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ORIGINAL ARTICLE

# Farming system change under different climate scenarios and its impact on food security: an analytical framework to inform adaptation policy in developing countries

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## Abstract

Developing countries are considered extremely vulnerable to climate change, due to their socioeconomic context (high levels of poverty) and high dependence of their livelihoods on natural resources. Rural areas in these countries concentrate most of the poorest and food-insecure people in the world, with farmers being among the most vulnerable to climate change. The impacts of climate change are expected to be spatially heterogeneous. In this sense, this paper aims at exploring the direct, marginal effect of climate change on farming system choice and its implications to food security in Mozambique, using a space-for-time approach. Our results suggest that major changes are to be expected in farming system choice and their spatial distribution due to climate change, which will potentially impact the livelihoods and food security status of smallholder farmers. Farming systems including food/cash crops and/or livestock, which are among the most food secure, will tend to be replaced by other systems in all climate scenarios. Mixed farming systems (including food and livestock) and livestock-oriented systems, mostly food insecure, predominant in arid areas are expected to expand with climate change. Food security and innovation stress maps were sketched out from the modelling results, identifying priority areas for public intervention. We also highlight how our approach can be an effective and easily replicable framework to address this type of issues in other developing regions facing similar problems.

**Keywords** Farming system change · Food security · Climate scenarios · Adaptation policy · Developing countries

## 1 Introduction

The multiple global crisis, including the climate crisis, has exposed the weaknesses of food and farming systems both globally and locally, contributing to worsening hunger in many countries, especially in developing countries (von Grebmer et al. 2022). Developing countries concentrate about 98% of the undernourished people

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in the world, with Africa being the region with the highest prevalence of hunger (20% of the population) and food insecurity (60% of the population) (FAO et al. 2021, 2022). In Mozambique, food insecurity affects chronically 24% of households (SETSAN 2014), being predominant in the central and northern regions, where most food is produced, with rural farmers being one of the most vulnerable (Abbas 2017). This paradox might be related to the fact that these areas concentrate most of the rural poor (MEF 2016), having agriculture as their main source of subsistence, thus, relying mostly on seasonal low agricultural incomes (SETSAN 2014; Abbas 2017).

Climate is also an important factor affecting farmers' livelihoods and food security, through changes in land use and cover (Marques et al. 2009), crop or cropping systems productivity and yields (Brito and Holman 2012; Moore et al. 2012; Knox et al. 2012; Habtemariam et al. 2017; Kontgis et al. 2019), and others. The latter is the most common approach among climate change studies, which enables to project yield and productivity changes for each crop, but not changes in crop areas, and thus, does not allow to project whether a crop may be replaced (completely or partially) by other crops in the context of climate change. To project changes in crop areas, it is important to model the effects of climate change on farmers' decisions and not only on crop growth and yields, which is done, under the proposed approach, at the farming system level. Some studies assessed the performance of farming systems (FS) under climate change (Souissi et al. 2018) or its impact on FS selection (Etwire 2020); however, these did not account for FS spatial distribution under climate change. The use of a farming system approach (FSA), using climate (among other biophysical and socioeconomic) variables as drivers of FS choice, estimated based on spatial variability in these variables and used to explore farming-system change (in time) under different climate scenarios would allow a much more direct, systematic, and holistic approach to the impacts of climate change on farmers' choices. In simple words, such a space for time FS analysis would allow to understand and explore when and where certain FS transitions would occur in the context of climate change (An et al. 2015).

Following a FSA, based on a FS typology and the drivers of the spatial distribution of FS estimated for Mozambique, this paper used a space-for-time approach (Buyantuyev et al. 2012; Blois et al. 2013; Frauendorf et al. 2020), based on a random forest model, aiming to: (i) explore the direct, marginal (i.e. other factors held constant) effects of climate change on FS choice; (ii) explore the implications of these direct, marginal effects of climate change on food security; and (iii) assess the potential and limitations of the used strategy to better inform about adaptation policy options for food security. This paper does not intend to project the map of FS and food security levels in the long run but solely to explore and map the direct effects of different climate scenarios on FS change, not considering the effects of climate change on population density, for example, which indirectly will also drive FS changes. Likewise, it does not intend to explore the consequences of technological, development or demographic scenarios driven by non-climatic factors. A farm-level analysis of the impacts of climate change through pressure for farming-system change, as well as the implications of this change for food security of farming-dependent households—which is done in this paper—is expected to provide useful insights on priority areas, that will be under high stress for change in the future. This kind of research would be particularly relevant for adaptation policies aimed at promoting food security in a context of climate change.

## 2 Materials and methods

### 2.1 The study area

The analysis in this paper is done for Mozambique, which is in the Southern Eastern coast of Africa (Fig. 1). Mozambique is among the poorest countries in the world, being considered the 48th most vulnerable and the 22nd least ready country to address climate change (ND-GAIN 2023).

### 2.2 The farming system typology in Mozambique

This paper adopted a FSA, based on a FS typology for Mozambique, derived based on a set of 42 computed variables (Online Resource 1, Table S1), representing farmers' individual productive decisions regarding agricultural land use/cover, livestock density and composition, and use of yield-raising (such as fertilizer) and labour-saving (mechanical or animal traction) inputs. These data were obtained from the latest agricultural census to date (INE 2011). Principal component (PCA) and hierarchical cluster (HCA) analyses were used to derive the FS. This typology was then used in the empirical analysis performed in this paper.

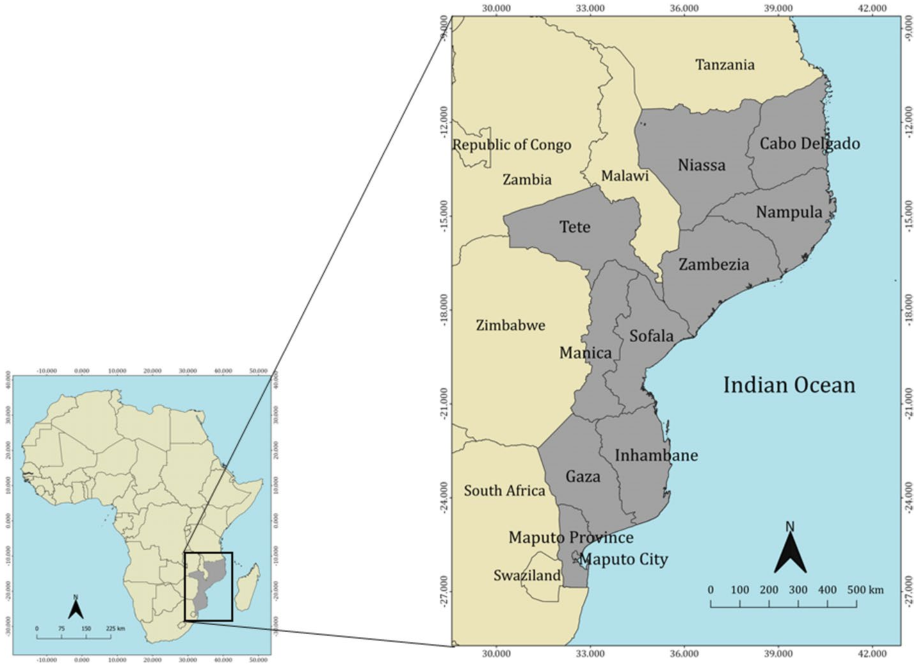

**Fig. 1** The study area: Mozambique. Source: Mozambique National Institute of Statistics (INE)

### 2.3 Farming systems and food security

Food (in)security was assessed based on farm-level analysis of agricultural census data (INE 2011) on food shortages, i.e. households' reports of food shortages, which refer to whether the household experienced a food shortage episode in a 12 months period—reflecting the stability dimension of food security (FAO 2008). A household was considered food insecure if they experienced food shortage in the period analysed and could not consume the food that they usually do. The data refers to the 12 months prior to the survey, therefore are very sensitive to the context and shocks that occurred only in that period (2009–2010). This analysis was possible considered that both FS typology and food security were derived from the same farm-level countrywide database (INE 2011), and therefore, it was possible to classify each farm-household by FS and assess its food security status. Scatter plots with confidence intervals were drawn in R, to explore the association between FS and food security.

### 2.4 Multivariate analysis of socioeconomic and biophysical drivers of farming system choice

A random forest model[1] was used to explain the current choice of FS by each farmer based on a set of socioeconomic and biophysical (including climate) drivers of FS choice (Table 1). This is a discrete choice model, where a farmer chooses a FS among the identified FS (section 2.2), rather than making gradual adjustments that remain within the same FS. Focusing on FS as discrete units instead of gradual adjustments has to do with our aim of projecting FS changes, and the intensity (stress) of this change or food security impacts under climate change, to identify priority areas requiring consistent long-term planned adaptation actions, rather than making detailed recommendations about the nature of those actions (for example, crop variety selection).

The estimation of this model[2] was based on the spatial covariation between the dependent variable (the FS type chosen by the farmer) and the independent variables (biophysical and socioeconomic drivers—Table 1). It is important to note that the effect of climate on FS choice was recovered in a multivariate frame, where the effects of other drivers are also controlled and thus should be interpreted as the marginal effect of climate, i.e. with all other factors (such as, farm size, population density and others) held constant.

### 2.5 Exploring the partial effect of climate change on farming system choice, stress for change and food security

The estimated model of FS choice (section 2.4) was used to project the FS each farmer would choose under each climate scenario holding all other (non-climate) drivers constant. This assumes the driver-FS choice cause-effect relationships captured with our spatial, cross-section data will hold throughout a projection period, an assumption that characterises our space-for-time substitution approach (Wogan and Wang 2018).

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[1] Random forest is an ensemble machine learning technique that uses a bagging-based approach (random sampling with replacement) to build a forest of classification trees (Breiman 2001). It is considered an effective tool in projection and has been widely used in agricultural research to project farmers' decisions (Mwanga et al. 2020) and spatial patterns of agricultural systems (Ribeiro et al. 2016).

[2] This model was built in R version 4.0.2, using the "randomForest" package with 500 trees, and the number of descriptors that are randomly selected to split each node (mtry) was set to 5.

**Table 1** Observed biophysical and socioeconomic drivers used to model farming system choice

| Drivers [(a)] | Description | mean (min–max) s.d. |
|---|---|---|
| Biophysical[(c)] | | |
| MINTEMP | Average minimum temperature in the coldest month 1970–2000 (°C) | 13.7 (7.5–18.5) 2.1 |
| AVGTEMP | Average annual temperature 1970–2000 (°C) | 23.8 (18.5–26.5) 1.4 |
| RAINFALL | Average annual rainfall 1970–2000 (mm) | 994 (413–1877) 224 |
| ARIDITY | Aridity Index | 0.78 (0.29–1.68) 0.22 |
| SLOPE5 | Proportion of administrative post area with smooth slopes (< 5%) | 0.54 (0–1) 0.32 |
| SLOPE10 | Proportion of administrative post area with steep slopes (> 10%) | 0.46 (0–1) 0.32 |
| HIGHFERT | Proportion of administrative post area with intermediate, high, and very high soil fertility | 0.17 (0–1) 0.26 |
| LOWAREA | Proportion of the farm area in lower, valley bottom locations | 0.33 (0–1) 0.46 |
| Socioeconomic | | |
| POPDENS | Population density (inhabitants/km$^2$) | 122 (0.1–6735) 442 |
| ROADDENS | Road density (km/km$^2$) | 0.1 (0–2) 0.1 |
| HOUSEHOLD | Household size | 5 (1–90) 3 |
| FARMSIZE | Farm size (ha) | 1.2 (0.0001–45) 1.4 |
| FEMMANAG | Proportion of farm area managed by women | 0.36 (0–1) 0.48 |
| MKTINTG | Market integration | 0.09 (0–1) 0.19 |
| PAIDWORK | Proportion of hired labour in total labour units[(b)] | 0.13 (0–1) 0.24 |

(a)Biophysical and socioeconomic drivers were computed at the administrative post level (fourth administrative level division). See Online Resource 1, Table S2 for details on the computation of these variables. The sample used to estimate the model included 26,421 farms

(b)Labour units correspond to the sum of all units of labour employed in agriculture and livestock activity, including family labour, full-time and temporary workers

(c)The maximum temperature was tested as a driver of FS choice. Nevertheless, this variable was not used to model FS choice as we considered that both the mean annual temperature (AVGTEMP) and minimum temperature of the coldest month (MINTEMP), alone, are sufficient to integrate the effect of temperature

A space-for-time substitution—widely used in biodiversity and ecological modelling (Elith and Leathwick 2009; Blois et al. 2013)—encompasses analyses in which contemporary spatial patterns, of biodiversity for instance, are used to understand temporal processes and project changes through time, most notably past and future events (Blois et al. 2013). The space-for-time substitution procedure relies on the assumption that the factors driving spatial turnover are also the ones driving temporal turnover, that is, the drivers of spatial variation are the same of the variation over time; therefore, time can be replaced by space to explore future change patterns (Wogan and Wang 2018).

### 2.5.1 Farming system transitions

The projected choices of FS by each farmer under each climate scenario were summarised at the administrative post level using a transition matrix approach. A transition matrix was computed for each climate scenario, presenting the percentages of the current area under a particular FS that would move to each other FS or persist in the same FS (persistence in the matrix diagonal).

### 2.5.2 Climate scenarios

Three climate scenarios were set, which correspond to the following three shared socio-economic pathways (SSPs) for 2081–2100 (Riahi et al. 2017; Hausfather 2018): (i) sustainability and equality (SSP1-2.6), (ii) regional rivalry (SSP3-7.0), and (iii) fossil-fuelled development (SSP5-8.5)—hereafter referred as the optimistic, intermediate and severe scenario (Table 4 in Appendix).

These three climate scenarios were considered to explore the effects of climate change on FS choice. All climate data, historical, and future were collected from WorldClim, version 2.1 (Fick and Hijmans 2017). The climate baseline scenario was set based on historical climate data for 1970–2000 (with spatial resolution of 2.5 min, i.e. ~4.5 km). For climate scenarios, the period 2081–2100 was considered given that manifestations of climate change will be more pronounced in the long term. Also, in the short term, farmers tend to adapt to changes in climate by adjusting, for instance, crop varieties (with shorter growth cycles, drought-tolerance) and, only later, change crop types, input intensity, and other attributes of farming systems (Ouédraogo et al. 2017). Therefore, a longer period was selected, as the main objective was to isolate the effect of climate on FS choice, while keeping all other drivers constant, to understand the role of climate change alone in driving FS change.

### 2.5.3 The direction and intensity (stress) of FS change

Climate change–related FS transitions were assessed based on their direction (for example, change from a purely crop FS to a grazing livestock FS) and intensity. Intensity refers to the magnitude of the effort (cost) required to adapt to climate change through FS change, which is related to knowledge gaps to be filled or required investments (financial, human and others) to make this FS change possible. For example, a farmer moving from a rainfed food crops FS to an irrigated crop or a livestock FS will need the technical knowledge to manage the new, very different FS; moreover, acquisition of irrigation infrastructures or cattle, if not facilitated or supported by the government, will require significant financial investments, often not affordable by small farmers. The higher the difference between the current and projected FS, the higher the magnitude of the required adaptation effort, and therefore the stress for change suffered by the farmer. This is why it was used an indicator for this stress for change (intensity of the transition) that simply measures the Euclidean distance (ED) between the centroids of the clusters corresponding to the current and projected FS.

The distance between the centroids of each pair of 16 FS was first computed in the hyperspace resulting from the Principal Component Analysis (PCA) that preceded the cluster analysis (section 2.2). By using a distance in the PC space, we are avoiding biases in the computation of the stress indicator that would result from using the original variables, which are measured in different scales and intercorrelated (redundant) with each other.

For each climate scenario, we identified all projected FS transitions made by the farmers in each administrative post. Each of these transitions was given a stress score corresponding to the ED between the current and projected FS. A summary stress score for the administrative post was computed as the weighted average of the stress scores for the identified transitions, using the area proportioned of each transition in the agricultural area of the administrative post. These average figures of stress for change were then mapped at the administrative post level to identify spatial patterns and priority areas requiring higher levels of support to farmers in the adaptation process.

The assessment of required support to farmers in a long-term, planned adaptation strategy proceeds in two steps: (1) identifying priority areas, where stress for change is higher; (2) exploring the direction of FS transitions in these priority areas, which may help identifying support actions needed.

#### 2.5.4 The food security variation

The variation in food security for each climate scenario was assessed at the farm/household level based on the corresponding current and projected FS, using the difference in food security levels associated with these two FS. This indicator was computed as the difference between the percentage of farmers reporting food shortages in the transitioned (projected) FS and the current FS. These percentages were computed based on farm-level analysis of agricultural census data on food shortages across FS (section 2.2). This indicator was interpreted as the variation in the probability of a farmer being food insecure (i.e. incurring a food shortage) due to FS change caused by climate change.

## 3 Results

### 3.1 Farming system typology

A solution of 16 clusters, representing the main farming systems in Mozambique (Table 2), was selected from the HCA. FS were named based on their orientation regarding crop-livestock integration, analysed through the cluster means for the background variables (Online Resource 1, Table S1). This typology constitutes the first detailed countrywide FS typology for Mozambique and is in accordance with other studies for Sub-Saharan Africa (Dixon et al. 2001).

### 3.2 FS and food security

An analysis of the FS typology as regards food security allowed to make a clear association between FS and food security levels. FS1 is the most food secure with only 13% of households reporting food shortages. Other FS considered mildly food secure are FS15, FS6, FS2 and FS3, with less than 40% of the households reporting to have experienced food shortages. These FS are market-oriented with intensive use of yield-raising inputs. Other FS are considered mildly or highly food insecure, such as FS9, FS4, FS8 (Fig. 2).

### 3.3 Biophysical and socioeconomic drivers of FS choice

To validate the estimated random forest model, used to identify the main drivers of FS choice, we used the overall out-of-bag estimate (classification error rate), which returned a 60.4% figure. This should be considered a positive result considering the high number of classes in the dependent variable: the 16 FS.

The analysis of the drivers showed that both biophysical (including climate) and socio-economic (such as market integration, and farm and household characteristics) variables

**Table 2** Farming systems in Mozambique

| Farming System (FS)[(a)] | Main characteristics |
|---|---|
| FS1—Tobacco and maize | Intensive use of yield-raising inputs. Medium economic intensity |
| FS2—Cotton | Pesticide-input user. Medium economic intensity |
| FS3—Sesame and maize | Labour intensive. Medium economic intensity |
| FS4—Annual food crops (horticultural crops, maize, and sorghum) | Labour intensive |
| FS5—Annual basic food crops (cassava, maize, and beans) | Labour intensive |
| FS6—Mixed livestock and maize | Intensive use of labour-saving inputs (animal traction and tractors). Medium economic intensity |
| FS7—Bovine, maize, and other food crops | High use of animal traction. Medium economic intensity |
| FS8—Roots (cassava and sweet potato) and mixed permanent crops | Labour intensive. Medium economic intensity |
| FS9—Cashew and mixed annual basic food crops | |
| FS10—Rice and mixed crops | Highly labour intensive |
| FS11—Small livestock and mixed crops | High economic intensity |
| FS12—Swine and mixed crops | |
| FS13—Sheep and mixed crops | |
| FS14—Goats and mixed crops | |
| FS15—Mixed livestock, horticultural and mixed permanent crops | Irrigated with intensive use of yield-raising inputs and animal traction. High economic intensity |
| FS16—Mixed livestock, coconut, and cassava | High use of animal traction |

(a) See the spatial distribution of FS in Online Resource 1, Fig. S1

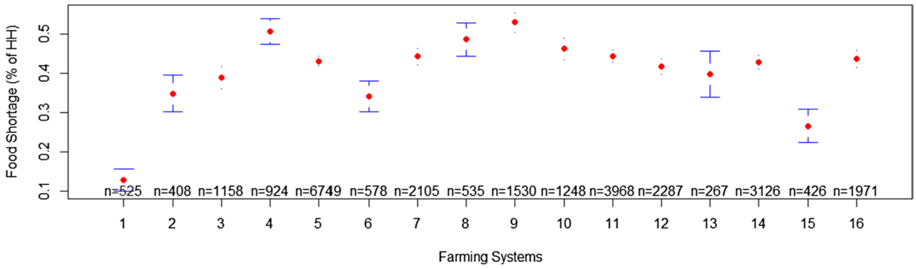

**Fig. 2** Proportion of households that reported food shortages by FS

play an important role in explaining why farmers choose a particular FS. From these results, biophysical variables proved to be important determinants of FS choice: among the ten most important drivers, six are biophysical, with emphasis to climate (Fig. 3). It was found a strong link between the spatial distribution of FS and the climate drivers, which enabled us to propose this FSA as a framework to assess the direct, marginal effect of climate change on FS choice and explore the implications of these effects on food security.

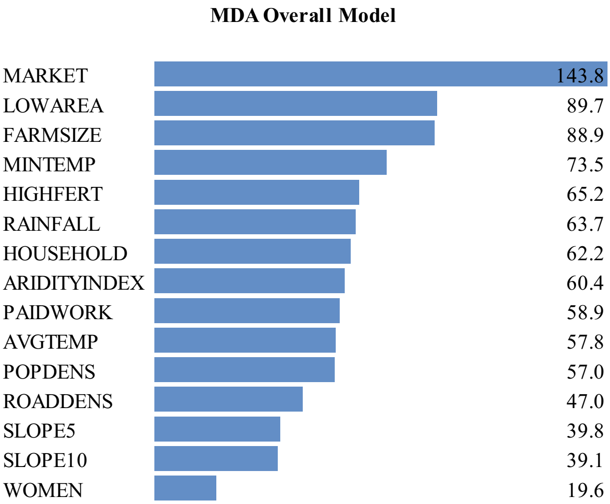

**Fig. 3** Random Forest variable importance based on mean decrease accuracy for the overall model. See variable description in Table 2

### 3.4 Climate scenarios

Climate projections indicate that both minimum and average temperatures are expected to increase by 2100, between 1–2 °C in the optimistic scenario and 4–5.4 °C in the severe scenario. This increase will be lower along the coast and higher in inland regions. Regarding rainfall, projections for the optimistic scenario show no substantial changes (+/− 50 mm) at the national level. In the severe scenario, it is expected a decrease in rainfall (50–100 mm on average) in most of the country. Areas currently showing higher levels of rainfall will experience stronger reductions (up to 165 mm). On the other hand, regions with observed low levels of rainfall (less than 600 mm) will see no substantial reduction in all scenarios.

Mozambique is currently characterised by a humid climate in most central and northern regions and a semi-arid climate occurring in the south-west and upper Zambezi Valley in the central region (Fig. 4d). It is expected an expansion of the semi-arid and dry subhumid areas under the optimistic scenario, by 2100. In the severe scenario areas that are currently humid/dry subhumid will become semi-arid, covering almost the entire country, and current semi-arid regions will become drier (arid). Only the mountainous areas in Northern and Central Mozambique will remain dry sub-humid or humid.

### 3.5 Farming system change under climate scenarios

Our results show that a shift of FS is expected in response to climate change in most of farmland (Table 3). Even in the optimistic scenario, FS choice is expected to change, although some FS will persist, with a significant share of the area under that system projected to remain within the current FS, e.g. FS5 (staple food crops), FS7 (bovine), FS1 (tobacco), FS11 (small livestock—such as poultry), FS14 (goats), and FS10 (rice and mixed crops). The most significant changes under this scenario are expected to occur under FS16 (coconut) which loses 49% of the area to FS5, 24% to FS11 and 13% to FS14; FS13 (sheep) shifts to FS5 (39%), FS11 (20%), and FS7 (18%); FS2 (cotton) transition to FS7 (30%) and FS5 (29%); and FS8 (roots) losing area mostly to FS5 (51%). On the other hand, although 64% and 51% of the area currently under FS3 (sesame) and FS4 (food

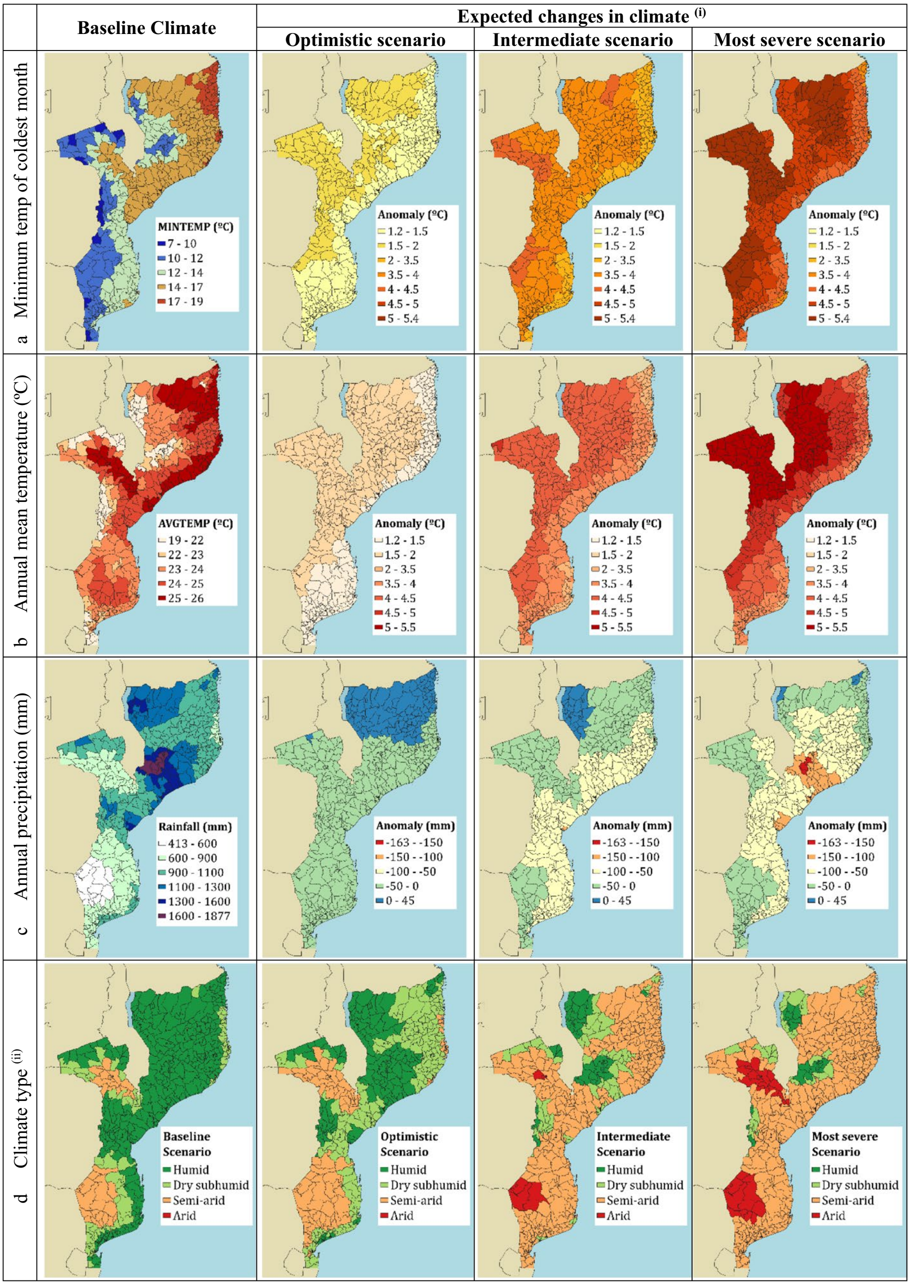

**Fig. 4** Observed (1970–2000) and expected changes (2081–2100) in climate for three climate scenarios: **a** minimum temperature of the coldest month (°C), **b** annual mean temperature (°C), **c** annual precipitation (mm), and **d** climate type—based on the median of 8 GCMs. (i)Future changes in temperature (**a** and **b**) and precipitation (**c**) are expressed as anomalies, representing the difference between future and the baseline climate. For example, a positive anomaly in temperature indicates that the expected temperature will be warmer than the baseline, while a negative anomaly indicates that the expected temperature will be cooler than the baseline. (ii)Climate types were classified based on the aridity index (Cherlet et al. 2018)

**Table 3** Farming system change under the three climate scenarios (2081–2100)(a)

| | Farming system (FS) | OPTIMISTIC SCENARIO | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | FS1 | FS2 | FS3 | FS4 | FS5 | FS6 | FS7 | FS8 | FS9 | FS10 | FS11 | FS12 | FS13 | FS14 | FS15 | FS16 |
| CURRENT SCENARIO | FS1 – Tobacco & Maize | 0.68 | | 0.04 | 0.00 | 0.18 | | 0.02 | | 0.00 | 0.00 | 0.06 | | | 0.02 | 0.00 | 0.00 |
| | FS2 – Cotton | 0.01 | 0.07 | 0.10 | 0.01 | 0.29 | | 0.30 | | 0.01 | 0.00 | 0.08 | 0.01 | | 0.12 | | |
| | FS3 – Sesame & Maize | 0.01 | | 0.36 | 0.01 | 0.27 | | 0.11 | | 0.00 | 0.00 | 0.12 | 0.00 | | 0.12 | | |
| | FS4 – Annual Food Crops – AnFC (Horticultural Crops, Maize & Sorghum+) | | | 0.01 | 0.49 | 0.29 | | 0.08 | | 0.00 | 0.00 | 0.05 | 0.00 | | 0.08 | | |
| | FS5 – Annual Basic Food Crops – AnBFC (Cassava, Maize & Beans) | 0.00 | | 0.01 | 0.01 | 0.85 | | 0.04 | | 0.00 | 0.00 | 0.04 | 0.00 | | 0.04 | | |
| | FS6 – Mixed Livestock & Maize | | | 0.03 | 0.01 | 0.13 | 0.17 | 0.48 | | | 0.00 | 0.04 | 0.02 | | 0.12 | 0.00 | |
| | FS7 – Bovine, Maize and Other AnFC | 0.00 | 0.00 | 0.02 | 0.01 | 0.08 | 0.00 | 0.79 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | | 0.07 | 0.00 | |
| | FS8 – Roots (Cassava & Sweet Potato) & Mixed Permanent Crops (PermC) | | | 0.03 | 0.00 | 0.51 | 0.00 | 0.04 | 0.09 | 0.00 | 0.03 | 0.20 | | | 0.09 | 0.00 | |
| | FS9 – Cashew & Mixed AnBFC | | | 0.02 | 0.03 | 0.40 | | 0.11 | | 0.26 | 0.01 | 0.09 | 0.00 | | 0.09 | | 0.00 |
| | FS10 – Rice Mixed (PermC and Livestock) | | | 0.01 | 0.00 | 0.34 | | 0.03 | | | 0.53 | 0.05 | | | 0.04 | | |
| | FS11 – Small Livestock & Mixed Crops | 0.00 | | 0.00 | 0.03 | 0.27 | 0.00 | 0.07 | | 0.01 | 0.00 | 0.53 | 0.00 | | 0.08 | 0.00 | 0.00 |
| | FS12 – Swine & Mixed Crops | 0.00 | | 0.02 | 0.01 | 0.41 | | 0.06 | | 0.00 | 0.00 | 0.19 | 0.15 | | 0.14 | 0.00 | 0.00 |
| | FS13 – Sheep & Mixed Crops | 0.01 | | 0.04 | 0.00 | 0.39 | | 0.18 | | 0.00 | 0.00 | 0.20 | | 0.07 | 0.11 | | 0.00 |
| | FS14 – Goats & Mixed Crops | 0.00 | | 0.01 | 0.03 | 0.23 | | 0.10 | | 0.00 | 0.00 | 0.10 | 0.00 | | 0.53 | | 0.00 |
| | FS15 – Mixed Livestock, Horticultural & Mixed PermC | 0.00 | | 0.02 | 0.00 | 0.19 | | 0.32 | | | 0.02 | 0.04 | 0.00 | | 0.14 | 0.26 | |
| | FS16 – Mixed Livestock, Coconut & Cassava | | | 0.04 | 0.01 | 0.49 | | 0.05 | | 0.01 | 0.00 | 0.24 | 0.01 | | 0.13 | | 0.02 |

| | Farming system | INTERMEDIATE SCENARIO | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | FS1 | FS2 | FS3 | FS4 | FS5 | FS6 | FS7 | FS8 | FS9 | FS10 | FS11 | FS12 | FS13 | FS14 | FS15 | FS16 |
| CURRENT SCENARIO | FS1 | 0.08 | | 0.11 | 0.01 | 0.43 | | 0.16 | | 0.01 | 0.00 | 0.06 | | | 0.14 | | |
| | FS2 | | 0.03 | 0.03 | 0.02 | 0.30 | | 0.46 | | | 0.01 | 0.06 | | | 0.09 | | |
| | FS3 | | | 0.16 | 0.02 | 0.34 | | 0.26 | | 0.00 | 0.00 | 0.07 | | | 0.15 | | 0.00 |
| | FS4 | | | 0.00 | 0.48 | 0.29 | | 0.12 | | 0.00 | 0.00 | 0.03 | 0.00 | | 0.07 | | |
| | FS5 | | | 0.00 | 0.04 | 0.73 | | 0.09 | 0.00 | 0.00 | 0.00 | 0.07 | 0.00 | | 0.06 | | |
| | FS6 | 0.00 | | 0.02 | 0.06 | 0.18 | 0.02 | 0.55 | | 0.00 | 0.00 | 0.05 | | | 0.11 | | |
| | FS7 | 0.01 | | 0.02 | 0.02 | 0.11 | | 0.68 | | 0.00 | | 0.06 | | | 0.10 | | |
| | FS8 | | | 0.00 | 0.03 | 0.57 | | 0.09 | 0.05 | 0.00 | 0.02 | 0.17 | | | 0.07 | 0.00 | |
| | FS9 | | | 0.00 | 0.08 | 0.43 | | 0.27 | | 0.06 | 0.00 | 0.06 | | | 0.09 | | |
| | FS10 | | | 0.01 | 0.01 | 0.47 | | 0.11 | | | 0.32 | 0.06 | | | 0.02 | | |
| | FS11 | | | 0.00 | 0.06 | 0.34 | | 0.11 | | 0.00 | 0.00 | 0.35 | 0.00 | | 0.13 | 0.00 | |
| | FS12 | | | 0.01 | 0.03 | 0.43 | | 0.16 | | 0.01 | 0.00 | 0.16 | 0.03 | | 0.16 | 0.00 | 0.00 |
| | FS13 | | | 0.03 | 0.01 | 0.33 | | 0.31 | | 0.01 | 0.00 | 0.19 | | 0.04 | 0.08 | | |
| | FS14 | | | 0.00 | 0.05 | 0.26 | | 0.22 | | 0.00 | 0.00 | 0.11 | 0.00 | | 0.34 | | |
| | FS15 | | | 0.08 | 0.02 | 0.25 | | 0.47 | | 0.01 | 0.02 | 0.08 | | | 0.05 | 0.02 | |
| | FS16 | | | 0.00 | 0.03 | 0.58 | | 0.11 | | | 0.00 | 0.12 | | | 0.16 | | 0.01 |

| | Farming system | SEVERE SCENARIO | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | FS1 | FS2 | FS3 | FS4 | FS5 | FS6 | FS7 | FS8 | FS9 | FS10 | FS11 | FS12 | FS13 | FS14 | FS15 | FS16 |
| CURRENT SCENARIO | FS1 | 0.00 | | 0.01 | 0.02 | 0.21 | | 0.66 | | 0.00 | 0.00 | 0.02 | | | 0.07 | | |
| | FS2 | | 0.00 | 0.03 | 0.01 | 0.25 | | 0.55 | | | 0.01 | 0.05 | | | 0.10 | | |
| | FS3 | | | 0.15 | 0.02 | 0.29 | | 0.33 | | | 0.00 | 0.07 | | | 0.14 | | |
| | FS4 | | | 0.02 | 0.45 | 0.27 | | 0.16 | | 0.00 | 0.00 | 0.02 | 0.00 | | 0.07 | | |
| | FS5 | | | 0.00 | 0.04 | 0.72 | | 0.11 | 0.00 | 0.01 | 0.00 | 0.06 | 0.00 | | 0.06 | | |
| | FS6 | | | 0.02 | 0.06 | 0.20 | 0.02 | 0.57 | | 0.01 | 0.00 | 0.03 | | | 0.09 | | |
| | FS7 | | | 0.00 | 0.02 | 0.09 | | 0.75 | | | | 0.05 | | | 0.09 | | |
| | FS8 | | | 0.00 | 0.04 | 0.53 | | 0.14 | 0.04 | | 0.02 | 0.13 | | | 0.10 | | |
| | FS9 | | | 0.00 | 0.07 | 0.41 | | 0.33 | | 0.04 | 0.00 | 0.04 | | | 0.11 | | |
| | FS10 | | | 0.01 | 0.01 | 0.47 | | 0.11 | | | 0.32 | 0.05 | | | 0.03 | | |
| | FS11 | | | 0.00 | 0.06 | 0.35 | | 0.13 | | 0.00 | 0.00 | 0.32 | 0.00 | | 0.14 | 0.00 | |
| | FS12 | | | 0.01 | 0.03 | 0.42 | | 0.19 | | 0.00 | 0.00 | 0.14 | 0.03 | | 0.17 | 0.00 | |
| | FS13 | | | 0.03 | 0.00 | 0.32 | | 0.38 | | 0.01 | 0.00 | 0.14 | | 0.04 | 0.07 | | |
| | FS14 | | | 0.01 | 0.06 | 0.27 | | 0.26 | | | 0.00 | 0.09 | 0.00 | | 0.32 | | |
| | FS15 | | | 0.07 | 0.02 | 0.24 | | 0.49 | | 0.00 | 0.02 | 0.07 | | | 0.06 | 0.02 | |
| | FS16 | | | 0.00 | 0.02 | 0.59 | | 0.13 | | | 0.00 | 0.11 | | | 0.13 | | 0.01 |

(a)Values refer to the percentage of the area currently under a particular FS that transitioned to other FS as well as the percentage that persisted in the same system (persistence expressed in the matrix diagonal). It was applied a green-white colour gradient to identify the main transitions/persistence occurring for each FS. The darker the green colour, the higher the percentage of the area of a particular FS that falls into another FS (or that persisted in the same FS—diagonal). Blank spaces mean that there was no transition from the particular FS to another, i.e. the percentage of the area of a FS transitioning to another FS is zero

crops), respectively, is expected to transition to other FS, i.e. FS5, FS14, FS11, and FS7, it is expected that farmers from other systems also transition to these systems. Therefore, the areas under FS5, FS7, FS11, and FS14 are expected to see an expansion as climate changes.

Under the intermediate and severe scenarios, many FS are expected to be replaced, with the staple food crops (FS5) and bovine (FS7) systems replacing most of the other FS. Under the severe scenario, FS3 (sesame) is the only cash crop system expected to retain some farm area. FS4 (food crops) loses a significant proportion of its area to FS5 and FS7; however, it is expected to continue to be adopted by some farmers. FS11 (small livestock) and FS14 (goats) also retain a significant proportion of their area and tend to expand by integrating some farmers from other systems (such as FS3, FS8, FS12, FS16).

Considering that each FS is usually linked to a knowledge system, which may be related to local knowledge developed by farmers practicing this system under historical circumstances (past climate conditions) and/or science-based knowledge (Kloppenburg

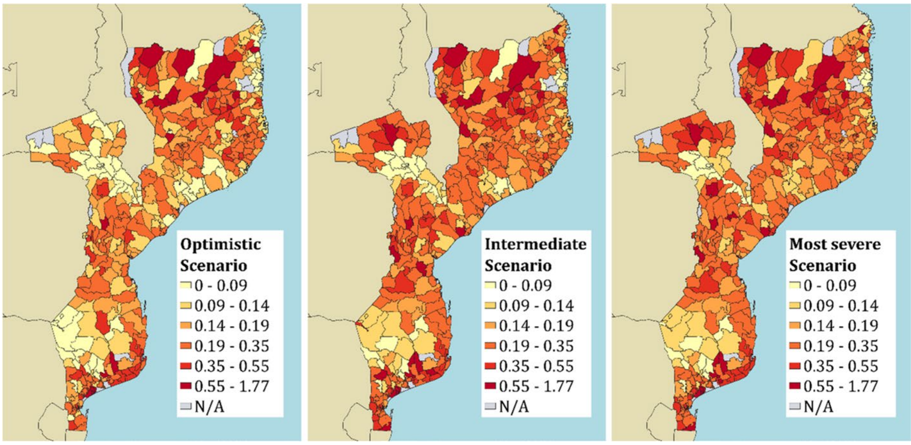

**Fig. 5** Stress for FS change. The stress indicator was computed based on the Euclidean distance between FS cluster centroids

1991), climate change-related FS transitions, which can move the farmer to particularly different FS, may thus require large changes in existing knowledge system and significant investments, putting the farmer under stress, due to the magnitude of the effort required when moving from one FS to another. The greater the difference, measured as the Euclidean distance (see results of this matrix in Table 5), between the current and projected FS, the greater the stress for change (Fig. 5), due to the need for very different knowledge system and capital to invest.

The results show that in all scenarios, the coastal areas—with emphasis to the south—and the inland northern region will suffer the highest stress for change, i.e. farmers in these areas are likely to face greater challenge for FS change, considering that the projected future FS is very different from the current FS. Moreover, as the climate conditions become severe, the stress for changing from one FS to another increases, covering larger areas of the country. The inland southern region and the upper Zambezi Valley showed the lowest stress for change, meaning that farmers in these areas are likely to adapt to climate change more easily, even in the severe scenario.

The expected changes in FS choice caused by changes in climate will impact food security in the country. The food security variation indicator (Fig. 6) shows the variation in the probability of a farmer becoming food insecure (i.e. experience food shortages) due to FS change.

The results indicate that coastal areas are more likely to benefit, in terms of food security, in a context of climate change, as the probability of farmers suffering food shortages decreases by 1 to 5%. Nevertheless, most areas of the country are expected to become more food insecure, as the probability of having food shortages increases up to 10% in the optimistic scenario, reaching 24% in the intermediate and severe scenarios. The inland regions are expected to record higher food insecurity levels, as most farmers in these regions become more likely to suffer from increased food shortages, due to climate-induced FS change.

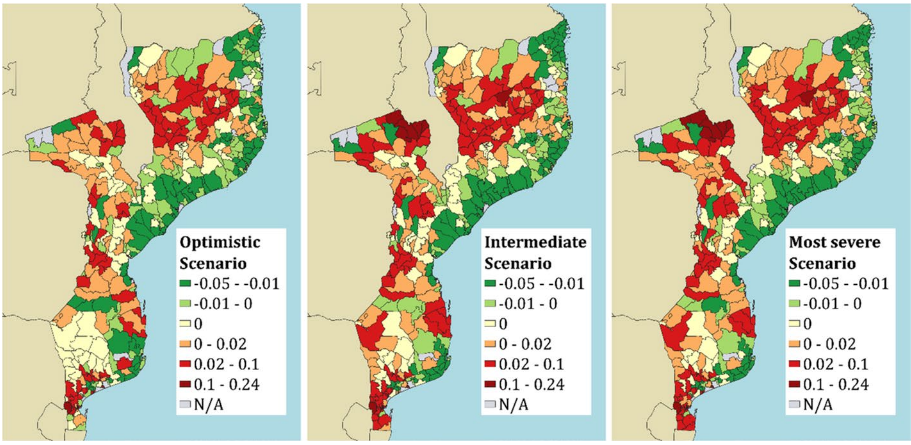

**Fig. 6** Food security variation (in percentage). Negative values (green areas) mean that the probability of farmers becoming more food insecure decreases (in percentage) as a result of FS change derived from a changing climate and positive values (orange and red areas) mean that the probability of farmers becoming more food insecure increases

## 4 Discussion

### 4.1 Exploring farming system change under climate scenarios using a space for time modelling strategy

The FSA made it possible to understand the dynamics of many different FS competing for land, at the farm level, in an adaptive response to climate change. The space for time modelling strategy enabled to explore FS transitions under different climate scenarios. Previous approaches have focused on changes in crop physiology, yields and productivity as a result of climate change (Marques et al. 2009; Brito and Holman 2012; Knox et al. 2012). These approaches enable the analyst to project yield changes for each crop, for instance, but not changes in areas of each crop, therefore do not allow to project whether a crop might be replaced by others. To project crop area changes, it is important to model the effects of climate change on farmers' decisions about FS and not only on crop growth and yields. This is exactly the point where the proposed approach innovates, providing results regarding changes in FS choice and its spatial distribution, that complement those of previous approaches. Additionally, such a FSA summarily expresses a broad set of production decisions made by farmers, rather than focusing on a single or a few such decisions, which is considered more appropriate to support policy making (Simmonds 1985; Woodward et al. 2008). Based on the proposed approach, it is also possible to indirectly gauge the effects of climate change on a specific crop by assessing the change in cropping pattern implied by each FS transition.

The application of the framework presented in this paper has some limitations, which are not necessarily limitations of the approach itself. One of these is assuming that socioeconomic (such as demographics, urbanisation, markets) and other biophysical drivers (except climate) will remain constant overtime, even though there will be significant changes in these factors in the long run. However, such a simplification was necessary to make it possible to isolate the direct, marginal effect of climate on FS choice, while keeping all other drivers constant, in a ‘controlled experiment’ approach, which allowed to understand the role of climate change alone in driving FS change. A full assessment of the effects of climate change on food security would also require considering the effects of climate change on other drivers of food security, such as demography, health, or economic diversification, as well as the effect of climate change on other choices. Provided that reasonable scenarios/narratives can be built for all these drivers, at the administrative post level, the estimated FS choice model can then be used to project the effects on food security of these multivariate scenarios. By addressing the marginal effect of climate change alone on FS choice and its consequences on food security, this paper paved the ground for this more integrated assessment.

A limitation of the approach is that it does not allow other crops/livestock activities and/or new FS (new combinations of activities and technologies) to appear as solutions or in response to climate change. Instead, the approach is based on existing activities—crops/livestock, and existing combinations among them (FS) as the building blocks of the approach. A limitation of the approach is, thus, that farmers are ‘allowed’ to choose a different FS in the future as an adaptation to climate change, but this choice needs to be done within the set of the currently existing FS. This assumption is robust because what currently exists under certain circumstances will be possible if the same circumstances are repeated somewhere in the future. It is, nevertheless, too conservative, as many new FS will certainly appear in the future because of new knowledge and innovation driven by climate change itself. To overcome this limitation, the approach needs to be expanded in future research by including in the farmer’s choice set, in future periods, new (currently inexistent) FS designed to improve the adaptation to climate change through short cycle cultivars, improved livestock breeds, or irrigation techniques, for example. The design of this new FS could rely on studies following other approaches based on the physiological reactions of a crop to different climate, implying for instance, shorter growing seasons (Cui and Xie 2022).

Moreover, considering that this model was based in a dataset of small and medium farmers, this analysis cannot be used to project changes of FS for large-scale famers. Changes in farm size structure are also beyond the scope of this study.

## 4.2 Climate change and its impacts on farming system choice

Based on our results, the study area is expected to become warmer and drier by the end of the century—which is consistent with other studies in Africa (Lötter 2017; Lewis et al. 2018). These changes in climate will significantly impact FS choice in Mozambique—consistent with other studies, which found that climate, especially rainfall and temperature are important drivers affecting FS choice (Greig 2009; Etwire 2020; Ribeiro et al. 2021). Even in an optimistic scenario (with increases in temperature limited at 2 °C and no substantial changes in rainfall), most FS will tend to be replaced by others. Smallholder FS across Sub-Saharan Africa have been recognised as highly vulnerable to climate change, shifting land use patterns, and crop choices (Mbow et al. 2019). Rainfed FS and where crops are grown near to their maximum temperature tolerance are particularly exposed to climate change impacting farmers’ livelihoods (Marques et al. 2009; Lewis et al. 2018; Mbow et al. 2019).

Cash crop systems were found to be highly impacted by climate change, with emphasis to cotton and tobacco, which are expected to be completely replaced under the severe climate scenario. These systems are currently located in areas that are expected to experience high levels of stress for change due to climate change. Although climate influences the choice of these FS, market integration is also an important driver to consider. Farmers in these systems are currently integrated in a value chain that facilitates their integration in the market—through the provision of inputs and access to output markets (Lukanu et al. 2004; Maggio and Sitko 2018). However, in face of climate change, farmers in these systems are expected to intensify the existing maize production and diversify into other food crops (e.g. FS5) and livestock (e.g. bovine—FS7), moving away from cash crops. This will imply a shift in the knowledge and resources required, as these farmers will move to more labour-intensive systems, with low use of yield-raising inputs. Moreover, acquisition of bovine may imply a whole new knowledge and investment dynamic to farmers. On the other hand, sesame is more tolerant to water stress, diseases, and pests, so it is likely that farmers may continue growing it, and the development of an integrated and inclusive value chain may contribute to increase the adoption of this FS.

In inland southern and upper Zambezi valley regions, the existing aridity is expected to intensify by 2100. These areas show the lowest stress for change, suggesting that there are fewer options for transitions to other FS or that the transitions will occur to particularly similar FS. The results confirm that the predominant FS in these regions (i.e. FS7) will persist and expand to the central and northern regions, integrating farmers from other systems as the country becomes arid. The concentration of bovine has always been higher in the south of the country, in part due to the prevalence of the tsetse fly, which is predominant in humid areas in the central and northern regions (Duarte 1993); however, the expected increase in aridity may allow this system to expand. Our study may not have succeeded in simulating the replacement of FS7 by other FS currently existing in more arid areas, west of Mozambique, simply because these areas were not included in our data. Two results are possible if including these areas: (1) a different FS (possibly more pastoral and less agro-pastoral in nature) is identified, which would replace FS7 in the areas that become arid in the severe scenario; (2) the same FS7 (or a subsystem of it) remains, but possibly with lower productivity and stoking rates.

The horticultural system (FS15), which is usually sensitive to high temperatures and aridity (Pandey et al. 2018), will be negatively affected, as temperatures are expected to increase, being replaced by other FS (such as FS14—goats, FS5—staple food crops and FS7—bovines, all including food crops mostly for family consumption, as cassava, maize, sorghum, rather than horticultural crops for the market). FS integrating heat and drought tolerant crops (such as sorghum) are expected to persist and expand as the country becomes drier. Our results indicate that mixed crop-livestock systems are expected to tolerate the changing climate.

Coastal areas are expected to become drier (lower rainfall), although these may experience the lowest increase in temperature compared with inland areas, negatively affecting the coconut mixed system (FS16). Climate change is expected to negatively impact tree crops such as coconut and cashew, which are usually produced in areas with higher rainfall and humidity (such as coastal areas) (Etwire 2020). These areas are expected to suffer higher stress for FS-change, which might be due to the fact that farmers in these areas may adopt significantly different FS, shifting from tree crops to more food crop and/or livestock-oriented systems (e.g. FS5, FS7, FS11) which may require additional resources (labour, capital, etc.) and knowledge.

Specialized livestock FS (e.g. FS7—bovine, FS11—small livestock and FS14—goats) are expected to be less affected by climate change and will expand. In many of the semiarid systems in sub-Saharan Africa, livestock production enables farmers to diversify incomes, helping to reduce income variability, and providing an alternative for cropping where crop production becomes marginal (Jones and Thornton 2009; Mbow et al. 2019). These systems (FS7, FS11 and FS14), although deriving most of their product from livestock, also grow food crops (such as maize, cassava, sorghum and millet, and legumes). We found that FS5, which is mostly specialized in food crops, will also persist and expand under climate change (unlike some studies, such as Etwire 2020). Overall, these systems are considered resilient to climate change as these already grow some drought-tolerant crops (as sorghum) and also include small livestock which have been considered to be less exposed to climate change compared to other animals, and can be sold in times of food shortages (Lewis et al. 2018). The resilience of FS mostly depends on the combination of activities that initially exist on the farm, offering more or less adaptation possibilities (Souissi et al. 2018). Moreover, Marques et al. (2009) found that land suitability in Mozambique for cassava, maize, sorghum, and groundnuts is likely to remain unchanged, by mid-century.

In general, the higher stress for change will occur in the Northern and Central regions and along the coast in the Southern region. In the North the emphasis lays on FS transitioning mostly from FS11 and FS14 to FS5, meaning that these systems that derive most of their product from livestock production, i.e. small livestock and goats, respectively, will dedicate more to food production (for example, maize and cassava), implying a reorganization in terms of livelihoods. This may suggest a potential problem related to farmers' incomes and food security, as livestock, in particular small livestock, is considered an important source for income generation, especially when coping with external shocks.

In the central region, the stress for change will also intensify as climate changes, with particularly visible impacts on FS14 that will transition to other different systems (e.g. FS7), therefore will continue to obtain most of their product from livestock, however bovine rather than goats—this implies a huge investment both in terms of capital and knowledge. In the southern region, the focus should be on FS16 which will transition from a diversified livestock (i.e. bovine, goats, swine, and small livestock) and coconut production to either bovine or staple food and small livestock production, i.e. FS7 and FS5, respectively.

The stress for FS change is expected to be higher in areas that are currently humid, and that will be considerably affected by climate change, as these become arid. On the other hand, the current semi-arid areas do not show high levels of stress from changing from one system to another. This is also true, because the bovine system (FS7) already predominates in these (arid) areas, which under the forecasted climate will not disappear but rather expand—meaning that farmers in these systems may continue to choose the system not forcing significant changes at the farm level (but consider the methodological caveat made above).

### 4.3 Implications of climate-induced farming system change on food security

The implications of climate change for food security are substantial, as the most food secure systems, FS1—tobacco, FS15—irrigated horticultural crops, FS2—cotton, and FS6—mixed crop-livestock, are expected to be replaced by others. These systems are considerably diverse, including food and cash crops and/or some livestock diversity; these are also the most market oriented, with the highest use of yield-raising inputs and ensure farm-based income diversification, factors contributing to food security. Under climate change, farmers in these systems are likely to become prone to food insecurity, as they are projected to move to more labour-intensive systems, with low use of yield-raising inputs and more focused on self-consumption, meaning reduction of market integration and thus lower incomes and lower food security.

On the other hand, an expansion of systems dedicated to crop-livestock production is expected, some being more crop oriented (FS5) than others (i.e. FS7, FS11, and FS14). Mixed crop-livestock systems are considered to provide resilience as incomes are diversified and also because livestock can be sold as assets to buffer episodes of low crop harvests (Lewis et al. 2018; Souissi et al. 2018; Tui et al. 2021). These FS grow food crops, largely for their own consumption since they are mostly not integrated in the market. Although these systems may be considered diverse, due to some crop diversity (maize, cassava, sorghum, legumes, and horticultural crops in lower proportions) and the existence of livestock (mostly poultry), households running these systems are considered relatively poor, being dependent on agricultural output, with low use of yield-raising and labour-saving inputs. Nevertheless, the existence of bovine (FS7) and goats (FS14) can contribute positively for the adoption of yield-raising and labour-saving inputs, such as animal traction and organic fertilizers, which may contribute to increase crop yields and labour productivity. Moreover, sorghum and cassava are generally considered drought-resistant crops, which makes them fit for food security in a changing climate, given their role as subsistence crops for already poor small-scale farmers (Lewis et al. 2018).

In coastal areas, the climate is likely to become drier, affecting the permanence of current FS, i.e., tree-based systems (coconut and cashew). Although these crops have some cultural and economic value in Mozambique, most of the trees managed by the smallholders are old with low productivity, with an extremely volatile market, (Abbas 2014) therefore, may not contribute much to improve food security among smallholders; for example, FS9 (cashew) is the most food insecure FS (Fig. 2). This means that by substituting these permanent crops for food crops that can be consumed and to some extent sold by the household (such as FS5) or that have better integration in the market (such as FS7, FS11) would likely benefit the farmers.

On the other hand, the inland regions from south to north are expected to experience an increase in food insecurity among farmers. This is motivated by the fact that farmers are transitioning from FS that are currently food secure (FS1, FS15, and FS6) to (mildly) food insecure systems (FS7, FS5, FS11, FS14, and FS4), i.e. with higher frequency of food shortages among farmers. Market integration and the use of yield-raising and labour-saving inputs may play an important role in improving food security in these areas (Dixon et al. 2001; Massawe 2017).

### 4.4 A framework to inform adaptation policy options for food security

Smallholder farmers in developing countries are already facing several challenges related to the sustainability of their livelihoods which, depending on the location and other factors, may be significantly amplified by climate change. Climate change will act as a risk-multiplier to already poor and food insecure farmers (Lewis et al. 2018). Therefore, there is a significant role for public policies in reducing the negative impacts of climate change on small farmers' livelihoods and improving their food security levels (Deressa et al. 2009). Small and medium farmers are the centrepiece of farming systems and food production in developing countries; therefore, action must focus on supporting them by creating the necessary mechanisms to make them more resilient to climate change and ensure that their food security needs are met (Lewis et al. 2018). The framework developed and proposed in this article is suggested as a useful tool to ensure better policy formulation and resource allocation to deliver these goals more effectively.

By assessing the expected changes in FS choice under different climate scenarios, our framework may help identifying priority areas for government intervention that will provide better results in dealing with the effects of climate change, while contributing to improve food security. With this knowledge, policymakers will be able to determine where their actions will be better suited and more needed, and, to help reinforcing the capacities of small-scale farmers to raise their productivity and food security levels under a changing climate.

Given that resources—either financial, human, or physical—are scarce, governments, especially in developing countries, need to identify priority areas for action. For the case of Mozambique, which is representative of many other developing countries, our results identified areas where the stress to deal with FS change will be higher, for example, the currently humid areas in central and northern regions (Fig. 5). In these areas, due to a drier climate, a FS currently non-existent in the area (i.e., FS7) will appear and expand (see maps of FS dynamics under climate change in Fig. 7 in Appendix). This means that, for many farmers, there will be an advantage of introducing cattle in FS currently specialized in crops, which requires new knowledge on how to rear livestock and investments (for example, buying livestock). So, our results not only identify priority areas for intervention but also suggest concrete policies for those areas. Critical areas where food insecurity will increase (i.e. increased probability of food shortages) as a result of prevailing FS transitions are also identified. For example, FS strongly associated with rural poverty, occurring in small farms with extremely low use of yield-raising and labour-saving inputs, and low market integration, will expand in inland areas in north and central Mozambique. In these areas, the promotion of yield-raising and labour-saving inputs and the expansion of market integration will thus be the key to prevent food insecurity as an adaptation strategy. This shows how our results can inform better policy formulation and better resource allocation, by targeting critical areas and key issues in these areas, which would result in better outcomes for small-scale farmers in developing countries.

## 5 Conclusion

Climate change, through increases in temperature, decreases in rainfall, and resulting increases in aridity levels, will have a significant effect on the agricultural sector, through changes in farming practices among farmers. Our results indicate major changes in FS choice and its spatial distribution in the context of climate change, which will impact considerably on the livelihood and food security status of small-scale farmers. While some regions may see some gains in terms of food security, others will experience the opposite trend. Moreover, the stress for changing from one FS to another, to deal with the impacts of climate change, will be significant in most parts of the country, especially in the current humid areas that are expected to become drier by 2100. The increased stress for change can be manifested, for instance, in two ways—through knowledge and investment gaps—as changes in farming practices may require different knowledge on farming management and increasing investment.

Overall, the framework presented, based on a farming system approach, allows to explore how farmers would respond in the context of different climate scenarios, as well as to understand the rationality behind these responses, which both provide the basis for understanding how government policies can help reducing the negative effects of climate change on smallholder farmers. The output of this analysis, i.e. the framework developed and suggested for future studies is relevant in supporting policy design for food security as it enabled the identification of priority territorial areas (and precise farming systems) that will most likely need government support, so that poor food insecure farmers in developing countries can guarantee their livelihoods and meet their food security goals. Given the lack of resources in poor developing countries, efficient allocation of resources in priority areas that will translate into positive outcomes for rural small-scale vulnerable farmers is of utmost importance. Nevertheless, government policy actions in the present should not ignore the challenges faced by FS today; therefore, these must address the challenges of today's FS while setting the fundamentals for the adequacy of the future adequate FS in each region.

The estimated FS choice model also showed that socioeconomic variables (that can be shaped by policy decisions) are important drivers of FS choice and therefore have a significant role in reducing the stress for FS change. Considering that the estimated FS choice model can be used to build multivariate scenarios where all drivers change in the long run, socioeconomic drivers will be explored in future research.

## Appendix

**Table 4** Climate data for the three climate scenarios for 2081–2100—median of 8 GCMs

| Variable | Climate scenario | | |
|---|---|---|---|
| | Optimistic | Intermediate | Severe |
| | Mean (min–max) s.d. | | |
| MINTEMP | 15.3 (8.9–20.4) 2.3 | 17.5 (11.3–22.2) 2.2 | 18.6 (12.4–23.1) 2.2 |
| AVGTEMP | 25.4 (20.2–28.3) 1.4 | 27.8 (22.8–30.8) 1.3 | 28.4 (23.5–31.8) 1.4 |
| RAINFALL | 977 (399–1865) 231 | 937 (379–1778) 223 | 928 (388–1714) 209 |
| ARIDITYINDEX | 0.6 (0.2–1.3) 0.2 | 0.4 (0.1–1.0) 0.1 | 0.4 (0.1–0.8)0.1 |

**Table 5** Euclidean distance matrix

| Farming Systems | FS1 | FS2 | FS3 | FS4 | FS5 | FS6 | FS7 | FS8 | FS9 | FS10 | FS11 | FS12 | FS13 | FS14 | FS15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FS1 \| Tobacco and maize | | | | | | | | | | | | | | | |
| FS2 \| Cotton | 5.9 | | | | | | | | | | | | | | |
| FS3 \| Sesame and maize | 9.1 | 6.7 | | | | | | | | | | | | | |
| FS4 \| Annual food crops (AnFC) | 4.4 | 7.2 | 10.0 | | | | | | | | | | | | |
| FS5 \| Annual basic food crops (AnBFC) | 3.4 | 4.1 | 7.7 | 4.8 | | | | | | | | | | | |
| FS6 \| Mixed livestock and maize | 4.5 | 3.5 | 7.5 | 5.8 | 2.9 | | | | | | | | | | |
| FS7 \| Bovine, maize and other food crops | 7.9 | 3.9 | 7.0 | 9.1 | 5.9 | 5.0 | | | | | | | | | |
| FS8 \| Roots and mixed permanent crops | 5.9 | 9.3 | 11.7 | 5.4 | 6.8 | 7.7 | 11.3 | | | | | | | | |
| FS9 \| Cashew and mixed AnBFC | 4.4 | 5.6 | 8.7 | 5.0 | 3.8 | 4.7 | 7.3 | 6.4 | | | | | | | |
| FS10 \| Rice and mixed crops | 8.0 | 7.0 | 9.7 | 9.7 | 7.3 | 6.5 | 7.9 | 9.8 | 7.6 | | | | | | |
| FS11 \| Small livestock and mixed crops | 9.7 | 13.8 | 15.6 | 9.7 | 11.2 | 11.9 | 15.7 | 8.4 | 10.6 | 14.8 | | | | | |
| FS12 \| Swine and mixed crops | 7.4 | 11.7 | 14.0 | 7.1 | 8.8 | 9.9 | 13.7 | 6.5 | 8.6 | 12.3 | 6.8 | | | | |
| FS13 \| Sheep and mixed crops | 6.2 | 10.6 | 12.9 | 6.0 | 7.6 | 8.7 | 12.7 | 5.8 | 7.5 | 11.5 | 7.5 | 4.4 | | | |
| FS14 \| Goats and mixed crops | 4.8 | 9.3 | 11.9 | 4.7 | 6.3 | 7.4 | 11.4 | 4.5 | 6.1 | 10.6 | 7.3 | 4.2 | 3.0 | | |
| FS15 \| Mixed livestock, hort. and mixed perm. crops | 10.1 | 14.3 | 16.1 | 9.5 | 11.5 | 12.5 | 16.2 | 8.8 | 11.2 | 14.7 | 8.5 | 6.6 | 6.8 | 7.0 | |
| FS16 \| Mixed livestock, coconut, and cassava | 4.3 | 7.8 | 10.5 | 4.8 | 5.2 | 6.2 | 9.7 | 4.9 | 5.4 | 9.3 | 8.5 | 6.0 | 4.7 | 3.7 | 8.6 |

The Euclidean distance (adimensional) was calculated based on the scores of the 16 PCs, used in the cluster analysis

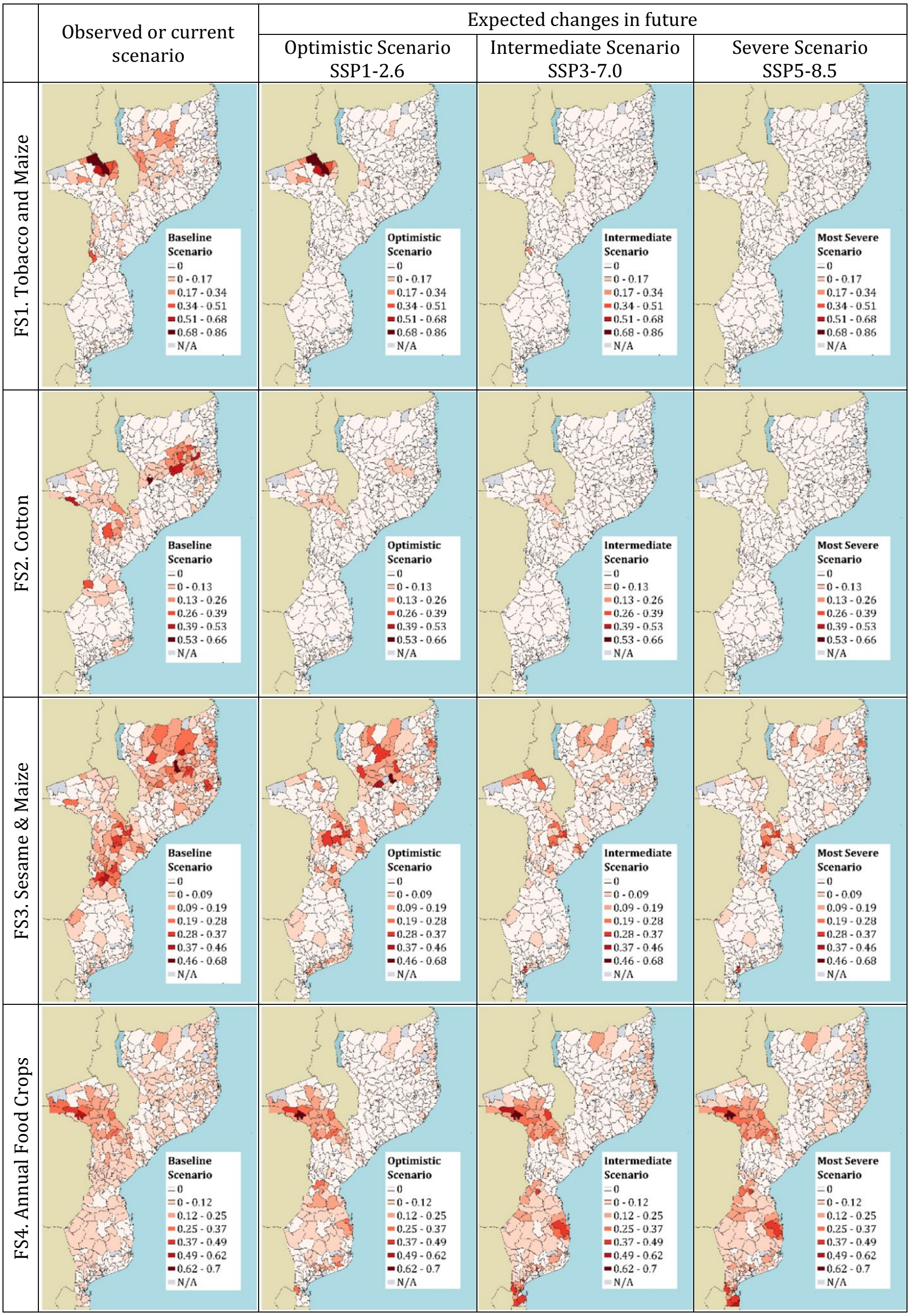

**Fig. 7** Current and expected spatial distribution of farming systems under climate change (% of total agricultural area of each FS in each administrative post)

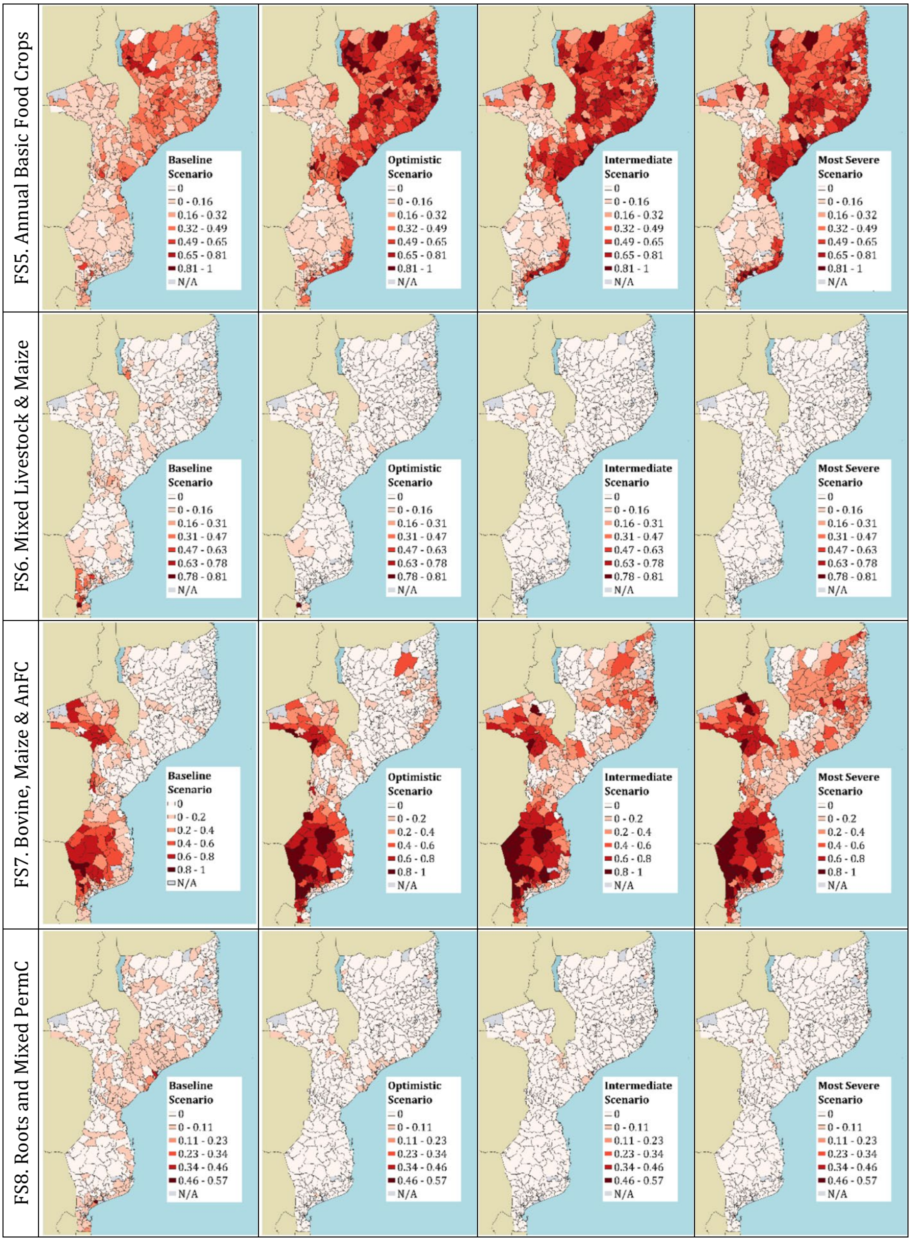

**Fig. 7** (continued)

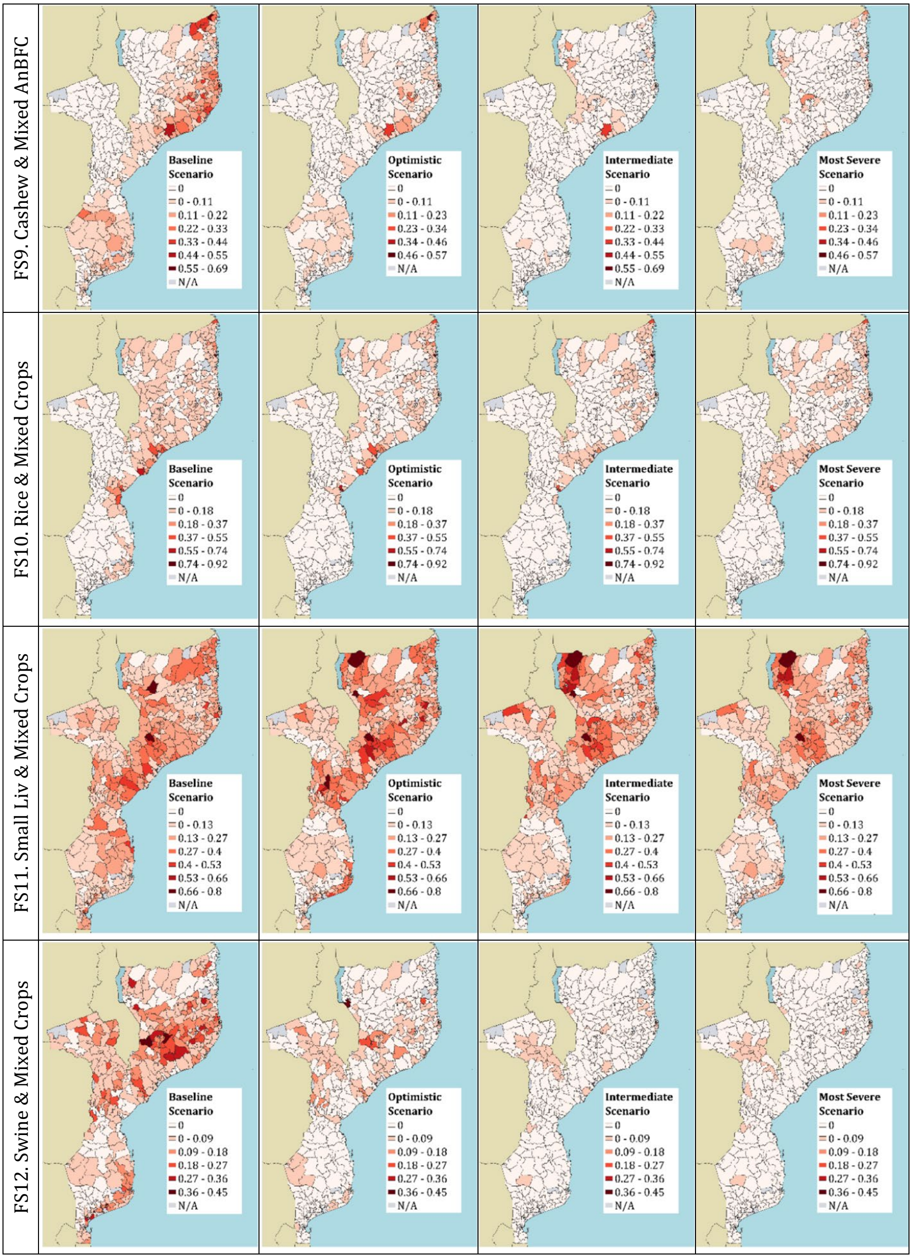

**Fig. 7** (continued)

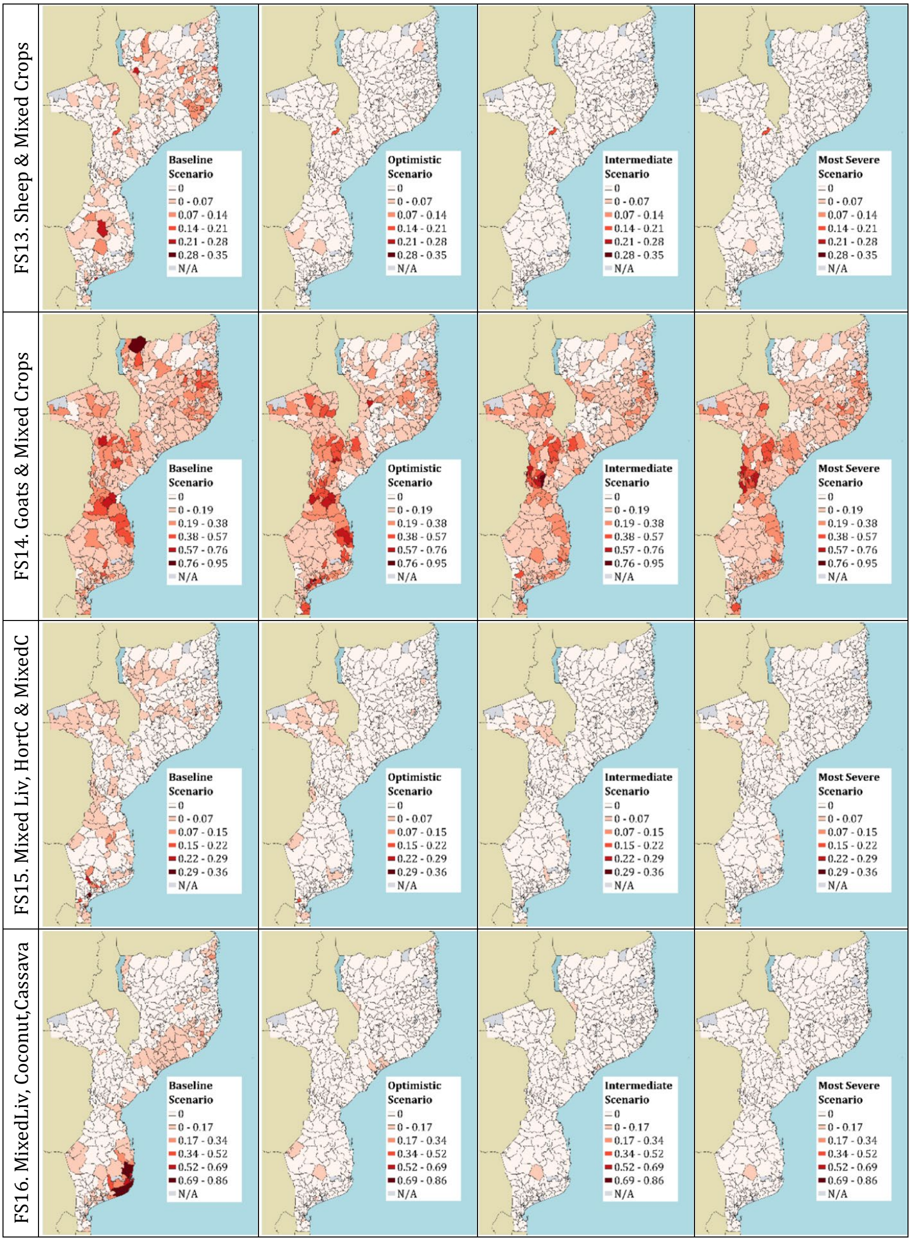

**Fig. 7** (continued)

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**Author contribution** All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Máriam Abbas, Paulo Flores Ribeiro, and José Lima Santos. The first draft of the manuscript was written by Máriam Abbas, and all authors commented and contributed on all versions of the manuscript. All authors read and approved the final manuscript.

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**Data availability** The climate data analysed during the current study are available in the WorldClim repository, https://www.worldclim.org/data/cmip6/cmip6climate.html. Agricultural data is available in the *Instituto Nacional de Estatística de Moçambique* repositor, upon request.

## Declarations

**Competing interests** The authors declare no competing interests.

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