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Crop Loss Due to Soil Salinity and Agricultural Adaptations to It in the Middle East and North Africa Region

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Abstract

Using data collected from 294 farm households across Egypt, Morocco, and Tunisia, this study quantifies crop losses due to soil salinity and analyzes the key factors associated with it. Further, it analyzes the factors driving the farmers' choice of adaptation measures against salinity. Almost 54% of households surveyed reported yield losses due to salinity, with a sizable portion experiencing losses above 20%. In response to salinization, farmers adopted five adaptation practices, including crop rotation, salt stress-tolerant varieties, drainage management, soil amendments, and improved irrigation practices. A generalized linear model is applied to examine the factors explaining crop loss due to salinity. Results show that a higher share of irrigated land correlates with greater salinity-related crop loss, particularly in areas with poor drainage and low water quality. Conversely, farms with good soil quality reported significantly lower losses. Crop losses due to salinity were much lower in quinoa compared to wheat. Farmers who received agricultural training or belonged to co-operatives reported lower losses. A multivariate probit model was employed to understand drivers of adaptive behaviors. The analysis shows credit access, cooperative membership, training, and resource endowments as significant predictors of adaptation choices. The results underscore the importance of expanding credit availability, strengthening farmer organizations, and investing in training for effective salinity management.

Keywords: salinity; Egypt; Morocco; Tunisia; adaptation measures

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1. Introduction

Salinity is one of the critical environmental concerns adversely affecting agricultural production across the Middle East and North Africa (MENA) region [1–4]. Recurrent droughts and desertification further exacerbate farming challenges. Climate change is expected to make the agriculture in this region more vulnerable through heightened pressure on soil and water resources. Salinity levels and their rate of increase vary across the different areas in the region, depending on local rainfall, temperature, and soil drainage capacity.

Salinity in agriculture stems from multiple interacting sources that affect soil and crop performance differently. It is essential to distinguish between soil salinity, which refers to salt accumulation in the root zone, and irrigation water salinity, referring to salt concentration in the applied water. These processes often co-exist in arid regions and lead to secondary salinization, especially where drainage is poor or evaporation rates are high [5,6]. In the MENA region, both primary and secondary salinization are common. Though multiple aspects of salinity have been studied in past literature, the agriculture loss at the farm household level due to salinity and farmer adaptation behavior against it are still less explored in the region [7,8]. This study therefore fills the existing knowledge gap by assessing crop loss due to salinity and exploring adaptation measures applied at the farm household level. While this study is based on farmers' perception of salinity, a mechanistic understanding of its sources—whether from soil, water, or management—is also crucial to guiding effective adaptation and appropriate policy design for agricultural adaptations [9,10].

Rising salinity has caused significant economic losses in cereal crops such as wheat, maize, and rice, indicating the urgent need for adaptation strategies, including improved farmer knowledge on choice of crops [11,12]. In response, farmers in the MENA region have implemented various adaptative agricultural measures, including crop rotation or diversification, the use of salt stress-tolerant varieties, improved drainage management, and enhanced irrigation practices to mitigate salinity risk [3,13,14].

In the southern part of Morocco, soil and groundwater salinity has become a major constraint on crop production, particularly forage crops [2]. Consequently, many farmers are turning to salt-tolerant alternatives. Blue panicum, sesbania, and pearl millet, for instance, have shown higher yield under saline conditions compared to traditional forage crops like alfalfa and forage corn. The adoption of such salt-tolerant crops and varieties is thus a critical adaptation measure that can improve farm income and overall food security in the region [2]. While wheat remains one of the most common and historically significant cereal crops in Morocco and the broader MENA region, it suffers considerable yield losses under high salinity. By contrast, salt-tolerant crops such as blue panicum, sesbania, and fodder beet tend to perform better under these conditions [3,15].

Globally, irrigation practices are leading contributors to increasing salinity in soils and aquifers [16–18]. In Morocco, for example, coastal groundwater resources are often highly saline and thus, largely unsuitable for agricultural use [19], negatively affecting crop yields [15]. Previous studies [15,20,21] further indicate that wheat yield declines significantly once the soil salinity stress reaches a level of 6–8 dS m^{-1} [20]. In Egypt, where most of the population resides near the banks of the Nile River to access arable land, approximately 35% of cultivated land suffers from salinity and drainage management problems [22]. Meanwhile, in Tunisia, around 80% of water resources and nearly 35% of agricultural soils are saline-affected, making effective irrigation management crucial for attaining food security in the country [23]. Thus, proper irrigation scheduling and the use of effective irrigation methods are essential components of salinity adaptation in agriculture [24].

Against this backdrop, the present study assesses crop production losses due to salinity in three MENA countries—Egypt, Morocco, and Tunisia. This study defines crop loss as the farmer self-reported proportion of yield reduction during the last season. Additionally, it examines the on-farm adaptation measures employed by the farmers to minimize salinity's adverse effect, along with key factors influencing farmers' choice of these practices.

The rest of the paper is organized as follows. The Section 2 describes the study area, sampling methods, and data. This is followed by a Section 3 dealing with the conceptual framework and empirical estimation methods used in the study. The Section 4 presents empirical results, a discussion, and policy implications, while the Section 5 concludes the study.

2. Study Area, Sampling Methods, and Data

The study is based on the data collected in 2022 from 294 farm households in three countries in the MENA region: Egypt (112 households), Morocco (100 households), and Tunisia (82 households). Of the 29 governorates of Egypt, the study collected data primarily from New Valley, North Sinai, and Suez; however, some sample households were also from the Alexandria, Beheira, Ismailia, and Matruh governorates. Of the 12 regions defined by the Moroccan government since 2015, the data for this study were collected from four regions, viz., Souss-Massa, Draa-Tafilalt, Beni Mellal Khenifra, and Marrakesh Safi. Tunisia has 24 governorates. This study covered 6 governorates in its sample (Table 1).

Table 1. Distribution of sample households across three countries.

Egypt		**Morocco**		**Tunisia**	
Governorates	Sample size	Regions	Sample size	Regions	Sample size
New Valley	50	Beni Mellal Khenifra	15	Nabeul	48
North Sinai	25	Draa-Tafilalt	37	Sfax	9
Suez	25	Marrakesh Safi	29	Siliana	12
Others *	12	Souss-Massa	19	Mahdia	8
				Sousse/Zagouan	5
Total sample	112	Total sample	100	Total sample	82

Note: * Includes Alexandria, Beheira, Ismailia, and Matruh governorates.

In collaboration with the regional offices of The Food and Agriculture Organization of the United Nations (FAO), the International Center for Biosaline Agriculture (ICBA) designed and supervised the fieldwork in the study countries. Structured surveys were designed to collect qualitative and quantitative data from the farm households in the project locations. Survey locations in the study countries were selected from those areas where quinoa was introduced and promoted by FAO projects. The survey collected the primary data on several indicators covering different aspects of quinoa farming, farm household characteristics, and perceptions regarding climate and environmental risks, farm income, market access, and salinity and its impacts. A two-stage sampling strategy was employed to first identify and select larger areas where quinoa has been introduced and produced. Following the selection of these primary sampling units, the final sampling units (i.e., farm households) were selected in the second stage. The sample size was calculated purposively based on the project areas and their coverage. Along with the best representation of the study populations, cost-effectiveness was also one of the guiding issues while making sample size decisions. Therefore, the survey was implemented with the help of local experts employing and training local enumerators so that survey questions were effectively communicated and reliable data were collected. Figure 1 shows the countries under study and the survey locations.

To better understand the environmental conditions facing farmers in the study regions, Table 2 outlines common types, source, and mechanisms of salinity in the MENA region. As the discussions on salinity type, their sources, and mechanisms of salinity are out of the scope of this study, we referred to some literature in Table 2.

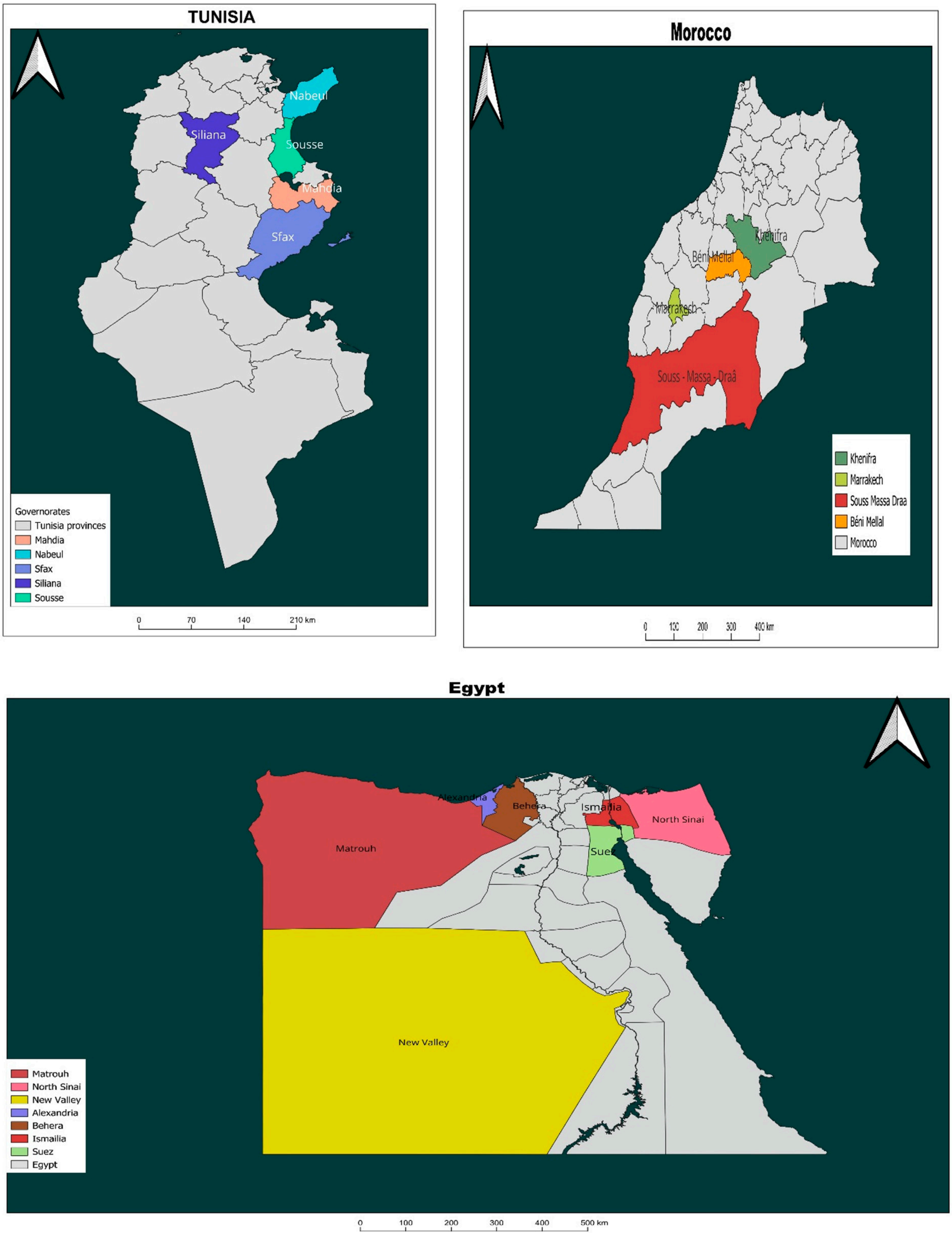

Figure 1. Study countries and locations under study.

Table 2. Typology of salinity sources and their underlying mechanisms relevant to MENA.

Salinity Type	Source	Mechanism	Example in MENA Region *
Primary soil salinity	Natural accumulation of salt	Weathering of parent material and deposition in low-lying areas	Inland salt flats in arid zones [25]
Secondary soil salinity	Irrigation with saline water	Deposition of salts from irrigation water, especially under poor drainage	Nile Delta regions experiencing waterlogging [9]
Water table salinity	Rising groundwater levels	Capillary rise of saline groundwater into the root zone	Coastal areas with shallow water tables [26]
Fertilizer-induced salinity	Excessive use of chemical fertilizers	Accumulation of salts from fertilizers, particularly in areas with low rainfall	Intensive farming regions with high fertilizer application [6]

Notes: * In this column the number within square brackets refers to respective references.

In arid and semi-arid regions of Egypt, soil salinization has become one of the crucial environmental concerns leading to lower soil fertility and reduced crop productivity, and hindering sustainable agricultural development [27,28]. Another critical issue in Egypt is its large dependence on food imports (almost 43%) [29]. Agriculture, one of the major sectors contributing to the economic development of Morocco, faces serious challenges due to increasing salinization of soils and groundwater. Marine intrusion in coastal areas, dissolution of saline aquifer rocks, and infiltration of poor-quality irrigation largely led to groundwater salinization, which in turn lowers agricultural yields [12,30]. In Morocco, nearly 21% of the irrigated land is salt-affected, and some estimates suggest that almost 5% of total agricultural lands are affected by different levels of salinity [4]. Tunisia suffers from severe water scarcity and salinity challenges [31]. It is estimated that nearly 50% of the irrigated land in arid and semi-arid regions of Tunisia is highly sensitive to salinity [10]. It is estimated that about 1.5 Mha of land (i.e., 10% of the total area) contains salt-affected soils in Tunisia [4]. About 505 ff of the 375,000 ha of total irrigated areas is affected by salinization [4]. Tunisia is the net importer of agricultural products. The main cereals it imports are soft wheat, corn, barley, and durum wheat.

3. Conceptual Framework and Empirical Estimation Methods

This study draws from past literature on adaptation to climate risks (for details, we refer to Refs. [32,33]) and considers that adaptation decisions against salinity are driven by multiple factors, including the livelihood assets possessed by the farmers. Livelihood assets encompass human, natural, financial, physical, and social capitals. These assets influence the farm household's ability to adopt the adaptation strategies against salinity risks. To capture this, we have included several variables in our empirical estimation. For example, to capture the effects of human capital on adaptation choice, we included variables such as training undertaken by the household, education of the household head, and age of the farmers (as a measure of farm experience). Similarly, in order to capture the impact of social capital, we included variables such as membership in the farm cooperatives, access to credit, and so on.

3.1. Generalized Linear Model

The response variable in our case is "crop loss due to salinity," which is measured in proportion (or in percentage) of the total crop produced by the individual farm household. Thus, the ordinary least square (OLS) regression model does not fit well in analyzing the factors explaining it. Since the OLS predicts the expected value of the dependent variable as a linear combination of a set of independent variables, any change in an independent variable leads to a change in the dependent variable indefinitely in either direction or in any quantity [34]. In our case, the expected value of dependent variables should fall within the range of zero and one. Generalized linear models (GLMs), due to their flexibility, are appropriate in such a case. In GLMs, we can use a logit link and binomial family to accomplish this task. Also, we obtain robust standard errors by correcting for heterogeneity and any misspecification of the distribution family [35,36]. The GLM can be specified as follows (for details: https://www.stata.com/features/generalized-linear-models/, accessed on 7 February 2025):

$$E(Y|\boldsymbol{X}) = \mu = g^{-1}(\boldsymbol{X\beta}), \qquad Y \sim F \tag{1}$$

In Equation (1), $E(Y|\boldsymbol{X})$ refers to the expected value of Y conditional on the vector of explanatory variables $(\boldsymbol{X})$. $\boldsymbol{\beta}$ is the vector of unknown parameters to be estimated. In a GLM, each outcome of the dependent variable is assumed to be generated from a specific probability distribution, such as normal, binomial, Poisson, gamma, etc. In this case, the conditional mean μ of the distribution depends on the set of explanatory variables. In Equation (1), g and F represent the link function and the distributional family. For ease of interpretation, we reported the marginal effects of each variable in the GLM.

3.2. Multivariate Probit Model

To assess the factors explaining the choice of adaptation measures that farmers applied to reduce the negative impacts of salinity on crop production, we use the multivariate probit model (MVPM). Though the decision to apply a particular adaptation measure is discrete in nature, the use of the univariate logit or probit model is not appropriate, and it is attributable to potential interdependence across the decisions to apply selected adaptation measures against salinity. In this context, using binary logit or probit models can lead to biased estimates, as these estimation methods assume the independence of error terms. The MVPM acknowledges the interrelations among the multiple adaptation measures, i.e., the possibility of correlation among the unobserved disturbances across them, thereby reducing the possibility of having a biased and an inefficient estimate [37]. Applying the MVPM, we can examine the existence of complementarities and substitutability between the salinity adaptation measures in agriculture.

Farmers in the study areas have applied five major adaptation measures: soil amendment (A), crop rotation (C), drainage (D), improved irrigation methods and practices (M), and adopting salt-tolerant crop varieties (S). An individual farmer is more likely to adopt a specific adaptation measure if they benefit from taking the adaptation measure rather than implementing no adaptation. Each farm household under consideration is confronted with a decision on whether to apply any of these adaptation measures. Assume that π_j and π_0 are benefits associated with the use of adaptation measures and without it, respectively. A farmer decides to apply an adaptation measure if the net benefit it brings to farm income is positive, i.e., $N_{ij} = \pi_j - \pi_0 > 0$. As the net benefit of adaptation is a latent variable, which is determined by a set of variables $\left(X_{ij}\right)$, including farmer characteristics and perceptions, farm attributes, and other institutional setup, it can be expressed as follows:

$$N_{ij} = X'_{ij}\beta_j + \epsilon_{ij} \text{ (where } j = A, C, D, M, S) \tag{2}$$

Following an indicator function approach, Equation (2) can be expressed in the form of an observed binary outcome equation for each of the adaptation measures applied against the salinity problem as follows:

$$N^*_{ij} = \begin{cases} 1 & if \quad N_{ij} > 0 \\ 0 & otherwise \end{cases} \text{(where } j = A, C, D, M, S) \tag{3}$$

Because of the possibility of selecting multiple adaptation measures, the error terms in the MVPM jointly follow a multivariate normal distribution with zero conditional mean and variance normalized to one [i.e., $(u_A,\ u_C, u_D, u_M, u_S) \sim MVN(0,\ \omega)$]. The covariance matrix is presented in Equation (4) as follows:

$$\omega = \begin{bmatrix} 1 & \rho_{CA} & \rho_{DA} & \rho_{MA} & \rho_{SA} \\ \rho_{AC} & 1 & \rho_{DC} & \rho_{MC} & \rho_{SC} \\ \rho_{AD} & \rho_{CD} & 1 & \rho_{MD} & \rho_{SD} \\ \rho_{AM} & \rho_{CM} & \rho_{DM} & 1 & \rho_{SM} \\ \rho_{AS} & \rho_{CS} & \rho_{DS} & \rho_{MS} & 1 \end{bmatrix} \quad (4)$$

In Equation (4), ρ denotes the pairwise correlation coefficient of the error terms of any two salinity adaptation measures applied by the farmers. Any non-zero values in the off-diagonal elements in the covariance matrix (i.e., in Equation (4)) validate the application of MVPM estimation in our case, indicating interdependence.

3.3. Variables Used in the Analysis and Hypothesis

Dependent Variables

This study has six dependent variables: one variable in proportion (i.e., proportion of crop loss due to salinity) and five binary variables (i.e., soil amendment (A), crop rotation (C), drainage management (D), improved irrigation methods and practices (M), and planting salt-tolerant crop varieties (S)).

Human factors such as inappropriate irrigation practices, poor drainage management systems, and excessive use of chemical fertilizers contribute to crop loss due to salinity. Hence, appropriate drainage management and irrigation practices are some of the adaptation measures against salinity [38]. In irrigated agriculture, drainage management largely contributes to adapting salinity risk [39]. In the study areas, about 7% of the total farmers have used appropriate drainage to reduce the effect of salinity on crops. Applying suitable irrigation management, there is a possibility to enhance irrigation efficiency and reduce salinity impacts [40]. Almost 47% of the respondents applied irrigation management to adapt to salinity.

Soil amendment is found to be a crucial measure to reduce soil salinity and the nutrient content of the soil [41]. Biochar and compost application have been used by farmers as organic amendments to soil for mitigating salinity [42]. About 25% of the total sample farm households applied soil amendment to reduce the negative impacts of soil salinity on agricultural production.

Crop rotation, such as alternating salt-sensitive crops with salt-tolerant varieties, helps disrupt the salt accumulation in soils, thereby relieving plant stress and preserving soil fertility [43,44]. A careful selection of salt-tolerant crops and crop varieties contributes to adapting to salinity, as these crops/varieties possess genetic characteristics to thrive in environments with higher salinity levels [44–46].

4. Results, Discussion, and Policy Implications

4.1. Descriptive Results

Table 3 presents the percentage of farm households reporting crop loss due to salinity in the last cropping season. Nearly 54% of the total sample households reported crop loss due to salinity. About 23% of farmers reported a loss of up to 20%, whereas almost 15% of farmers reported a loss of 60% or more. This shows that farmers need to seek some adaptation measures.

Table 3. Proportion of crop loss due to salinity.

Crop Loss Due to Salinity	Farm Households Reporting Loss	
	Number	**Percentage**
No loss	136	46.26
Up to 20%	67	22.79
More than 20 and less than 60%	47	15.98
60% or more	44	14.97

Table 4 depicts the major adaptation measures undertaken by the farmers in the study countries. Improved irrigation methods and practices (46.60%) are the most common adaptation measures applied to mitigate crop loss due to salinity, followed by soil amendment (24.49%) and planting salt-tolerant crops (23.63%). Farmers also applied crop rotation (15.44%) and improved drainage (7.14%) as measures to mitigate the negative effects of salinity on agriculture.

Table 4. Major agricultural adaptation measures applied against salinity.

Adaptation Measures	Percent of Households *
Crop rotation	15.44
Adopting salt-tolerant crops	23.63
Drainage	7.14
Improved irrigation methods and practices	46.60
Soil amendment	24.49

Note: * Due to the possibility of multiple responses, the total percentage does not sum up to 100.

In Table 5, we present the explanatory variables and their descriptive statistics. Farmers reported that about 56% of the total land being held is irrigated land. The majority of farmers (71%) stated that the land they possess has average soil quality, followed by good soil quality (16%), and the remaining 13% has poor-quality soil. Quinoa and wheat farming are commonly practiced in the study area. Farmers experienced increased drought (90%) and extreme temperatures (78%) as major environmental risks along with increasing salinity. The average land holding size is 3.45 hectares.

Table 5. Descriptive statistics of the variables used in the study.

Variables	Mean	Standard Deviation
Land quality		
Share of irrigated land (C)	0.56	0.49
Soil quality: good (D)	0.16	0.37
Soil quality: average (D)	0.71	0.46
Soil quality: poor (D)	0.13	0.34
Type of crop cultivated		
Wheat (D)	0.34	0.47
Rice (D)	0.05	0.17
Quinoa (D)	0.44	0.49
Environmental risks (other than salinity)		
Extreme temperature (D)	0.78	0.41
Increased drought (D)	0.90	0.29
Farmer economic capacity		
Land owned (in hectares) (C)	3.45	4.67
Labor–land ratio (adult family labor to cultivated land ratio) (C)	1.07	0.83

Table 5. *Cont.*

Variables	Mean	Standard Deviation
Farmer knowledge and awareness		
Training undertaken (D)	0.59	0.48
Household head education (in years) (C)	11.95	6.94
Age of household head (in years) (C)	48.89	10.11
Social and institutional variables		
Membership in farm cooperatives (D)	0.56	0.49
Distance to market (in km) (C)	13.28	15.82
Distance to extension service (in km) (C)	0.79	0.41
Access to credit facilities (D)	0.28	0.45
Household income (in USD)	5320.06	3750.19
Work off-farm (D)	0.62	0.48
Male-headed household (D)	0.93	0.25
Countries		
Egypt	0.38	0.49
Morocco	0.34	0.47
Tunisia	0.28	0.45

Note: C and D refer to continuous and dummy variables, respectively. Household incomes of the countries under study are expressed in United States dollar (USD). The annual average exchange rate of EGP 1 was equivalent to USD 0.0519; MAD 1 was equivalent to USD 0.0986, and TND 1 was equivalent to USD 0.3249 in the year 2022.

4.2. Factors Explaining Crop Loss Due to Salinity (Results of Generalized Linear Model)

Table 6 presents the results of the analysis of factors explaining the proportion of crop loss due to salinity. There is a positive association between irrigated land and crop loss due to salinity (the coefficient is significant at the 1% level). Crop loss due to salinity is relatively lower on farms with good soil quality as compared to farms with low soil quality. The type of cultivated crops is another crucial factor explaining crop loss due to salinity. Of the three major crops, farmers producing wheat and rice farmers face more crop loss due to salinity, while quinoa production suffers less crop loss due to salinity. Agricultural training is found to be negatively associated with crop loss due to salinity, indicating that trained farmers might use appropriate adaptation measures against salinity. Similarly, cooperative membership and crop loss proportion are negatively associated. Wealthy farmers are more likely to have a lower proportion of crop loss, and it may be due to sufficient resources to invest in adaptation measures. Results in Table 5 indicate the differences across the study countries regarding crop loss due to salinity. Both Morocco and Egypt are found to have less crop loss due to salinity as compared to Tunisia.

Table 6. Factors explaining crop loss due to salinity (results of GLM).

Variables	Marginal Effects #	Standard Error
Land quality		
Share of irrigated land	0.102 ***	0.031
Soil quality: good (base category low quality)	−0.109 **	0.040
Soil quality: average (base category low quality)	−0.034	0.032
Type of cultivated crop		
Wheat	0.232 ***	0.034
Rice	0.074 *	0.031
Quinoa	−0.108 ***	0.029
Environmental risks (other than salinity)		
Extreme temperature	−0.037 *	0.017
Increased drought	0.007	0.022

Table 6. *Cont.*

Variables	Marginal Effects #	Standard Error
Farmer capacity		
Training	−0.094 ***	0.019
Education of household head	−0.002	0.007
Member cooperatives	−0.053 *	0.023
Work off-farm	−0.032 **	0.015
Log of total income	−0.080 ***	0.017
Country dummy		
Morocco (base category: Tunisia)	−0.184 ***	0.041
Egypt (base category: Tunisia)	−0.156 ***	0.036
Constant	0.558 ***	0.136

Notes: # Marginal effect (dy/dx) is for discrete change in dummy variable from 0 to 1; *, **, *** refer to significance at the $p < 0.10$, $p < 0.05$, and $p < 0.01$ levels, respectively.

4.3. Factors Determining Farmers' Choice of Adaptation Measures Against Salinity

Farmers reported five commonly applied adaptation measures against crop loss due to salinity. These measures were improved irrigation methods and practices, soil amendments, use of salt-tolerant crops/varieties, drainage management, and crop rotation. There is a possibility that these five measures can be mutually inclusive, i.e., the application of one measure may not preclude the application of another by the farmers in response to salinity problems. Hence, we applied the multivariate probit model to analyze the factors determining the farmers' choice of adaptation measures against salinity. We tested the potentiality of the correlation of error terms across selected adaptation measures against salinity and found that many of the pairwise correlation coefficients are non-zero and are statistically significant (Table 7), indicating that the error terms in the choice of adaptation measures are correlated. The non-zero correlation of any of these terms justifies the application of the multivariate probit model in the analysis.

Table 7. Covariances across the adaptation measures.

Adaptation Measures	Coefficient	Standard Error
Crop rotation × salinity-tolerant varieties	0.184	0.138
Crop rotation × improved irrigation methods	−0.403 **	0.126
Crop rotation × soil amendment	−0.126	0.159
Crop rotation × drainage management	0.536 ***	0.177
Salinity-tolerant varieties × improved irrigation methods	−0.592 ***	0.194
Salinity-tolerant varieties × soil amendment	0.097	0.154
Salinity-tolerant varieties × drainage management	0.331 **	0.161
Improved irrigation methods × soil amendments	−0.589 ***	0.169
Improved irrigation methods × drainage management	−0.275 **	0.126
Drainage management × soil amendments	0.083 *	0.047

Notes: Standard errors are reported in parentheses; *, **, *** refer to significance at the $p < 0.10$, $p < 0.05$, and $p < 0.01$ levels, respectively; likelihood ratio test of rho12 = rho13 = rho14 = rho15 = rho23 = rho24 = rho25 = rho34 = rho35 = rho45 = 0; chi-square (10) = 113.393 and Prob > chi-square = 0.000.

Table 8 presents the results of the multivariate probit model that explores the factors explaining the choice of adaptation measures against salinity. Results indicate that farmers with a higher share of irrigated land are more likely to adopt improved irrigation practices, salt-tolerant crops, crop rotation, and drainage management to mitigate the risk of crop loss due to salinity. Farmers are more likely to apply improved irrigation practices on farmland with good soil quality as compared to farmland with low soil quality (statistically significant at the 1% level). Similar findings are observed in the case of salt-tolerant crops and crop rotation.

Table 8. Factors explaining the choice of adaptation measures.

Independent Variables	Improved Irrigation Practices	Salt-Tolerant Crops	Soil Amendment	Crop Rotation	Drainage Management
Farm characteristics					
Share of irrigated land	0.217 **	0.152 ***	0.234	0.137 ***	0.331 ***
	(0.102)	(0.021)	(0.205)	(0.049)	(0.110)
Soil quality: good (base category low quality)	0.197 ***	0.202 *	−0.179	0.046 **	−0.219
	(0.068)	(0.151)	(0.267)	(0.018)	(0.213)
Soil quality: average (base category low quality)	0.543	0.077	−0.344	−0.094	−0.344
	(0.538)	(0.334)	(0.322)	(0.103)	(0.322)
Farmer knowledge and awareness					
Training	0.046 **	0.085 **	0.264 ***	0.250 ***	0.109 **
	(0.018)	(0.039)	(0.079)	(0.088)	(0.061)
Education of hh head (in years)	−0.062	−0.236	0.225	−0.369	0.225
	(0.048)	(0.348)	(0.804)	(0.607)	(0.804)
Age of hh head (in years)	0.029 *	0.012 **	0.125	0.136 **	0.145
	(0.012)	(0.005)	(0.122)	(0.059)	(0.133)
Social and institutional variables					
Member cooperatives	0.360 ***	0.520	−0.826	−0.292	0.126 **
	(0.085)	(0.593)	(0.804)	(0.817)	(0.054)
Market distance (in km)	−0.203	−0.107 **	−0.113	−0.211 **	−0.208
	(0.273)	(0.051)	(0.097)	(0.085)	(0.073)
Credit access	0.055 **	0.173 ***	0.138 **	0.187 ***	0.078 **
	(0.023)	(0.045)	(0.056)	(0.053)	(0.036)
Work off-farm	−0.365 **	0.162 ***	0.152 ***	0.213 **	−0.152 ***
	(0.157)	(0.048)	(0.023)	(0.099)	(0.023)
Gender of head	−0.340	0.030 **	0.059	−0.028	0.091 *
	(0.378)	(0.012)	(0.660)	(0.024)	(0.049)
Farmer economic capacity					
Land owned (in ha)	0.117 ***	0.197 ***	−0.023	0.391 ***	−0.103
	(0.014)	(0.028)	(0.032)	(0.122)	(0.132)
Labor–land ratio (adult family labor to cultivated land)	0.078 ***	0.077	0.114 ***	0.215 ***	0.114 ***
	(0.015)	(0.064)	(0.016)	(0.073)	(0.016)
Country dummy					
Morocco (base category: Tunisia)	0.840	0.331 ***	−0.267 ***	0.527	0.218
	(0.563)	(0.106)	(0.098)	(0.634)	(0.194)
Egypt (base category: Tunisia)	1.705 **	1.899 ***	−0.680 ***	0.295	−0.180 ***
	(0.587)	(0.558)	(0.197)	(0.323)	(0.053)
Constant	−3.124 ***	1.845 *	−3.198 ***	−1.201 ***	−2.267 ***
	(0.731)	(0.862)	(0.930)	(0.392)	(0.403)
Log likelihood	−412.66				
Wald chi-square (75)	357.15				
Probability > chi-square	0.000				
Number of observations	294				

Note: Standard errors are reported in parentheses; *, **, *** refer to significance at the $p < 0.10$, $p < 0.05$, and $p < 0.01$ levels, respectively.

To improve the interpretability of the multivariate probit results, Figure 2 presents a heatmap of the average marginal effects derived from the multivariate probit model. Marginal effects indicate how much the probability of adopting a specific adaptation measure changes when a key variable (e.g., credit access, training) increases, holding other factors constant. The results show that access to credit significantly increases the probability of adopting drainage management (0.153) and soil amendments (0.117), reflecting the importance of liquidity for capital-intensive practices. Cooperative membership has a broad influence, particularly on improved irrigation (0.147) and crop rotation (0.139), indicating the value of collective action and information sharing. Agricultural training is most strongly associated with the adoption of salt-tolerant varieties (0.121) and improved irrigation (0.134), underscoring its role in enabling knowledge-based decisions. Land size has the largest effect on drainage (0.101), while household labor availability moderately affects several strategies, especially drainage and crop rotation.

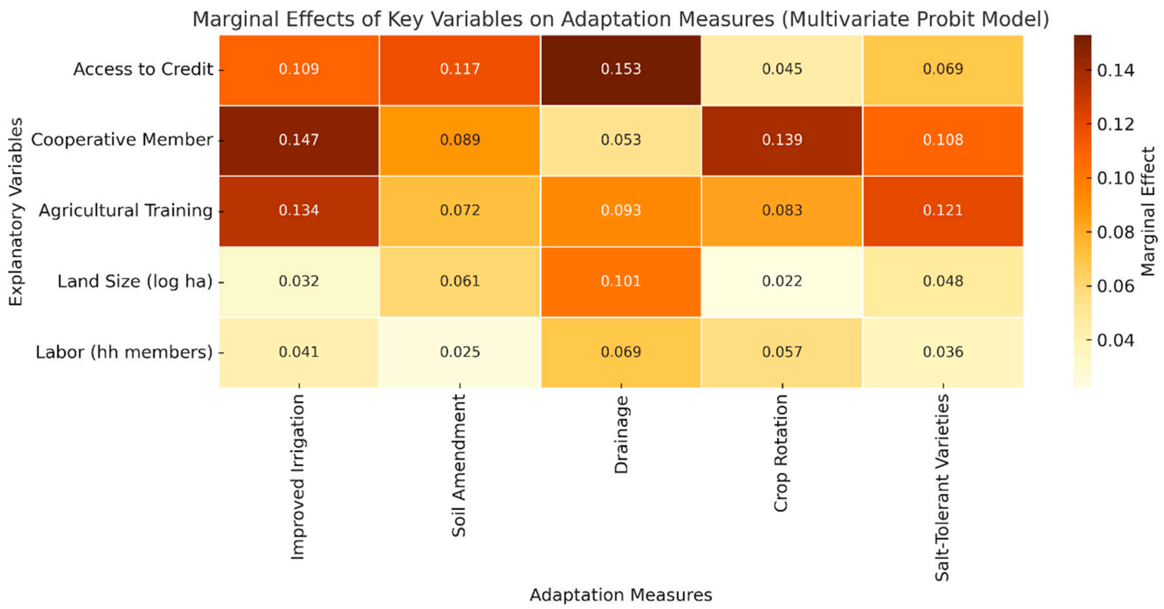

Figure 2. Heatmap showing marginal effects of key explanatory variables on the adoption of salinity adaptation measures, based on the multivariate probit model.

Our analysis indicates that training is one of the most important factors influencing the choice of adaptation measures against salinity. Results in Table 8 show that training has a positive association with the likelihood of adopting the entirety of the adaptation measures under study. Agricultural training is found to be more important than farmers' formal education. Farming experience (expressed in terms of age of household head in years) is also found to have a positive association with the likelihood of adopting improved irrigation practices (statistically significant at the 10% level), salt-tolerant crops (significant at the 5% level), and crop rotation (significant at the 5% level).

Among the social and institutional variables, access to credit is found to be the most important one, as it has a significant positive association with all adaptation measures applied against salinity risk in agriculture. Working off-farm has a positive association with the likelihood of adopting salt-tolerant varieties, soil amendment, and crop rotation, while it is negatively associated with the application of improved irrigation practices and drainage management. Households living far from the market are less likely to adopt salt-tolerant crops and crop rotation. The main reasons for this may be the unavailability of seeds on time or higher transaction costs of obtaining good-quality seeds. Membership in the local farmer cooperative is positively associated with the likelihood of adopting improved irrigation practices and drainage management, indicating that such practices require some collective action. Gender of the household head is found to affect the likelihood of adopting some practices—salt-tolerant crops (significant at the 5% level) and drainage management (10% level of significance).

Land and the labor–land ratio influence the adoption of many of the adaptation measures considered in the study. Large farmers are more likely to adopt improved irrigation practices (significant at the 1% level) and salt-tolerant crops (significant at the 1% level), and follow crop rotation (significant at the 1% level). The labor–land ratio (the ratio of adult family labor to cultivated land area) is found to have a positive association with the likelihood of adopting improved irrigation methods, soil amendment, crop rotation, and drainage management, and the association is statistically significant at the 1% level for all of these adaptation measures.

Our analyses also show the variation in the choice of adaptation measures across the study countries. The likelihood of adoption of salt-tolerant crops is higher among the farmers in Morocco as compared to farmers in Tunisia, while the likelihood of adoption of soil amendment is lower among the farmers in Morocco compared to farmers in Tunisia. Farmers in Egypt are more likely to adopt improved irrigation practices and salt-tolerant crops than the farmers in Tunisia, while it is the opposite in the case of soil amendment and drainage management. These variations may be due to some spatial variations and differences in environmental variables as well as policy variables across the study nations.

4.4. Discussion and Policy Implications

Our findings show that only 7% of the farmers surveyed have implemented appropriate drainage management (see Table 4) to reduce the impact of salinity on crops. This small proportion indicates that most irrigated land lacks proper drainage management, exacerbating problems of salinity and waterlogging [47,48]. Given that natural drainage alone is insufficient to control soil salinity, policies should focus on improving farmers' awareness and expertise regarding the importance of appropriate drainage management in irrigated agriculture. To this end, governments should integrate irrigation expansion programs with drainage management strategies, which will help address soil salinity problems while enhancing the sustainability of irrigation systems.

Improved irrigation methods and practices emerged as the most commonly adopted measures to cope with salinity. These methods are vital for mitigating salinity problems in irrigated agriculture [24,48]. Yet, adoption can still be increased by making the necessary technologies more accessible while enhancing and expanding agricultural training opportunities (see Table 8).

Agricultural training has a positive impact on the likelihood of adopting all five adaptation measures: improved irrigation methods, salt-tolerant crops, soil amendments, crop rotation, and drainage management. These results aligned with similar findings in the coastal areas of the Mekong Delta, Vietnam [49], and Bangladesh [50,51]. Local agricultural extension offices can play a pivotal role by offering training programs that use visual aids to demonstrate the effects of salinity on the crops and effective strategies to mitigate its impact [50–52]. Such initiatives can help farmers recognize the severity of salinity issues and adopt suitable adaptation measures.

Access to credit is another key determinant of adaptation, showing a significant positive effect on all salinity-focused measures (see Table 7). This finding is consistent with prior studies on agricultural risk management and adaptation [32,53,54]. In our sample, however, only 28% of the total sample of farmers reported having access to credit facilities (see Table 4). This finding carries an important message that there is room to enhance farmer adaptation to salinity through better provision and utilization of credit facilities. Obviously, providing improved credit access to farmers to undertake agricultural activities is a policy requirement.

The significant effects of both land owned and the labor–land ratio (i.e., adult family labor per unit of cultivated land) indicate the presence of multiple market imperfections that prevail in the study areas. Additionally, "work off-farm" shows a significant negative association with the likelihood of adopting improved irrigation practices and drainage management, likely due to reduced on-farm labor. Conversely, off-farm work can increase income, and thus, it relaxes the credit constraint, implying that they are more likely to adopt methods like salt-tolerant crops, soil amendments, and crop rotation. Overall, these results indicate that labor, land, and credit market imperfections shape farmer adaptation decisions and influence productivity [55–58]. Enhancing market access and improving infrastructure and market networks help reduce transaction costs in labor, land, and credit markets, thereby supporting farmers' adaptation to salinity and any other risks related to farming. Strengthening collaboration across government institutions related to credit support, rural infrastructural development, and land and labor regulations can be a policy option.

Finally, local farmer organizations play a crucial role in disseminating innovative agricultural practices and technologies that mitigate the adverse effects of climate-related risks [55,59,60]. Indeed, Manda et al. [59] reported that cooperative membership significantly increases the probability of technology adoption. In our case, cooperative members displayed a higher likelihood of adopting improved irrigation practices and drainage management (see Table 7). Nevertheless, only 56% of the total sample of farmers surveyed are cooperative members; thus, there is ample room to increase the adoption of several salinity risk-mitigating measures by expanding cooperative membership among farmers. Policy initiatives should thus prioritize establishing, strengthening, and networking farmer organizations and ensuring close collaboration among agricultural banks, input/output traders, value chain actors, and research institutions to create an enabling environment for salinity risk mitigation.

The findings suggest that activities that contribute to farmer knowledge and awareness, particularly farmer training at the local level, along with improved social and institutional setup such as improved credit access for small farmers and market development, are crucial in all countries, despite the individual country-level differences.

5. Conclusions

This study investigated crop losses due to salinity and identified factors associated with those losses using data collected from 294 farm households from three countries of the Middle East and North Africa (MENA) region, namely, Egypt, Morocco, and Tunisia. In addition, it examined the determinants of farmers' choice of adaptation measures to mitigate salinity's adverse effects.

Overall, 54% of total households in our sample reported crop losses attributable to salinity. Notably, farmers with a larger share of irrigated land in their total land holding suffer a higher proportion of crop loss due to salinity. The choice of crops is also one of the crucial factors determining crop loss due to salinity. Our results suggest that the proportion of crop loss due to salinity is much lower in the case of quinoa compared to wheat and rice. The proportion of crop loss due to salinity is much less in the case of land with good soil quality than in land with bad soil quality. Agricultural training helps reduce crop loss due to salinity because several measures are adopted to mitigate such risks. Wealthy farmers are also less prone to crop loss.

Farmers applied a range of adaptation measures, including crop rotation, salt stress-tolerant varieties, drainage management, soil amendment, and improved irrigation practices, to address salinity challenges. Several factors were found to significantly influence the decision to apply agricultural adaptation measures against salinity, including share of irrigated land, access to agricultural training, credit availability, membership in cooperatives, and farmers' endowment. Strengthening credit access, developing the agricultural market with the integration of wider market facilities, and strengthening local farmer organizations are crucial to disseminating innovative practices and technology required to reduce the adverse effects of salinity. Innovative agricultural training seems to be very important in the choice of crops and other adaptive measures to address salinity problems. Similarly, there is potential to enhance farmer adaptation capacity through better provision and utilization of credit facilities and rural agricultural organizations such as farm cooperatives, input suppliers, and other agriculture-related institutions. Overall, adaptation decisions are driven by multiple factors—both external and internal—and thus, climate policy in the agriculture sector needs to consider all these issues to better respond to climate risks.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author(s).

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