direct impact of flooding on assets and people, the government is currently assessing flood risk and investing in flood risk management, such as levees. Although Mozambique does not have national flood protection standards, new flood adaptation plans are being implemented to protect people and assets, for example, around the city of Beira. However, most government projects focus on the population in urban centres and often exclude the rural population. Rural households are mostly dependent on individual flood adaptation measures, such as raising houses. (3) If climate adaptation measures, either by the government or by individual households and farmers, fail, people may have no choice but to leave the affected low-lying areas (Fion De Vletter, 2007). Internal socioeconomic-driven migration has already been an issue in Mozambique since the 1980s (First, 1983) and has led to internal migration from the poor rural south to the northern cities in search of better employment opportunities. SLR, increased flooding and land degradation due to salinization may further trigger migration from the coast to safer areas.

## 3 Methods

Figure 2 shows how we extend the DYNAMO-M ABM of Tierolf et al. (2023) with a salt intrusion module. The ABM simulates household migration and adaptation decisions based on the discounted expected utility (DEU) theory. These decisions are tested under SLR (RCPs 4.5 and 8.5) and socioeconomic development (SSP2) over the period 2020–2080 with annual time steps. While the ABM simulates the adaptation and migration behaviour of households living in the 1/100 coastal flood zone, a coupled gravity-based migration model simulates internal migration flows towards the coastal flood zone and between inland areas (departments). At each annual timestep, farmers can (a) reduce flood risk by implementing floodproofing measures to protect their homes and (b) reduce soil salinity on their farmland by switching to a more salt-tolerant variety. These decisions are influenced not only by the level of salinization and flood risk but also by the socioeconomic characteristics of farming households and their farm size based on available statistics. Every year, soil salinity increases due to a steady SLR (Figure 3). In addition, a flood event may occur each year within the flood zones with a probability associated with return periods of up to 1,000 years (i.e., the flood associated with a 5-year return period has a 20% probability of occurring each year). If such a flood occurs, the salinity of the soil will also increase due to the salt deposited by the flood water.

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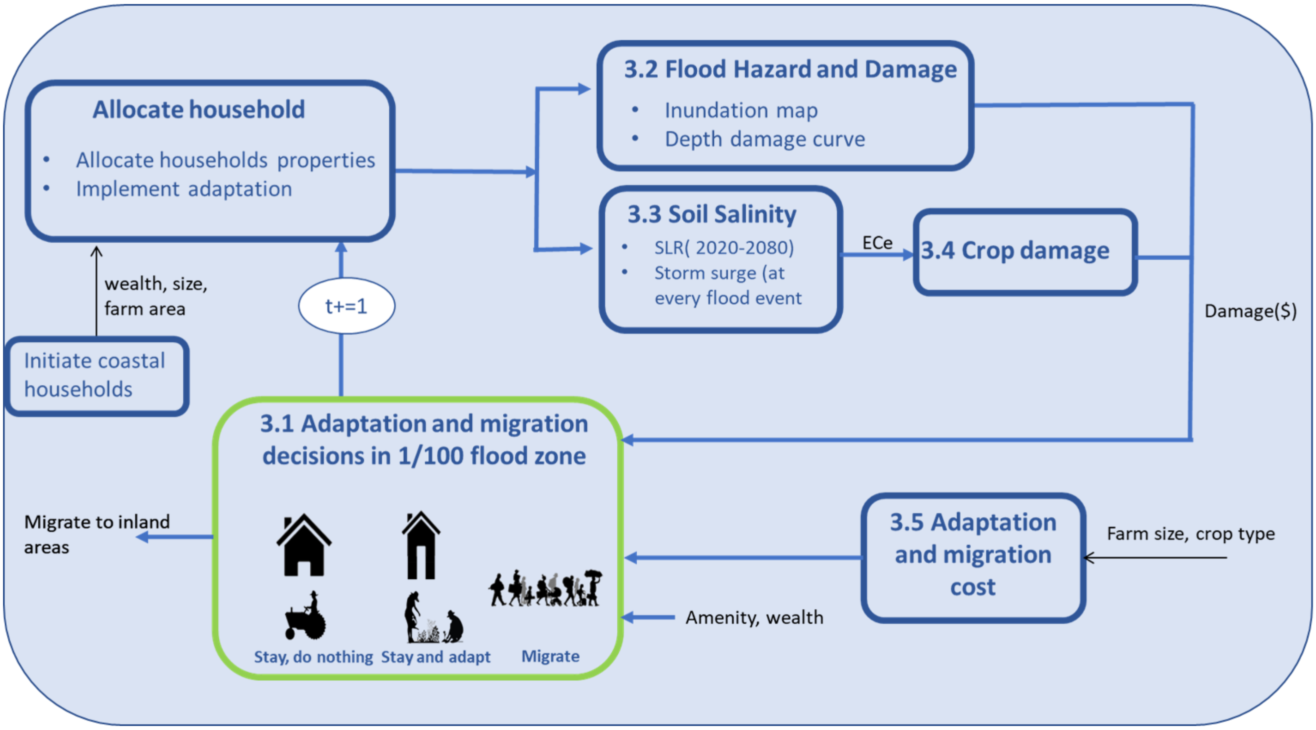


**Figure 2.** Modelling framework. We expand the DYNAMO-M model (Tierolf et al., 2023) Error! Reference source not found.by addressing the relationship between salinity intrusion and farmers' adaptation and migration decisions. We focus on households in the 1/100 flood zone that make boundedly rational adaptation and migration decisions based on the discounted expected utility (DEU) theory.

## 3.1 Adaptation and migration decisions in the 1/100 flood zone

Before running the model, we first generate household agents and their key socio-economic characteristics (income, education, age) that are statistically similar to the actual population in the 1/100 flood zone using Ton, Marijn,'s (2023) database. Each farmer is assigned a farm of a certain size. The farm size is important because it determines the potential yield, damage, and income of a farmer. Therefore, each farmer is initially assigned a farm size based on probability distributions of statistical information on farm sizes per county based on Lowder et al. (2016; see Supplementary 1.4 for details). Natural population change and GDP growth are based on population change rates available for all departments in 2016 and a medium population growth scenario based on SPP2 (see Supplementary information S1.3).

Migration and adaptation decisions of households in the 1/100 flood zone follow the DEU theory (**Error! Reference source not found.**Fishburn et al., 1981). This method allows households to weigh adaptation options against migration, taking into account the costs and benefits of adaptation and migration, as well as risk perceptions and preferences related to their experience of flood risk. The model runs from 2020 to 2080, with annual time steps. In each time step, households maximize their DEU according to the following decisions:

- Do nothing (Eq. 1).
- Implement elevating measures and adapt to salt intrusion (Eq. 2).

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- Migrate to another region *y* (Eq. 3).

$$DEU_1 = \int_{p_i}^{p_I} \beta_t * pi * U \left( \sum_{t=0}^{T} \frac{W_t + A_{x,t} + Inc_{x,t} - D_{x,t,i}}{(1+r)^t} \right) dp \quad \text{(Eq. 1)}$$

$$DEU_2 = \int_{p_i}^{p_I} \beta_t * p_i * U \left( \sum_{t=0}^{T} \frac{W_t + A_{x,t} + Inc_{x,t} - D_{x,t,i}^{adapt} - C_t^{adapt}}{(1+r)^t} \right) dp \quad \text{(Eq. 2)}$$

$$DEU_3 = U \left( \sum_{t=0}^{T} \frac{W_t + A_{y,t} + Inc_{y,t} - C_{y,t}^{migration}}{(1+r)^t} \right) \quad \text{(Eq. 3)}$$

In these equations, DEU is a function of $W_t$ (wealth), $A_{x,t}$ (amenities: e.g. the value of living near water) in region $x$ and $A_{y,t}$ in region $y$, $Inc_{x,t}$ (income) in region $x$ and $Inc_{y,t}$ in region $y$, $D_{x,t,i}$ (flood damage to buildings + salt damage to crops), $C_t^{adapt}$ (costs of adaptation to both flood and salt intrusion), and $C_{y,t}^{migration}$ (costs of migration). We refer to De Ruig et al. (2022) and Tierolf et al. (2023) for the values of the risk perception parameter $\beta_t$ and the risk aversion parameter of the utility function $U$. We apply a time discounting factor $r$ of 3.2% (Evans & Sezer, 2005) over a time horizon of 15 years, which is the number of years a homeowner stays in their home on average (see Supplementary material S1.1). If households decide to migrate away from the flood zone, they can move to other inland departments or to another coastal department with a flood zone.

### 3.2 Flood hazard and damage

We assume a general coastal protection standard in Mozambique of 1/10 years for all coastal areas and exclude higher return periods from our analysis (Scussolini et al., 2016). The simulated flood level at each household's geographical location is based on a range of return periods, including once every 20, 50, 100, 200, 500 and 1,000 years, as shown on coastal flood maps produced by the AQUEDUCT flood analyzer framework (Ward et al., 2020). We interpolate between historical and projected flood levels in 2030, 2050, and 2080 to derive annual inundation levels under RCPs 4.5 and 8.5 (de Ruig et al., 2023; van Vuuren et al., 2011). Following Tierolf et al.'s (2023) method, each household samples inundation levels for all return periods for their current location in the floodplain based on the selected climate change scenario. Synthetic future flood events are simulated by randomly selecting for each administrative unit and the exceedance probability of each flood event (e.g. a 1/ 10-year flood has a 10% chance of occurring at each time step; a 1/ 200-year flood has a 0.5% chance, etc.). A maximum damage value specific to Mozambique is used together with depth damage curves for residential structures to determine flood damage as a function of inundation level, which were both obtained from Huizinga et al. (2017). Dry flood proofing measures prevent water from entering the structure. This is captured by modifying the depth damage curves such that damage is reduced

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by 85% for water levels below 1 m (De Ruig et al., 2022). Inundation above 1 m overcomes the dry flood proofing, resulting in complete damage.

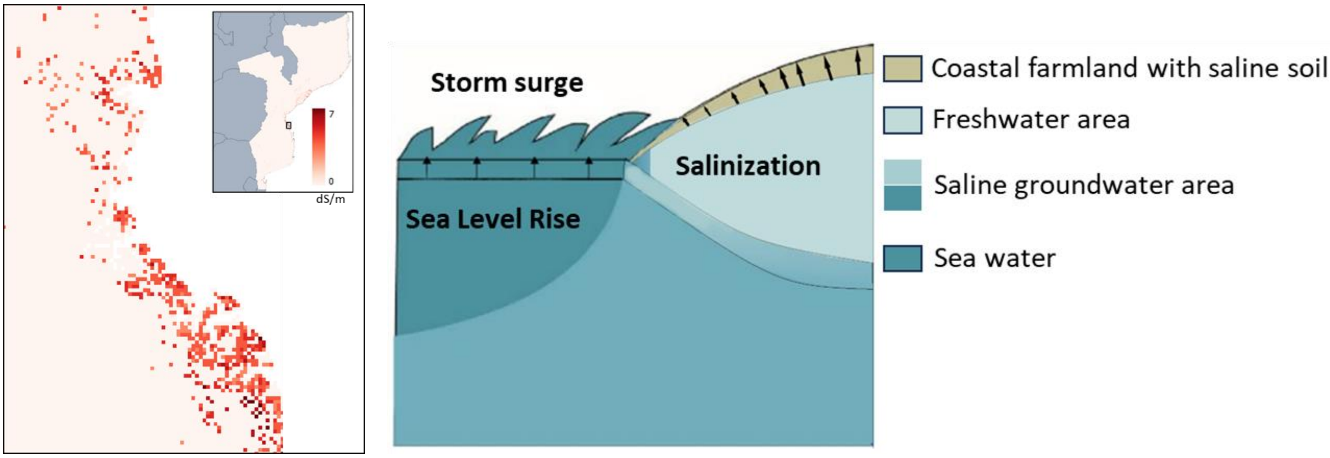


**Figure 3.** *Left:* soil salinity in dS/m for the year 2015 in coastal Mozambique based on Hassani et al. (2020). *Right*: conceptual diagram of salt intrusion processes adapted from Klassen and Allen (2017). Here, soil salinity is influenced by SLR and the synthetic storm surges.

### 3.3 Soil salinity

*Initial soil salinity:* Figure 3 shows the initial soil salinity values (dS/m) at the beginning of the simulation, which is simulated using data from Hassani et al. (2020; see Supplementary 1.4 for details).

*Future soil salinity:* We assume that topsoil salinity is only affected by two processes: (a) a gradual increase in salinity due to SLR (e.g. increased saltwater intrusion) and (b) flooding events (see Section 3.2), which increases the salinity levels after a flooding event. The two values are then added together to obtain the total salt deposition in the topsoil at the end of the year. The geographical location of the farm determines the relative influence of SLR and flood events on the salinity levels of the farm. In the simulations, the initial salinity map is updated at each annual time step, following Klassen and Allen's (2017) concept of salt intrusion processes (Figure 3, right). We conceptualized the two salinization processes as follows:

(a) *Soil salinity due to SLR*: We use the latest available global soil salinity map from Hassani et al. (2020) as our baseline map in 2015. We extrapolated these values to 2080 under SLR scenarios, assuming increases of 50% and 100% for RCP4.5 and RCP8.5, respectively, all based on Hassani et al. (2021). These assumed increases in salt intrusion are interpolated for each time step of the model. Figure 4 shows the soil salinity under RCP4.5.

(b) *Soil salinity due to flood events*: Increases in salinity levels can also be caused by saltwater flooding of land (Taylor & Krüger, 2019). To simulate this effect during a flood event, we assume that salt accumulates in the top layer of the soil ($EC_{e,soil}$) according to Equation 4. The total salt level (measured in dS) in the topsoil layer depends on the farm size $A_i$. In order to calculate the increased salinity levels, it is assumed that all the salt from a flood event is absorbed by the top 1 m soil layer, using flood depths to calculate volume from Ward et al. (2020).

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$$EC_{e,soil}^{flood} = \sum_{i=1}^{n} \frac{WL_i * A_i * EC_{e,sea}}{V_{farm}} \quad \text{Eq. (4)}$$

Where $n$ represents the total number of farming households in the coastal region, $WL_i$ is the flood water depth at the farm location, $A_i$ is the farm area, $EC_{e,sea}$ is the sea surface salinity (Boutin et al., 2021), and $V_{farm}$ is the volume of affected soil, considering the root depth as 1 m.

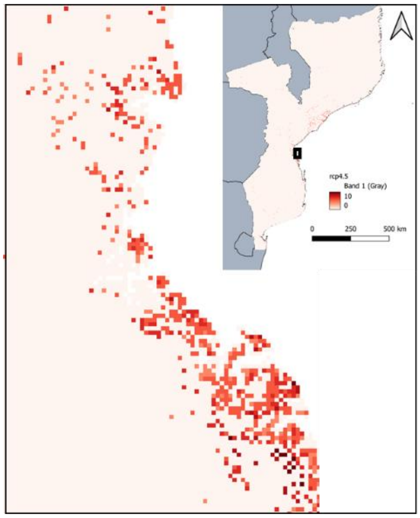


**Figure 4** Soil salinity for an area in central Mozambique (small black square) in the year 2080 under RCP4.5 SLR scenarios

### 3.4 Crop damage

Using the updated salinity levels from Section 3.3, we can calculate the annual salinity damage to crop yields. To do this, we first initialize the model by assigning one of the four dominant crops to a farm: rice, maize, sorghum or cassava (see Supplementary material S1.4 for details). These four crops account for 98% of the cultivated land in Mozambique (World Bank, 2017). The agricultural map for some crops is shown in Figure S1.

Next, we will convert the annual salinity levels into losses per crop yield type $Y_r$, following Maas and Hoffman (1977; Equation 5):

$$Y_r = 100 - b(EC_e - a) \quad \text{(Eq. 5)}$$

Where $Y_r$ is the percentage crop yield loss relative to an optimal yield $Y$, $EC_e$ is the predicted electrical conductivity expressing soil salinity, and the constants $a$ and $b$ are crop-dependent parameters. $a$ is the threshold at which crop yield begins to deteriorate, and $b$ is the rate of deterioration type and is regularly updated by FAO (Tanji and Kielen, 2002: Annex 1). ,

Next, we convert the percentage yield losses $Y_r$ into monetary damages per farm using a damage function (Equation 6):

$$D = \sum_{j,k=0}^{j=n,k=3} Y_r(k) * \mathrm{Y}(\mathrm{j},\mathrm{k}) * A(j,k) * P(k) \quad \text{(Eq. 6)}$$

Where $k$ is the crop index for the four crops, $j$ is the farm index. For each value of $k$, $Y_r$ is the relative yield as compared to $Y$, the current yield. $A$ is the individual farm size, and $P$ is the selling price. We use the spatial distribution of yields across existing farms in Mozambique from the GAEZ v4 portal (https://gaez.fao.org/). Farm sizes $A$ for different farmers are simulated based

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on a farm size distribution following Lowder et al. (2016). Using the producer prices for different crops from FAO (2015) and farm size, we can calculate damages to farming households.

Due to salt intrusion, farmers can adapt with one measure: switch to a salt-tolerant variety of their crop if the projected damage *after* the adaptation ($D_{x,t,i}^{adapt}$) is lower than without adaptation, all subject to the salt tolerance parameters in Equation 5. Van Straten et al. (2021) conducted field trials on salt-tolerant varieties of potatoes and observed that salt tolerance can increase up to twofold, and the rate of deterioration is reduced by half. Salt Farm Texel (2016) observed similar factors in their field trials with six other crops. Therefore, we considered the same factors for four crops commonly used in Mozambique (see Table 1). These coefficients are then used in Equation 5 to calculate $D_{x,t,i}^{adapt}$.

### 3.5 Adaptation and migration costs

#### 3.5.1 Adaptation cost

The variable $C_t^{adapt}$ in Equation 2 is the total adaptation cost for a household in a given year and is the sum of the cost of elevating the house $C_{annual}^{building}$ and the cost of crop adaptation $C_{annual}^{crop}$.

*Cost of flood adaptation:* $C_{annual}^{building}$: Households can floodproof their homes by elevating them. In determining the cost of adaptation $C_{annual}^{building}$, we used a fixed cost $C_0^{building}$ of $1,861 per building at a fixed interest rate *r* (World Bank, 2022) and loan duration *n* as in Equation (7). These fixed costs are considered a fixed proportion of the property value, as calculated by Hudson (2020) and Huizinga et al. (2017). Aerts (2018) estimates similar values for other developing countries, such as Bangladesh and Vietnam.

$$C_{annual}^{building} = C_0^{building} * \frac{r*(1+r)^n}{(1+r)^n-1} \qquad \text{(Eq. 7)}$$

*Cost of crop adaptation:* In order to reduce the impact of salinization, farmers can switch to a salt-tolerant crop variety (for four crop types, see Table 1). The cost associated with switching a crop is represented by $C_{annual}^{crop}$. The decision to switch to a salt-tolerant variety depends on the crop itself and other parameters, such as exposure to previous risks. However, for simplicity, we assume that this is the cost quoted by seed companies. Seed Co., founded in Zimbabwe, has testing and production sites in Mozambique, so we use their prices as a proxy for crop switching (*Mozambique - Access to Seeds*, 2019). The seed cost per hectare is calculated using the seed requirement (kg) per hectare of 25 kg/ha (*Crop Production Guidelines*, 2017) and the seed cost ($/kg) from a local seed company (SC 419 - Seed Co. Zimbabwe Online Shop, 2023). By multiplying the seed cost ($/kg) by the seed requirement (kg/ha) and farm size (ha), the total crop adaptation cost per farm can be calculated in US dollars.

**Table 1 Regular and salt-tolerant crops in Mozambique and their salt-tolerant varieties**

| Crop type | Regular variety | | | Salt-tolerant variety | | Costs | |
|---|---|---|---|---|---|---|---|
| | Crop yield (t/ha) | Tolerance threshold (a) | Rate of deterioration (b) | Tolerance threshold (a: Eq 5) | Rate of deterioration (b; Eq 5) | Adaptation cost($/ha) $C^{crop}_{annual}$ | Selling price($/tonne) ($P_k$; Eq. 6) |
| **Rice** | 1.50 | 3 | 12 | 6 | 6 | 75 | 729.2 |
| **Maize** | 1.55 | 1.8 | 7.4 | 3.6 | 3.7 | 75 | 299.5 |
| **Sorghum** | 2.13 | 6.8 | 16 | 13.6 | 8 | 75 | 220 |
| **Cassava** | 6.4 | 0.65 | 9.6 | 1.3 | 4.8 | 75 | 207.4 |

*Budget constraints:* In estimating the maximum available budget for adaptation per household, we assumed a household can afford a fixed percentage of disposable income as defined by Kousky and Kunreuther (2014) and further applied in Hudson (2018). However, we assume that farmers can use 6% of their disposable incomes to adapt to damage to houses. When adapting their farms, we assume that farmers can afford up to 50% of their disposable income, as this is an investment in their work. We found these parameters by calibrating the model to surveys conducted in Beira and Nova Sofala by Duijndam et al. (2023).

### 3.5.2 Migration costs

*Migration decisions:* According to Equation (3), push factors (increasing coastal flood damage and salinity damage, $D_{x,t,i}$) and pull factors (income differentials $Inc_{x,t}$ , wealth $W_t$, and amenities $A_x$) interact with mooring factors (fixed migration costs $C_{migration}$) and shape the migration decisions of households in the coastal zone. These factors are calculated as follows: Each node *y* contains information on income distributions, amenity values, and a distance matrix to all other nodes. The amenity value of node *y* is a function of the distance to the coast and wealth. We derive the monetary value of these coastal amenities from hedonic pricing studies based on the distance to the coast. We now describe income, migration costs and amenity values in more detail:

*Expected income and migration costs*: For each node *y* per district, households sample their expected income $Inc_{y,t}$ based on their current position in the log-normal income distribution in the Ton, Marijn, (2023) database.

*Migration costs* $C_{migration}$ to district *y* is a function of geographical distance and fixed migration costs (e.g., psychological costs of leaving friends and relatives and moving to an unfamiliar environment). We capture these latter “place attachment costs” with a fixed monetary cost of migration $C_{fixed}$. Ransom (2022) estimates this fixed cost to be between \$105,095 and \$140,023 for movers in the United States and estimates the total cost of a 500-mile move to be between \$394,446 and \$459,270. Kennan and Walker (2011) estimate the fixed costs of migration at \$312,146 for the average mover in the United States. Based on these figures, we construct a logit function and set the fixed cost of migration (Eq. 8). We assume that the fixed cost of migration is proportional to the cost of housing and thus scale these migration costs to Mozambique price levels using the differences in housing costs between these countries. Tierolf et al. (2023) use the same logit function for France, with $C_{fixed}$ as EUR 125,000, and Huizinga et al. (2017) provide property costs at the national level. Based on these figures and GDP per capita ratios in 2015 (World Bank, 2015), we scaled the fixed migration cost for Mozambique to EUR 2,026, which results in a maximum migration cost of EUR 4,052 for very long distances from the coast (Eq. 8).

$$C_y^{migration} = \frac{2 * C^{fixed}}{1 + e^{-0.05 * dist_{xy}}} \quad \text{(Eq. 8)}$$

*Amenity value*: We derive the amenity value (scaled to GDP) of living near the coastline based on hedonic pricing studies of coastal property values (e.g. Muriel et al., 2008). However, the coastal amenities for households in Mozambique are based on different values than in similar studies in France and the United States. While in wealthier countries, coastal views increase property values, the data from Mozambique suggest that attractiveness to fisheries is one of the coastal amenities. Therefore, we base our amenity function on Conroy & Milosch (2011) and Muriel et al. (2008) and construct a distance decay function for coastal amenities (Supplementary material S2.2). Households located within 500 m of the coastline experience a coastal amenity premium of 60% of their wealth, which decreases to 3% when located 10 km from the coast. A similar distribution of amenity values as in DYNAMO-M (Tierolf et al., 2023) is applied (Figure S6, Supplementary section) and downscaled based on property values for Mozambique from Huizinga et al. (2017). These estimates perform better than the United States and French estimates, firstly because they account for the dependence of employment on the coast and secondly, because the downscaling with property values captures the income differences between developed and developing countries.

### 3.6 Behaviour settings

The model can also be run for different adaptive behaviour settings. Table 2 shows four settings defined by turning parameter models on and off. First, risk perception $\beta_t$ from Equation 1 can be turned on or off and refers to learning from a flood event (Eq. S2, Supplementary S1.1). Higher risk perceptions lead to a higher uptake of adaptation measures. A second parameter is a household's level of awareness of two adaptation measures: (a) the availability of salt-tolerant seeds from seed companies and (b) knowledge about elevating a house to avoid direct flood damage. When these behavioural settings are turned off, as in the 'no adaptation' case (Table 2), agents do not implement adaptation measures and migrate to inland areas (Eqs. 1 and 3). Third, the 'no migration' behaviour setting runs with no resources provided to migrate to inland areas (Eqs. 1 and 2). Finally, the 'full behaviour' setting allows agents to use all options.

Furthermore, these different behavioural settings can be run for different RCP and SSP scenarios (see Supplementary material 1.4). We first simulate the different behaviour settings under a baseline scenario (without future SLR and salt intrusion). Then, the model and behavioural settings are run for two RCP-SSP-coupled scenarios, RCP4.5-SSP2 and RCP8.5-SSP5. Under different climate scenarios, SLR and salt intrusion projections change, while SSP scenarios capture uncertainty in population and income growth (Supplementary S1.3). Income growth changes every year and has a direct influence on input parameters such as property price, adaptation costs, average income, seed costs and producer selling price in the market (Eq. S4, Supplementary S1.3).

**Table 2 Description of different behaviour settings**

| *Behaviour setting* | *Dynamic behaviour to perceive risk* | *Awareness of adaptation techniques* | *Migration to inland areas* |
|---|---|---|---|
| ***Full behaviour*** | Yes | Yes | Yes |
| ***No adaptation*** | Yes | No | Yes |
| ***No migration*** | Yes | Yes | No |
| ***No perception*** | No | Yes | Yes |

## 4 Results

In this section, we present the main results of the model runs for farming households in the coastal flood zone of Mozambique. We first present the results of salt intrusion and asset losses under a full behavioural setting. Section 4.2 shows the results of a single model run, particularly focusing on the exposed population and household adaptations over the model run. Later, in sections 4.3 and 4.4, we present model results under different model settings and adaptation costs, respectively

### 4.1 Salt intrusion and asset losses under full behaviour

Figure 5 shows the projections of salt intrusion and building losses due to flooding and SLR for farming households only in the coastal flood zone (i.e. households with a house and a farm). The projections are the result of 50 model runs with a mean (dark green line) and uncertainty band in light green. Panels a, b and c show the risk of saline intrusion (USD million/year) for different crops under the current climate (Panel a), RCP4.5-SSP2 (Panel b) and RCP8.5-SSP5 (Panel c). The results show that the coastal farmers in Mozambique face total damages of up to US$12.5 million per year due to salt intrusion and US$800 million due to flooding under RCP8.5 in the year 2080 (note that these figures are simulated under the full adaptation option in Table 2). This increase is exponential and is mainly due to SLR and an increase in the frequency of flood events, which add large amounts of salt to the soil. It can be observed that there is a sudden increase in risk in 2075, which is due to the lifespan of adaptation (Aerts and Botzen, 2011).

Households that adapted in the first spin-up run before 2015 (see Supplementary 2.1 for the definition of "spin-up") damaged their adaptation and entered the high-risk category. With a GDP of US$17.8 billion (World Bank 2022), an investment of US$812.5 million for adaptation would be about 5.5 times the current climate funds allocated to Mozambique (~US$147.3 million; HBS, 2016). Looking at Figure 5b (salt intrusion risk projection under RCP4.5), the risk is slightly lower than in the baseline scenario (Figure 5a). The low risk observed can be attributed to the growing trend of migration among coastal farmers(Supplementary S1.5, Figure S4) towards inland locations. As farmers migrate, the exposure of farms and their crops decreases, as does the risk of salt intrusion, despite the natural population growth driven by SSP2 and an increase in soil salinity. The increase in risk under the RCP8.5 scenario offsets the migration flow and the decrease in exposed farms, so the net salt intrusion risk increases much more than under the current climate.

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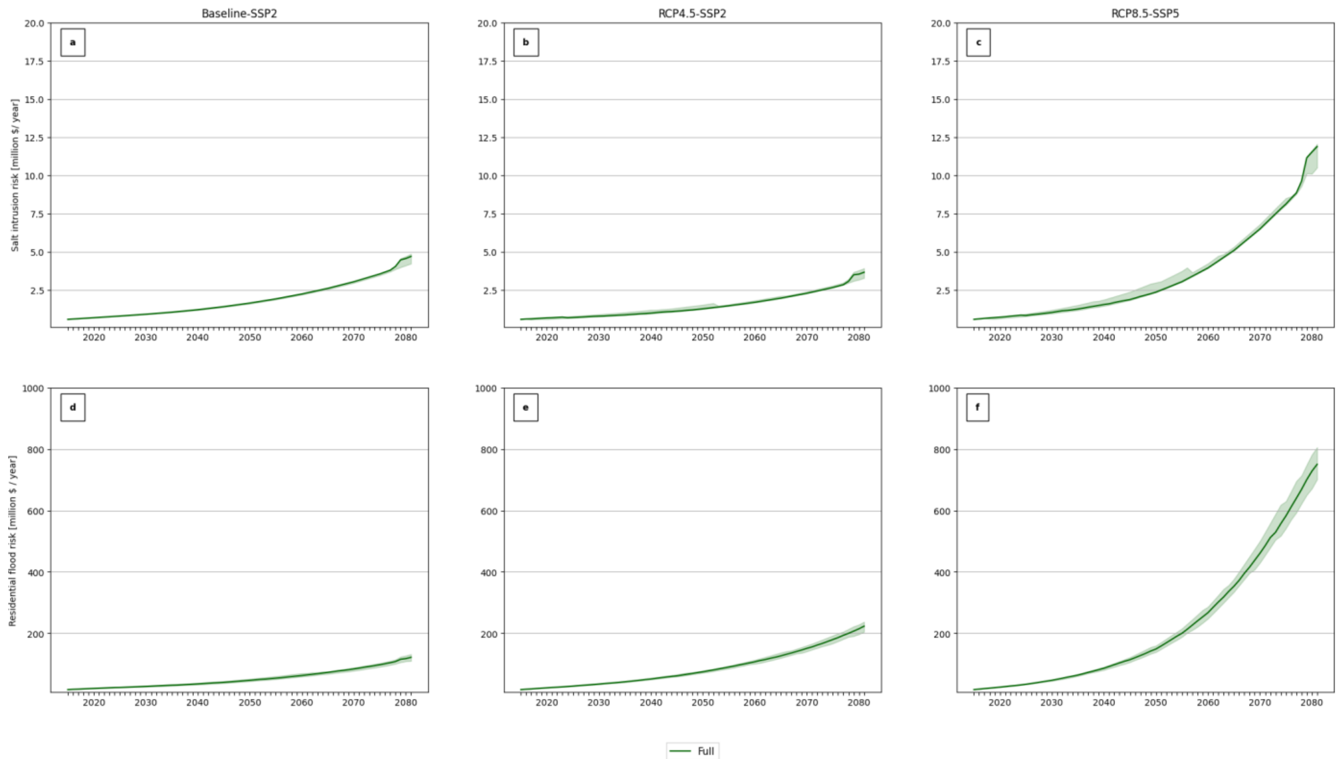


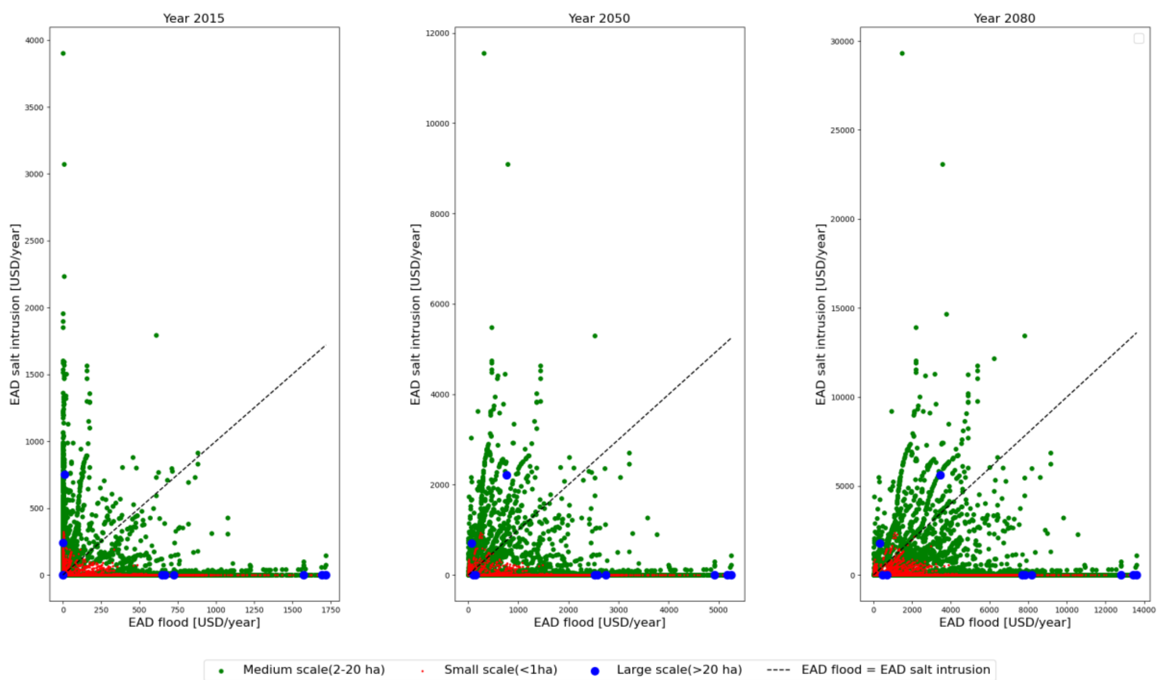

**Figure 5.** Panels a, b and c show the salt intrusion risk (USD million/year) under the current climate, RCP4.5-SSP2 and RCP8.5-SSP5, respectively, under the full behaviour setting (Table 2). Flood risk projections (USD million/year) are shown in panels d, e and f for the current climate, RCP 4.5-SSP2 and RCP 8.5-SSP5, respectively. The green band around the mean line shows the uncertainty in the model due to randomness. Note the shifting ***y***-axis.

Flood risks to buildings (USD$ million/yr) with the full behaviour settings (Table 2) are shown in panels d, e and f for the current climate, RCP 4.5 and RCP 8.5, respectively. The risk numbers are much higher than for the salt flooding risk, ranging from USD$100 million per year to USD$800 million per year in 2080 under the current climate and RCP8.5, respectively. Similar to the salt intrusion risk, flood damage to buildings does not increase as much when comparing the current climate with the RCP4.5-SSP2 scenario. When a farmer faces salt intrusion damage, 50% of the annual income can be spent on adaptation, which most farmers do and continue to do. However, only 6% of the income can be spent on reducing housing damage which means under RCP4.5-SSP2, farmers do not adapt as much and migrate. As migration reduces exposure, the net result is that building damage only increases slightly compared to the current climate.

Figure 6.1 (panels a, b and c) provides more detail on how farmers in the coastal zone experience flood losses to buildings (*x*-axis) and crop losses from salt intrusion (*y*-axis) for the years 2015, 2050 and 2080, respectively. In addition, the graph also includes a 45-degree line showing farmers who are equally exposed to flood damage to buildings and salt intrusion. Thus, any farmer above the line has a higher risk of salt intrusion, and vice versa. Furthermore, to assess how households with different farm sizes are distributed across these two risk axes, we represent each individual farmer household with a coloured dot depicting farm size (e.g. Esquivel et al., 2021). For the current climate, the building losses per farmer vary from USD$0 to $1,750 per year, while salt intrusion losses vary from USD$0 to $4,000 per year.

For the year 2080 (RCP4.5-SSP2), these figures range up to $30,000 per year. The values of these damages are quite high compared to the average annual income of farmers in the floodplain ($3,800/yr; Duijndam et al., 2023). It can be observed that Mozambique does not have many large-scale coastal farmers (large blue dots) and that most large-scale farmers have already adapted by 2015 because, even though they have high losses due to salt intrusion (an annual loss of $4,000), they also have a high capacity to reduce losses. Thus, the net risk is relatively low, except for some outliers who are closer to the middle-scale farmers in terms of size and wealth. For example, a farmer with a farm area of 21 ha would fall into the large (>20 ha) category. However, both the spending capacity (as a function of annual income) and the risk of salt intrusion (as a function of farm area) are similar to those of medium-scale farmers (1–20 ha). In addition, small-scale farmers suffer more damage to buildings from flooding than from salt intrusion. This can be explained by the low adaptation cost to reduce salt risk: cost is a function of farm size, and hence, the cost is relatively low for a small-scale farmer ($150–$1,500).

Figure 6.2 shows the same graphs as in Figure 6.1, but farmers are now classified based on their crop type. Sorghum farmers experience little to no salt intrusion damage since sorghum is more salt-tolerant than other crops. This can be derived from the threshold $a$ (Equation 5) and the values in Table 1. It can also be observed that rice farmers experience the most risk (in US$) as compared to any other crops (up to $15,000/yr), which is due to the high producer price of 729 US$/ton (Table 1). This means the loss per hectare is much larger than for other crops, and the larger income that rice farmers derive (and thus the higher adaptive capacity) does not offset the losses due to salt intrusion.



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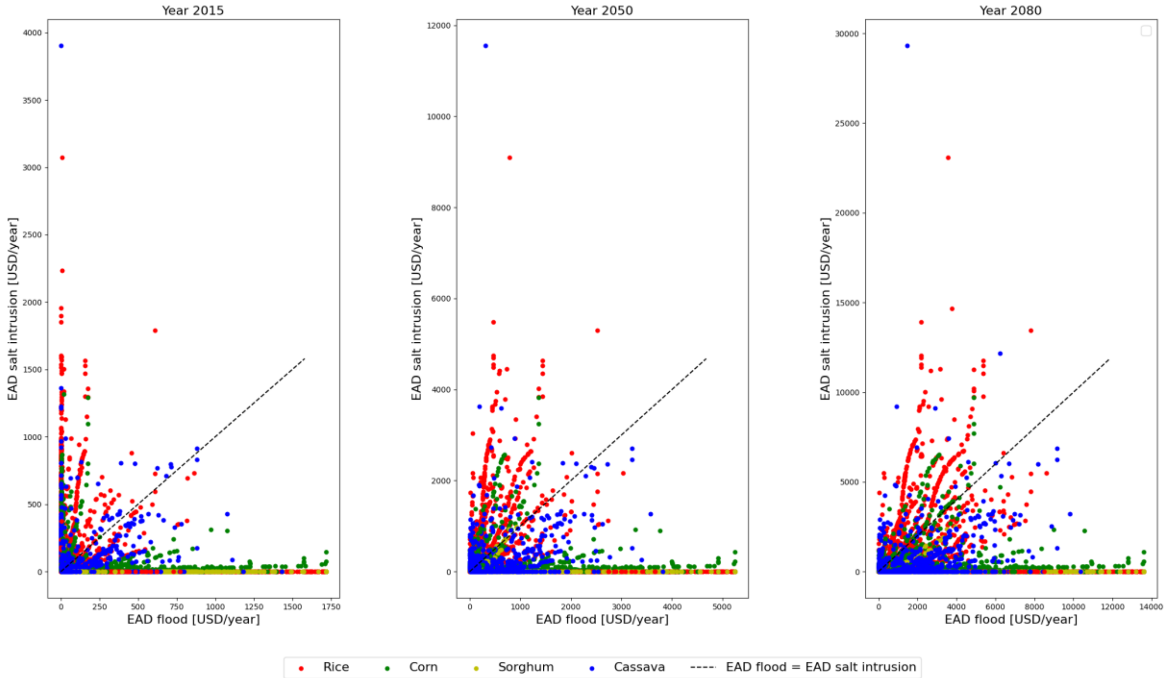


**Figure 6 Salt intrusion risk (*y*-axis) vs. flood risk (*x*-axis) for individual farming households in the Mozambique floodplain under the RCP4.5-SSP2 scenarios (panels a, b and c); panels d, e and f show the same, but now broken down by crop type.**

### 4.2 Dynamic exposure and adaptation

Figure 7 shows the evolution of the exposed and adapted population of the province of Sofala, the survey location in Duijndam et al. (2023), and flood events, which are represented by vertical dashed lines. Since we assume a flood protection standard with a return period of 10 years for all floodplains, including Sofala, flood events with shorter return periods cannot occur. The random simulation of stochastic flood events generates eight flood events in the province of Sofala by 2080. Another form of adaptation is migration, and it can be observed in Figure 7a that a significant population (~16%) migrates away from the floodplain, reducing the exposed population from about 31,321 in 2015 to about 26,291 in 2080.

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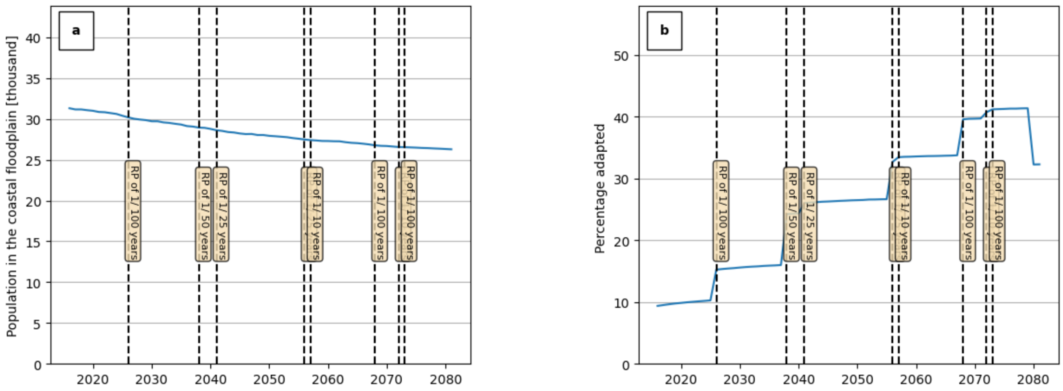


**Figure 7** ***a:*** Population exposed to the risk of flooding and salt intrusion in the floodplain, *b:* percentage of households adapted. Both simulations are made for the coastal province of Sofala under RCP4.5-SSP2 and full behaviour setting.

Migration increases, even though the percentage of households with adaptation measures increases from ~9% to 41% (Figure 7b). People adapt, particularly after major flood events, with the largest increase after the first two events. The figure also shows that at the beginning of the model run, about 9% of the population in the flood zone in the Sofala Province had adapted to flood risk, which is confirmed by empirical data from surveys in the Sofala and Beira areas (Figure 1; Duijndam et al., 2023). It can be observed that the percentage of adaptation decreases around 2079 (Figure 7b), where some households lose adaptation due to the maximum lifespan of adaptation of 75 years (Aerts and Botzen, 2011). These are the households that adapted at the beginning of the model run in the spin-up period, which is done to initiate the agents (see Supplementary S 2.1).

### 4.3 Model results under different behaviour settings

Figure 8 shows the average of 50 model runs for coastal Mozambique under the four different behaviour settings (Table 2). Overall, the risk to buildings and crops increases over time, while the number of people in the flood zone gradually decreases due to migration (except for the 'no migration option'). The figure shows that under the 'no adaptation setting' (red line), households experience the highest salt intrusion and building damage. This is because in the 'no adaptation setting', households do not migrate, remain in the floodplain, and only experience the increasing damage under SLR. The lowest salt intrusion damage is experienced in the 'full behaviour setting', where farmers either fully adapt or migrate and are driven by increased risk perceptions immediately after a flood event. The lowest building damage (bottom three panels) is achieved under the 'no migration' scenario. Figure 8 shows that the coastal population in the floodplain is highest under the 'no migration' scenario (~555,000 people under SSP2 and 420,000 people under SSP5) and lowest under the full behaviour scenario (~260,000 people for the RCP4.5-SSP2 scenario and 240,000 people for RCP8.5-SSP5). Under full behaviour, the coastal population will be around 300,000 people in 2025. By 2080, there will be an out-migration of 13% for RCP4.5-SSP2 and 20% for RCP8.5-SSP5.

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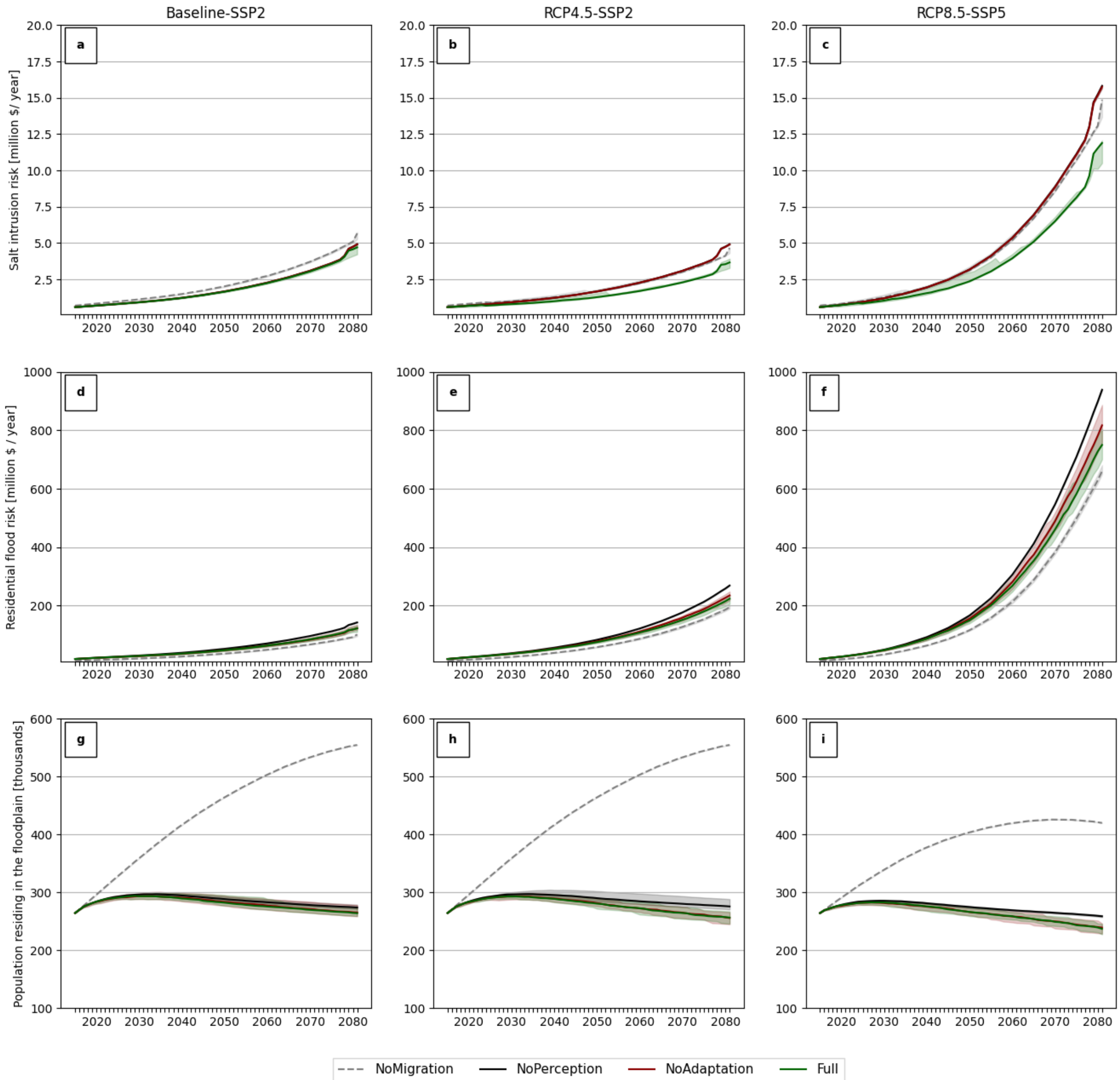


**Figure 8 Losses to farmers from salinization (panels a, b and c), damage to buildings (panels d, e and f), and coastal population (panels g, h, i) under the four different behaviour settings (Table 2) and RCP-SSP scenario combinations.**

Figure 9 shows the percentages of adapted farmers (combined salt and building adaptation) per coastal province under all behaviour settings. Each of these maps shows results assuming RCP4.5 and the ‘No migration’ and ‘Full behaviour’ settings. Under the full behaviour settings, the highest percentage of farmers adapt. However, over 65% of the population does not have the means to adapt because the adaptation and migration costs are too high. The province of Cabo Delagado shows the largest percentage of adapted households (32.8%). The percentages of adapted households decline even further under the other behavioural settings. For example, under a ‘no migration setting’, people cannot move away and have only two options: adapt or not adapt. However, households face financial constraints as only 6% of the annual income can be used for building

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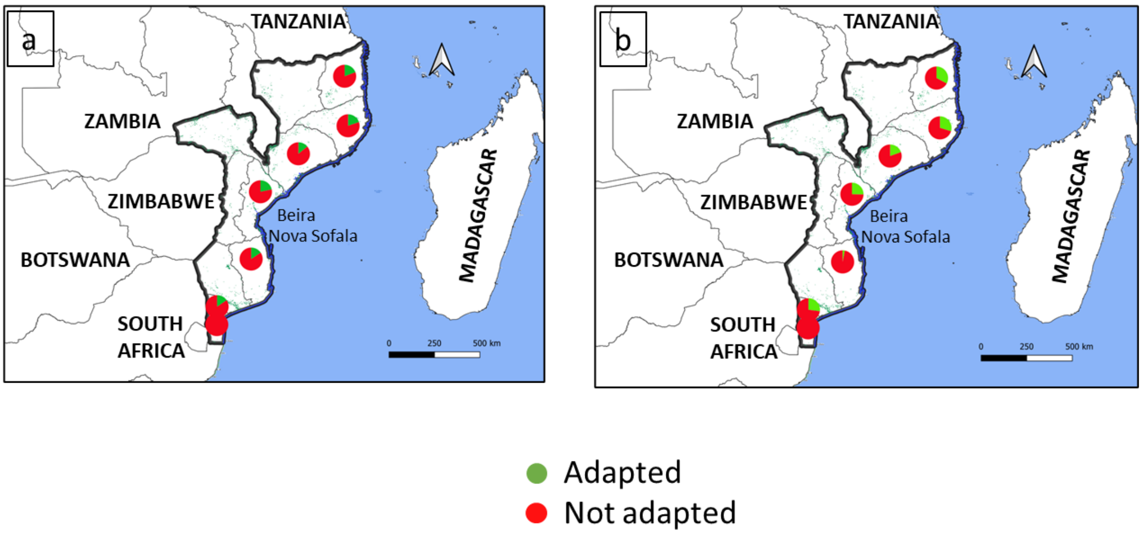
adaptation and 50% for reducing yield loss and cannot adapt. However, something interesting can be observed for the households living in the Inhambane region, where only 3% of households adapt under the 'full behaviour' setting (Figure 9b) compared to 15% in the 'no migration' scenario (Figure 9a). Thus, households tend to move when given the option to migrate, and when they are not, they tend to stay with the damage. This is why many farmers in this scenario do not adapt. For example, in the province of Cabo Delgado, only 13.1% adapted the 'no migration setting'.




425 **Figure 9.** The percentage of farmers adapted (to salt intrusion and building damage) in each province under RCP4.5 assuming (a) no migration and (b) full behaviour settings.

### 4.4 Adaptation cost

Under the influence of increasing building damage and salt intrusion risk, adaptation costs are projected to increase as well. Figure 10 shows a single model run for the province of Sofala: exposed population (panel a), the number of people adapted (panel b), and the combined adaptation cost for flooding and salt intrusion (panel c). It can be seen that by 2060, the cumulative adaptation cost in Sofala will rise to 1.1 million USD, further increasing in the next 20 years to 2.5 million dollars in 2080, nearly twofold in two decades (Figure 10c). It can be observed that after every flooding event, the total adaptation cost of the Sofala floodplain (Figure 10c) shows a sudden increase due to more people adapting to SLR and salt intrusion; moreover, the rate of change of adaptation cost with time also increases.

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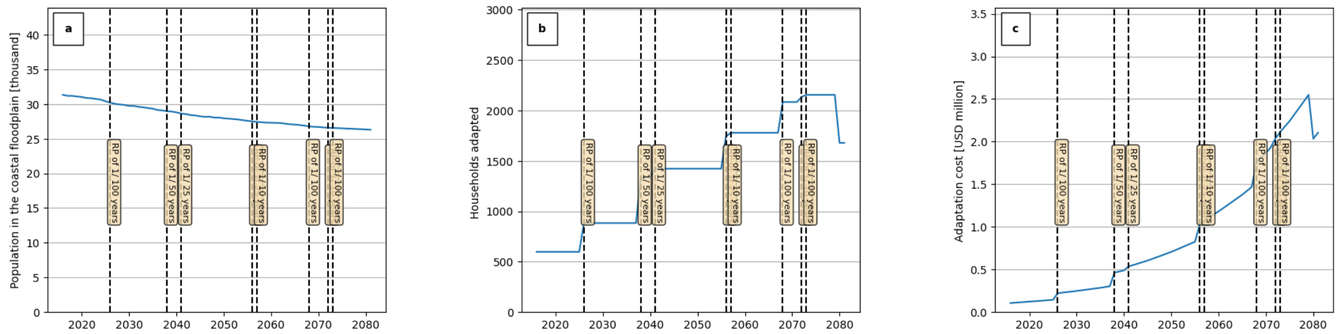


**Figure 10** Left: population in the Sofala floodplain, centre: adapted population, right: adaptation cost. All projections are made for the province of Sofala only.

## 5 Discussion of model sensitivity, limitations and recommendations

### 5.1 Sensitivity analysis

Table 3 summarizes a sensitivity analysis that examines the model's robustness to uncertainties in three model parameters due to their high variability found in the literature: (a) spending capacity (budget constraints), (b) adaptation costs for farmers and (c) varying property values, considering that the rural value is one-sixth of the urban value (World Bank 2000). We compare the higher and lower values of these parameters with the standard values of the parameters discussed in the previous sections.

**Table 3** Sensitivity of the number of coastal households adapted in the year 2080 to (a) expenditure capacity, (b) crop switching costs, and (c) property value for the baseline and RCP 4.5 and RCP 8.5 coupled with SSP scenarios. Here, Column 2 is the actual number of households, and other columns show the deviation (**here we assume standard parameter values: 6% can be spent on building adaptation, 50% on crop adaptation, the seed cost is $75/ha for crop variety SC419, and the property value is $13,370).

| **Input parameter/Scenario** | **Modelled values with standard parameters** | **Expenditure capacity (a)** | | **Seed cost (b)** | | **Property value (c)** |
|---|---|---|---|---|---|---|
| | Standard parameters* | Low<br>4%, 40% | High<br>10%, 60% | Low<br>57.3 $/ha<br>(SC301) | High<br>118 $/ha<br>(SC608) | (2228$) |
| Baseline (no SLR) | 1777** | -46.20% | 36.07% | 1.07% | -2.81% | 330.16% |
| RCP 4.5- SSP 2 | 8415** | -34.31% | 23.24% | 6.41% | -6.29% | 187.21% |
| RCP 8.5 – SSP 5 | 10051** | -28.07% | 27.07% | 0.69% | -1.23% | 157.06% |

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*Expenditure capacity:* In our model, a household can spend up to 6% of their annual income on elevating homes against flooding and up to 50% on switching to a salt-tolerant crop, based on Hudson (2018). Two low and high scenarios of expenditure capacity (low: 4% on homes and 40% on farms; high: 10% on homes and 60% on farms) were studied. Results show a high sensitivity of the number of adapted households to variations in expenditure capacity. For the baseline scenario, when there is no SLR, around 1.7 thousand households adapt under an expenditure cap of 6% on elevation cost and 50% on crop switch. With a low scenario expenditure capacity, the number of adapted household numbers will decrease by around 28%–46%. On the other hand, under a high expenditure capacity scenario, the number of adapted households increases by around 27–36%.

Under the baseline parameters, most of the households (especially in Inhambane province) are not able to adapt due to unaffordability (Figure 9). However, under the RCP 4.5 scenario, the number of adapted households increased to nearly 8.5 thousand. The sensitivity to lower expenditure capacity is high but less than comparing differences in adapted people under no SLR and RCP4.5 using standard settings. However, an increase in adaptation capacity (10% on houses and 60% on farms) enables a 90% increase in households that adapt. This shows that government support, such as adaptation loans or climate funds, could accelerate adaptation and risk reduction.

*Adaptation costs for salt intrusion (crop switch cost):* Adaptation to salt intrusion is simulated, assuming that every farming household buys from the same seed company (Seed Co.) variety SC419 at a homogeneous adaptation cost (75$/ha) (Section 3.5.1). However, in reality, costs vary based on the seed type (SC608: 97$/ha; SC301: 57.3$/ha; SC608: 118$/ha; SSZO, 2019). Based on these alternative values, we tested a low (57.3$/ha) and a high (118$/ha) number. In the baseline scenario, a cost reduction of $57.3/ha results in only 1.07% more households adapting compared to a standard crop variety cost of $75/ha. Similar trends are seen in other climate scenarios (RCP 4.5 and RCP 8.5), where a cost decrease led to 6.41% and 0.69% more households adapting, respectively. A decrease in adapted farmers is observed under a scenario where the adaptation cost increases by a few percent.

*Property value:* The model considers a standard mean property value of $13,370 (Huizinga et al., 2017). However, these numbers are based on urban areas, where prices are significantly higher than in rural areas. A study by the World Bank (2000) on flooding in Mozambique addressed costs in urban versus rural areas. It is estimated that property prices and the cost of reconstruction in rural areas are six times lower than in urban areas. This overestimation of the rural houses can underestimate the number of adapted households. Applying this factor to our mean number would yield a property value of $2,228 – here used as a lower value. Results show that there can be a difference of more than 300% in the number of houses that can adapt to the baseline scenario of no SLR. Also, under the climate scenarios, the sensitivity of the number of people adapted to the changing property values is high.

After running sensitivity analyses for different input variables, it can be seen that the model needs some improvement when upscaled or applied to another coastal plain. Some improvements to the current model could consider social vulnerability to define adaptation affordability due to its high sensitivity. The heterogeneity of property values needs to be accounted for in a robust analysis, especially in countries with high income inequality. Seed costs vary widely but did not show large differences,

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which could be due to the fact that house adaptation costs ($1,861) are very high compared to farm adaptation costs ($75/ha), with the average farm size in Mozambique being 1.5 hectares.

### 5.2 Limitations and recommendations

This study was limited by the unavailability of empirical data on salinity levels and projections. We addressed this gap by interpolating the existing global maps from Hassani et al. (2020) into the future. Based on two RCP scenarios, we made two projections of salt intrusion, which can be seen as a sensitivity analysis allowing comparison of future salinity levels with current levels. We project future salt intrusion scenarios assuming a 50% increase in soil salinity for RCP4.5 and 100% for RCP8.5 and neglecting spatial heterogeneity, which is a major limitation and source of uncertainty. In addition, the soil salinity simulation does not take into account the spatial heterogeneity of the soil profile for sea salt uptake in coastal soils, which is indeed rather complex. There are three main sources of uncertainty associated with Hassani et al.'s (2020) input map. The first relates to the quantification of error propagation within two processes of classification and regression. Second, the calibration samples are also gathered between 2000 and 2005, and the time domain uncertainty is neglected. Third, The input soil salinity map is rather coarse (~1 km), which is not directly suitable for farm-level research and is therefore interpolated.

Furthermore, we showed in the sensitivity analysis that the model output (number of adapted farmers) is sensitive to the spending capacity. However, there are many other variables that play a role in spending capacity that are not included in our model, such as the psychological cost of investing in adaptation (e.g., Kori, 2023). The effects of income inequality, average household age and gender distribution are not considered, although these factors influence adaptation decisions as they affect social vulnerability. For example, older households face mobility constraints (Cutter et al., 2003), and countries with high income inequality tend to suffer more, as the Gini index is highly correlated with flood fatalities (Lindersson et al., 2023). Meijer et al. (2023) calculated a social vulnerability index to flooding for Madagascar using socio-economic parameters (age, gender, education), and such an approach could be used to improve the realism of the model.

Finally, we use household data from Ton, Marijn, (2023), which is aggregated data at the district level. We sampled our agent data from this database. Although in this sampling procedure, we used population density and farm type to place agents on a map, there is considerable uncertainty in assigning agents to a geographic location. Therefore, a more spatially explicit household database could improve the robustness of the model. Two main lessons can be drawn from the sensitivity analysis when applying the model to another location or when modelling on a global scale. Firstly, housing prices play a crucial role in estimating damages and modelling adaptation behaviour, with geographical location (rural or urban) and household income serving as essential factors to account for these dynamics. Secondly, adaptation behaviour is strongly influenced by the spending capacity or affordability of the household, with socioeconomic and national poverty line data being used to define affordability (Hudson et al., 2016).

## 6 Conclusions

SLR will lead to more frequent flooding, and salt intrusion in coastal areas will be a major concern for farming households that are highly dependent on the soil quality for their livelihoods. In this study, we simulated the risk of SLR and flooding to coastal farmers by assessing salt intrusion risk and flood damage to buildings. The results show that the coastal farmers in Mozambique face total losses of up to $12.5 million per year from salt intrusion and up to $800 million per year from flooding under RCP8.5 in the year 2080. Sorghum farmers experience little or no damage from salt intrusion, while rice farmers experience the largest losses, up to $15,000 per year. We show that medium-sized farmers (1–20 ha) face the highest risk because they have large farms but do not have high capacity (i.e. disposable income) to adapt to the increasing risk (Esquivel et al., 2021).

The number of households adapting varies across the province (6%–50%), with salt adaptation being the most adopted because it is the least costly. Despite adaptation measures, of the total of 300,000 farmers in coastal flood zones, about 13%–20% will migrate to safer areas under different settings of adaptive behaviour and different climate scenarios. In some provinces, such as Sofala, the cumulative adaptation costs will increase from $2.5 million to $5.3 million in 2080. The paper provides a novel approach to studying the combined effects of SLR and salt intrusion. It illustrates the importance of considering the heterogeneity in human behaviour in flood impact assessment. The model could be applied to other countries (and/or the globe) impacted by the combined effect of salt intrusion and SLR by changing the input parameters. However, the inclusion of social vulnerability will provide robust results. These outcomes open the door for future research and application of the model on a global scale.

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## Author Contributions

KP coded and designed the main model, JAdB assisted in coding the main model, JAdB, HdM, WB and JCJHA contributed to the conceptualization and methodology, and KP prepared the manuscript with contributions from all co-authors.

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## Conflict of Interest

*The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest*.

## Code/Data availability

The code is freely accessible at *https://zenodo.org/records/10456055* and input data can be downloaded from mentioned open sources and pre-processed using scripts provided under directory prepare_input_data.