

<https://doi.org/10.1038/s43247-024-01242-9>

Risk-adjusted decision making can help protect food supply and farmer livelihoods in West Africa

Check for updates

Debbora Leip ^{1,2}, Elena Rovenskaya^{1,3} & Matthias Wildemeersch ^{1,4}

Weather extremes are challenging the achievement of Sustainable Development Goal (SDG 2) – Zero Hunger globally and, most notably, in West Africa where it is further aggravated by rapid population growth. Here we present a stylized stochastic food production model to show how optimal crop allocations change depending on food security risk targets. To guarantee stable livelihoods for farmers, we examine the viability of a contingency fund that supports farmers in the event of low crop yields. Applied to the West African context, accounting for weather variability can substantially improve the reliability of the food supply and boost the fiscal sustainability of a contingency fund. Yet, setting reliability targets for food security is costly and leaves high residual risk in certain regions. Spatial risk-sharing through regional cooperation at the West African scale can eliminate the risk of insufficient food supply and further enhance the fund solvency.

Recent assessments show that Africa is not on track to meet SDG 2 Zero Hunger¹. The lack of progress in meeting this goal is specifically evident in West Africa, where a rapidly growing population, increasing rural-to-urban migration, violent conflict, and weather extremes compound the problem^{2,3}. A stable and reliable food supply is a prerequisite for food security^{4,5}. In Africa, however, the food production is seriously threatened by the variability of crop yields across years due to extreme weather events whose frequency and intensity are exacerbated by climate change⁶. Indeed, crop production in low-latitude countries is projected to be consistently and negatively affected by climate change⁷, and current data show that the risk of food production losses in Africa has already increased from undetectable risk to moderate risk between 2010 and 2020⁸. Sub-Saharan Africa is expected to be among the most affected regions, with 51 million people in the Sahel and West Africa currently at risk to fall into a food and nutrition crisis^{2,9–11}.

Apart from the direct impact on food security, the fluctuation of agricultural productivity due to weather variability has also important repercussions on revenues in farmer communities¹². Extreme weather events such as droughts can push households to adopt negative coping strategies, for instance through the choice of low-risk, low-return livelihood strategies, with adverse implications for their long-term welfare and potential feedback effects on the food supply^{1,13,14}. The absence of savings combined with the absence of appropriate food storage in rural farming communities further aggravates the fragility of the African food system¹⁵.

Another common risk-mitigation strategy in farming communities in Africa is informal risk-sharing. However, in the face of covariate risks such as droughts that affect an entire community, informal risk management tools are largely insufficient to cover households that are affected simultaneously^{16,17}.

The growing frequency of drought events¹⁸ in conjunction with rapid population growth demands for an agricultural transformation, climate adaptation, and a package of measures to improve the reliability of the food supply and to protect agricultural livelihoods under weather extremes^{19,20}. In this respect, governments play a crucial role to create financially sustainable mechanisms for supporting their citizens and to prevent farmers from reverting to negative coping strategies²¹. Several social protection systems already exist in Africa and other world regions to support vulnerable households under climate shocks, such as Niger's cash transfer mechanism²², Kenya's Hunger Safety Net Programme, or the Mahatma Gandhi National Rural Employment Guarantee Scheme²³.

To address the vulnerabilities of the food system and improve its resilience, the setup of contingency funds has been highly recommended^{24–26}. Contingency funds provide immediate liquidity in the aftermath of a catastrophic event, and offer local governments a suitable mechanism to increase their financial response capacity. Contingency funds are recommended to be included as part of a risk-layering approach, whereby such funds can be applied to finance frequent risks with moderate severity, while contingent credit and reinsurance is advisable to provide the

¹International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. ²Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany.

³Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, Moscow, Russia. ⁴Environmental Change Institute, University of Oxford, Oxford, UK. e-mail: matthias.wildemeersch@eci.ox.ac.uk

financial capacity for rare events with higher severity^{27–30}. A crucial question surrounding contingency funds is their fiscal sustainability. In this context, major international institutions such as the FAO, OECD, and the World Bank recommend the use of risk pooling for disaster risk financing³¹. The Caribbean Catastrophe Risk Insurance Facility was the first multi-country risk pool dealing with natural disasters such as earthquakes and hurricanes, and is successfully capitalized by the participating countries, the international donor community, and the World Bank²⁵. In Africa, the African Risk Capacity (ARC) pool was established in 2012 by the African Union, and focuses on disaster risk management, including drought risk. The ARC provides index insurance to countries in order to ensure food security and protect the income of vulnerable populations³⁶. Cross-regional risk pooling has also been proposed at the global scale to take advantage of the independence of production losses across global breadbaskets³².

In order to design a food production system that guarantees a reliable food supply and stable farmer incomes under severe drought events, we need to account for uncertain future trends and develop agricultural strategies able to perform well under variable conditions. In the existing literature, the effects of crop yield uncertainty on food security have mainly been studied by means of scenario analyses and sensitivity analyses, including the study of shock disturbances³³. Scenario analysis is based on an incomplete set of hypothetical constructs, and a course of action that is optimal under a given scenario can produce suboptimal outcomes under a different future. In essence, scenario and sensitivity analyses deliver what-if assessments and fall short to produce food production solutions that are robust across a wide range of uncertain parameters. However, in a rapidly changing world with high levels of uncertainty, policy robustness is increasingly important for policy-makers³⁴. Policy robustness can be achieved using robust decision making, but this approach does not guarantee optimality³⁵. Robust optimization is an alternative method that ensures optimality under worst case conditions³⁶, but due to its conservative approach robust optimization can possibly provide overly costly solutions. Stochastic optimization, on the other hand, allows us to manage an acceptable risk level by regulating the probability of not fulfilling the considered targets. When a probabilistic characterization of the uncertainty is available, stochastic optimization provides decision-makers with a tool to embed policy robustness into the policy design process, to translate risk targets into actions, and to balance the desirable risk reduction with the corresponding cost.

Few studies treat the achievement of food security as a probabilistic event, and even fewer integrate yield uncertainty into the decision-making process³⁷. In response to this research gap, we propose here a stochastic modeling framework that allows to study the reliability of food production under crop yield uncertainty, and explore different strategies to increase this reliability at a minimum cost by sharing risk over time and space. We focus on food availability as a prerequisite for food security, and do not consider other dimensions of food security such as access or food utilization. To share the financial risk of farmers over time, we include a contingency fund that is capitalized by means of annual contributions from farmers. The fund is used in the context of agricultural insurance to guarantee a minimum income for farmers in the event of very low harvests. Risk-sharing over space is being explored by modeling different scenarios of cooperation across regions, which helps to counteract covariate risk. The modeling framework is applied to the area of West Africa and represents a simplified version of the regional food system. Despite the stylized nature of the food production model, this study serves as a proof of concept for the contingency fund in combination with inter-regional cooperation. The analysis helps us evaluate whether the regions in West Africa, individually or collectively, can ensure self-sufficiency in food production with high levels of reliability, and whether the protection of farmer livelihoods can be integrated in the objective of self-sufficiency. Specifically, the proposed modeling framework aims (i) to demonstrate that the exclusion of distributional information in the design of policy guidelines can lead to policies with very high levels of residual risk; (ii) to analyze the trade-off between reliability and costs of food production; (iii) to establish the viability of a contingency fund to protect farmer livelihoods

and to demonstrate the reliability gains through spatial risk-sharing in terms of food supply and fund solvency.

Results

Optimizing food production under crop yield uncertainty

To study the attainable food security and fiscal sustainability, we developed a stochastic modeling framework that provides the least-cost cultivation decisions that satisfy local calorie demand on average or with a given probability (production reliability), despite uncertain crop yields. The model produces the optimal crop selection and allocation over time under different scenarios of risk-aversion and risk-sharing among sub-regions within a larger region, in the absence of imports and food storage¹⁵. We use data from FAOSTAT³⁸, regional case studies^{39–43}, and the United Nations World Population Prospects⁴⁴, among other sources, to specify cultivation costs, farm gate prices, available arable land, crop yields, calorie demand per capita, and population projections to customize the model to the considered area in West Africa (see Methods for details).

We model a contingency fund through which farmer livelihoods are protected in case of low-yield events that are beyond the capacity of households or informal mechanisms to deal with¹⁶. Under such circumstances, farmers receive a payout from the fund that compensates their loss of income. As such, the risk of farmers is transferred to the holder of the contingency fund, and the indemnification policy corresponds to an insurance scheme. We assume that the contingency fund is financed by annual contributions of farmers as a share of their farming income, rather than through actuarially fair insurance premiums. For this reason, the most productive regions bear the largest cost of the risk management scheme, and not necessarily the regions that are most exposed to the risk of low-yield events. In order to control the administrative cost of the insurance program, index-based solutions including crop yield insurance⁴⁵ and weather-index insurance⁴⁶ have been implemented at large scale, for instance in India⁴⁷ and Africa²⁶. Still, the capital accumulated over time in the fund may not be sufficient to pay out the full compensation to farmers following a low-yield event. Using the model, we will evaluate the fiscal sustainability of the contingency fund under different reliability targets for the food production and risk-pooling scenarios as a means of inter-regional cooperation.

We apply the model to West Africa, and divide this supra-national region into smaller regions that represent decision-making units in the model, but we note that the region boundaries do not necessarily correspond to national borders (Fig. 1). Acknowledging that multiple factors including fertilization and irrigation mediate yield outcomes, we assume that annual yield variations in these regions are mainly driven by weather patterns. Each region constitutes therefore an area with a high degree of similarity in terms of weather. Of the four major crops in the world (maize, rice, wheat, and soybean), maize and rice are prevalently cultivated in West Africa^{48,49}. In our stylized model, the analysis is restricted to these two crops, which therefore need to supply the full calorie demand. Maize and rice feature contrasting characteristics in terms of yield and cultivation cost in West Africa. We derive yield projections for both crops in each region over the period 2017–2036 based on a linear regression model using the Global Dataset of Historic Yields (GDHY)⁴⁸. The linear yield trends for each region capture the combined effect of changes in, among others, fertilization, irrigation, and climate, while the yearly uncertainty around these trends is assumed to be the result of weather variations. We refer to the Methods section for details on the division of West Africa in smaller regions based on a clustering algorithm, and on the computation of yield projections.

Strategies for cultivation decisions can be adjusted to prioritize the risk reduction of food insecurity over the corresponding cost of overproduction. Higher reliability levels require cultivating larger areas of cropland to ensure sufficient food supply in the event of reduced yields. We consider here a three-stage strategy ladder, in which each stage aims at the cost-efficiency of food production, yet with a different outlook on risk management: (i) The risk-neutral strategy aims to ensure that the food production satisfies the food demand on average⁵⁰; (ii) The risk-target strategy incorporates explicit risk targets to ensure a desired level of reliability of food production, i.e., the

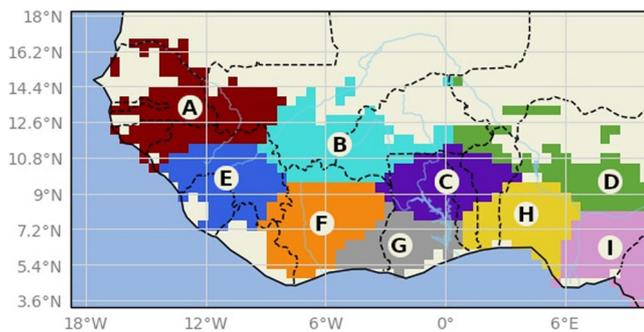


Fig. 1 | Clustering the considered area in West Africa. We consider the supra-national region between -19 and 10.5° longitude, and between 3 and 18.5° latitude where agriculture is profitable. The considered area covers 16 countries, i.e., Mauritania, Mali, Senegal, Gambia, Guinea Bissau, Guinea, Sierra Leone, Liberia, Ivory Coast, Burkina Fasso, Ghana, Togo, Benin, Nigeria, Niger, and Cameroon. The regions A to I represent areas with similar weather patterns, and are determined by clustering SPEI (Standardized Precipitation-Evapotranspiration Index) grid cells into nine regions⁷⁸. The regions exhibit strong correlation in weather patterns (and hence crop yield variations) within each region, and low correlation in weather patterns (and hence crop yield variations) across regions (see SI, Section 1 for more details on the definition of the regions). Here, yield distributions of different regions are assumed independent, which captures the best achievable performance under risk pooling. Given the limited amount of historical observations available, this approach allows to incorporate reasonable approximations of heterogeneity as well as spatial correlation of yields in West Africa.

likelihood that food supply meets food demand. This strategy requires to balance the reliability of food production with the corresponding cultivation cost. (iii) The risk-sharing strategy allows for cooperation with one or more regions, in addition to including reliability targets for food production. The cooperating regions can benefit from aggregation of statistically uncorrelated risks in a risk pool. We consider two types of cooperation strategies: (a) a proximity-based cooperation strategy, where cooperation is established between geographically adjacent regions, and (b) an inequality-reducing cooperation strategy where cooperating regions are determined to minimize the inequality among the risk pools in terms of net surplus food supply. A schematic overview of the modeling framework and different strategies is shown in Fig. 2, and a detailed formulation of strategies (i), (ii), and (iii) can be found in the Method Section.

We examine the outcomes of the risk-neutral, risk-target, and risk-sharing strategies under three different development scenarios covering different assumptions about population growth and crop yield developments: (i) a stationary scenario with constant population and stationary yield distributions, (ii) a high-pressure scenario with stationary crop yields and high population growth according to the United Nations World Population Prospects⁴⁴, and (iii) a low-pressure scenario with constant population and increasing yield trends following the current overall trend in West Africa. The parameters used in the different development scenarios can be found in section 4.2 and 4.3 of the Methods. In terms of food security, the pessimistic high-pressure scenario and optimistic low-pressure scenario delimit the potential range of scenarios to be considered in our risk management framework.

Distributional yield information allows for considerable reliability gains for food production. Under the risk-neutral strategy, optimal crop allocations are based on expected crop yields. Crop yields deviating from the expected values result in a mismatch between the actual food production and food demand leading to either shortages or surpluses. As such, relying on expected crop yields results in high risk levels of food insecurity and high probability of large shortages. A distinction can be made between regions that have sufficient versus insufficient arable land to meet the food demand locally under average (expected) yield conditions. In the latter case, food production can only meet the local food

demand in rare cases of exceptionally high yields. This happens for instance in Nigeria, which is densely populated and corresponds to region H and I in the model. In these regions, the reliability level of food production is 0% (Fig. 3b). In regions where the arable land is sufficient to meet the demand on average, the optimal annual food production is smaller than the demand with probability 50%, since the modeled yield distributions are symmetric in all regions (see purple distribution in Fig. 3a for region B). The 50% risk of regional food insecurity occurs in conjunction with food shortages up to 30% of the regional demand approximately (Supplementary Fig. 7 in SI). Both the frequency and magnitude of food shortages under the risk-neutral strategy are inconsistent with sustainability goals and call for cultivation planning that anticipates low crop yields.

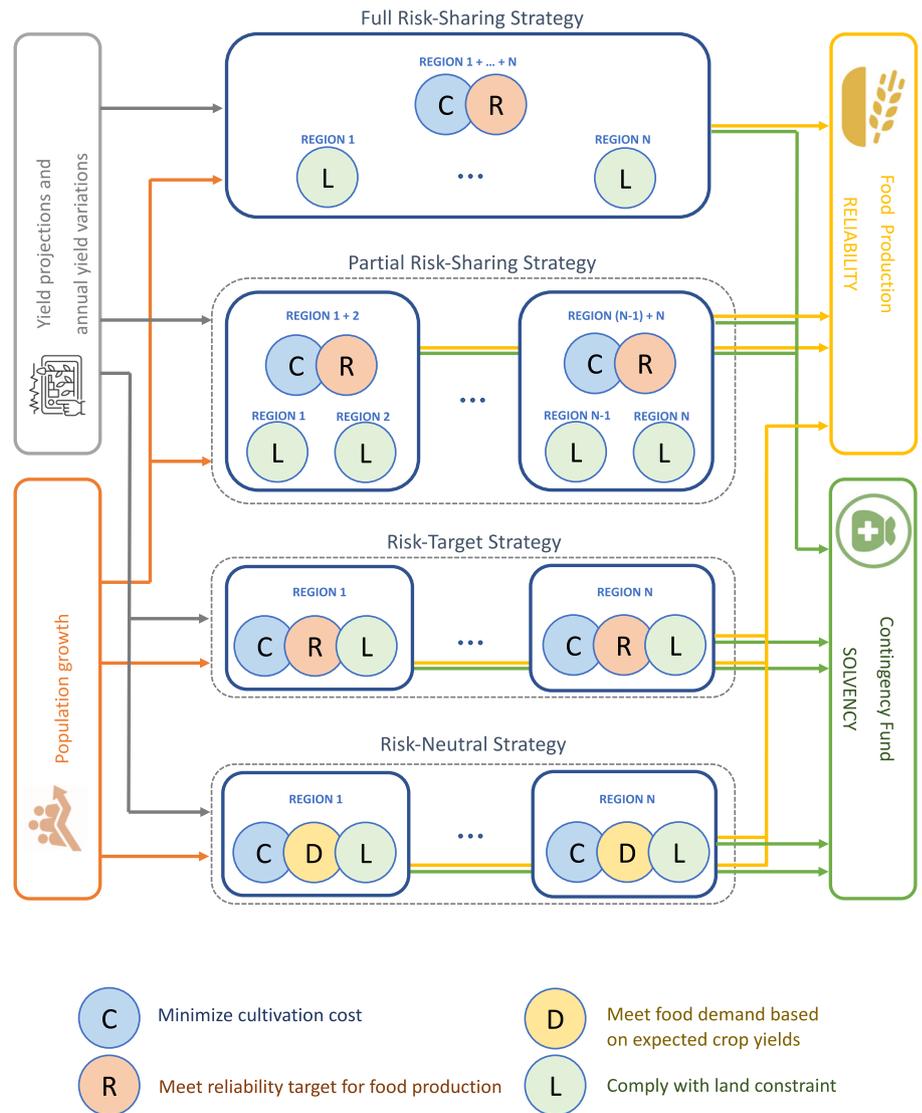
In the risk-target strategy, cultivation decisions are defined that achieve a lower risk for food insecurity by using distributional yield information and incorporating reliability targets for food production. More ambitious reliability levels for food production require to cultivate more land or higher yielding crops, albeit at a higher total cultivation cost. As the reliability target for food production increases, the distribution of food production shifts to higher values (Fig. 3a for region B as an example). When the arable land is insufficient to accommodate the food demand under the risk-neutral strategy, the risk-target strategy does not provide any food security benefits since in those regions all available land is already used for crop production (see Fig. 3b for region I as an example). Of the considered nine regions in West Africa, 6 (7) regions are able to accommodate reliability targets for food production of 99% (90%) in the stationary development scenario (see Supplementary Fig. 7 in the SI).

The trade-off between cultivation cost and food security is strong at the West African scale (Fig. 3c): Imposing a food security target of 99% (90%) leads to additional cultivation costs of 29% (14%) with respect to the risk-neutral strategy under the low-pressure development scenario, and 12% (8%) under the high-pressure development scenario. This means that substantial expenditure is required in terms of cultivating crops with higher yields or additional available farmland, in order to improve the reliability of food supply. Overall, the analysis demonstrates that the risk-neutral strategy produces very poor reliability of food supply, and potentially big shortages. However, regional decision-makers can capitalize on distributional crop yield information and the resulting trade-off between cultivation costs and food security to set reliability targets and define crop production guidelines accordingly.

At the West African scale, the 99% (90%) reliability target allows to reduce the expected food shortage by 7.8% (6.8%) with respect to the risk-neutral strategy under the low-pressure scenario, and by 3.4% (3%) under the high-pressure scenario (see Supplementary Fig. 8 in SI). In the absence of cooperation, the reduction in average food shortage is modest due to regions with high population in Nigeria that have insufficient arable land to meet the food demand. Note that the reduction of expected food shortages is tied to diverse crop allocation guidelines resulting from different reliability targets and development scenarios (see Supplementary Figs. 9–11 in the SI). We observe a large heterogeneity across regions in the optimal crop mix, i.e., the composition of crops that minimizes total costs while fulfilling the reliability targets for food production. This is a result of the heterogeneity in the cost per produced calorie, across regions and crops, and the respective risk profiles.

Fund solvency at the regional scale only achievable for infrequent events and high annual contributions. Regional decision-makers need to decide upon the magnitude of events to be covered by the contingency fund, as well as on ways to capitalize the fund. There are multiple policy levers that can affect the fiscal sustainability of the contingency fund. Here, we consider the annual farmer contributions to the fund (as a fraction of their realized profits in a given year), the level of guaranteed income (as a fraction of their expected profit at an agreed upon time), and the risk coverage (i.e., the threshold frequency of events to be covered). We investigate here contributions from farmers to the contingency fund

Fig. 2 | Schematic overview of the strategic risk management options. Regional decision-makers need to address the reliability of food production under different sources of uncertainty. Annual crop yield variations due to weather events cannot reliably be predicted, crop yield improvements and reductions due to technological change and climate change are uncertain, and population trends are also subject to high degrees of uncertainty (Left). Sources of deep uncertainty (population growth and long-term yield trends) are included by means of scenarios, while uncertainties that can be estimated based on data (crop yield variations due to weather) are incorporated through their corresponding probability distributions. In order to cope with these layers of uncertainty, decision-makers can select from a set of strategies according to their preferences (Center). The risk-neutral strategy uses the best estimate of crop yields to ensure that the expected food production meets the regional demand. The risk-target strategy allows the decision-maker to set a reliability target for food production, at the expense of higher cultivation costs. The risk-sharing strategies use risk pooling across regions to reduce the exposure to covariate risk within the regions. In the risk-sharing strategies, cultivation costs and the reliability of food production are considered at the collective scale. Progressively introducing food security reliability targets and cooperation into the modeling framework allows us to evaluate the differential impact of these strategy options both on the reliability of food production and on the fiscal sustainability of the contingency fund (Right).



varying between 1% and 10% of their profit, a guaranteed income corresponding to 90% of the expected profit, and catastrophic risk levels between 1% and 5%. The effect of payouts from the contingency fund is observable in the truncated lower tails of the farmers' profit distributions, ensuring minimum levels of income after catastrophic events (Supplementary Fig. 12 in SI).

The fiscal sustainability of the contingency fund can be measured by the observed probability for fund solvency after payouts (Fig. 4). Under the stationary development scenario, eight of the nine regions can achieve a solvency probability of the fund above 90%, but this result holds only for the coverage of infrequent events (1% risk coverage) and under high farmer contributions ($\geq 5\%$ of farmer profits). For more frequent events, the solvency probability drops considerably. For instance, only one (three) of the nine regions achieve a 90% solvency probability for a 5% risk coverage and a 5% (10%) tax rate. Similar to the moderate reduction of food shortages through stringent reliability targets (Supplementary Fig. 8 in the SI), the improvement of the financial sustainability of the fund is modest. Although the considered policy levers are able to improve the fiscal sustainability, their effectiveness is limited at the regional scale and large amounts of debt still have to be taken in most of the regions to cover the obligations to farmers (see distributional information on fund capital after a catastrophe in Supplementary Fig. 13 in the SI). In order to remain solvent after catastrophic yields, the contingency fund holder can also make use of contingent credit lines or reinsurance²⁷. Allowing for debt under extreme circumstances

relaxes the capital requirements of the fund holder, while also avoiding unrealistically high contributions from farmers. Alternatively, other financing mechanisms can be used to ensure the fiscal sustainability of the fund, including capitalization by society at large, international aid, or capitalization through regional cooperation.

Risk pooling is highly effective for improving food security and reducing debt. Without cooperation in a risk pool, some regions never reach the 99% reliability target for food production, and averaged over all regions this results in reliability levels of 52% and 43% for the low-pressure and high-pressure development scenario, respectively (Fig. 5a). Despite this, even limited levels of risk pooling generate sizeable improvements in the reliability of food supply, and full cooperation over the nine regions allows for achieving the reliability target of 99% (Fig. 5a), while virtually eliminating food shortages (Fig. 5b). This is a robust finding over a range of population and yield scenarios bounded by the considered low-pressure and high-pressure development scenarios, and over different cooperation strategies. Even in the high-pressure development scenario, the food security can be guaranteed at the target level of 99%, although this requires full cross-regional cooperation under the proximity-based cooperation strategy. When the inequality-reducing cooperation strategy is applied, risk pools consisting of two regions are already sufficient to achieve a 99% reliability of food production (Fig. 5a). The inequality-reducing cooperation strategy combines productive

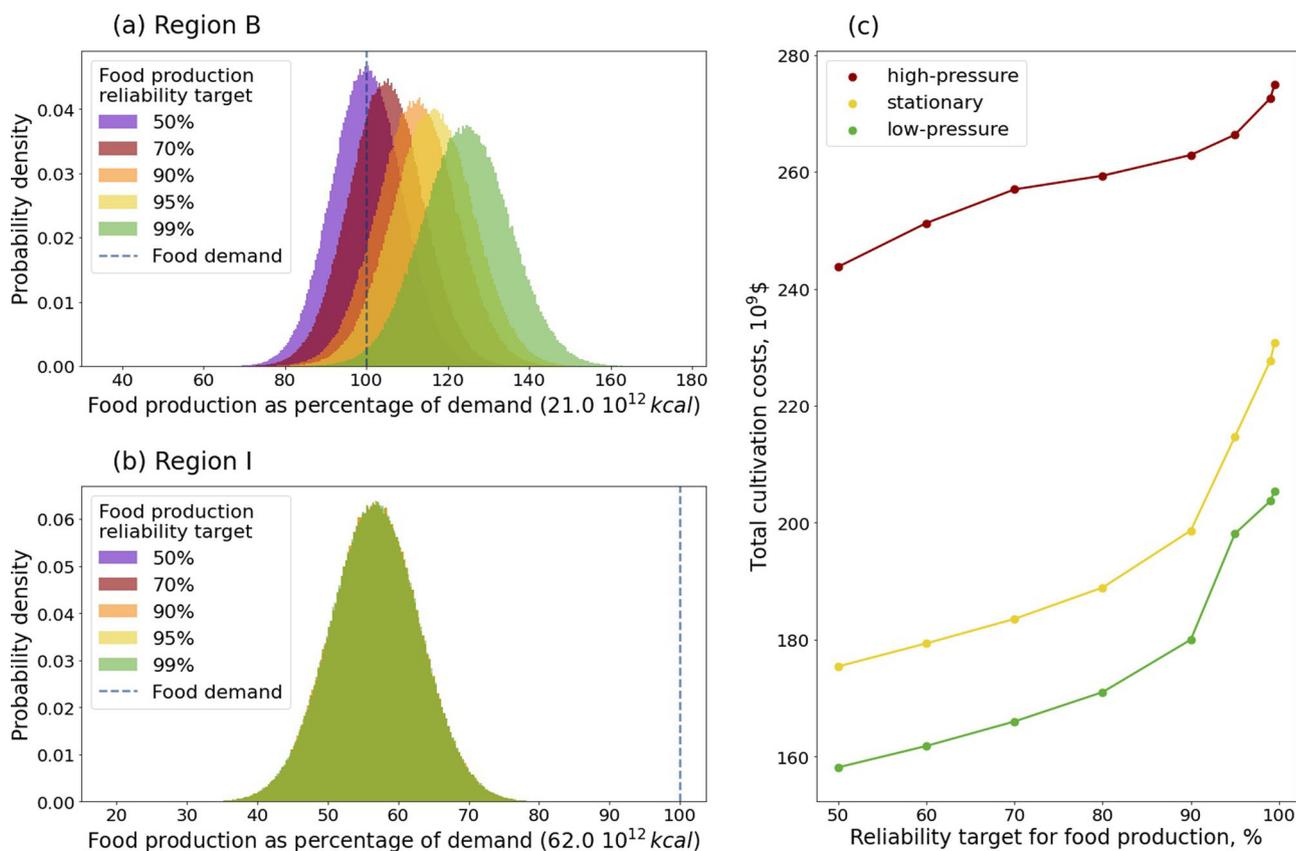


Fig. 3 | Food production distributions under the stationary development scenario and trade-off between food security and cultivation cost. **a** With symmetric crop yield distributions, the risk-neutral strategy results in a 50% reliability for food production in regions that have sufficient arable land to meet the food demand, indicated in purple for region B in this case. Under the risk-neutral strategy, seven of the nine regions show a food supply distribution with 50% risk of food insecurity (Supplementary Fig. 7 in SI). The introduction of reliability targets for food production produces a shift of the food production distribution according to the imposed reliability level. **b** If the arable land is insufficient to meet the food demand,

introducing reliability targets has no effect on the food production distribution, which is the case for instance for region I, located in Nigeria, featuring the highest population density in West Africa. Two of the nine regions have insufficient arable land and food production never meets food demand, corresponding to an actual reliability level of 0%. **c** In all development scenarios (high-pressure, stationary, and low-pressure), there is a strong trade-off between reliability targets for food production and the corresponding cultivation cost aggregated over all 9 considered regions and time.

regions with poorly performing regions, and although less realistic, demonstrates the potential of a cooperation strategy that accommodates trade over longer distances.

In terms of fiscal sustainability, risk-pooling can considerably decrease the magnitude of insolvency already with limited cooperation, shown by the observed average debt levels (Fig. 5d). Full cross-regional cooperation allows to reduce the average debt per capita by approximately a factor 5.7 and 7.5 for the low-pressure and high-pressure development scenario, respectively, indicating that the reliance on external aid can be reduced substantially through cooperation. However, the benefits of risk-pooling on the overall probability for fund solvency are ambivalent. Two competing effects are at play with increasing levels of risk pooling. First, due to increased risk pooling, the occurrence of the first low-yield event in one of the partnering regions is sped up, leading to a reduction of the time to capitalize the contingency fund. Second, increased risk pooling results in more regions that can compensate for the losses born by one or several of the partnering regions, alleviating the pressure on the fund capitalization. These opposing effects result in a decline of the solvency probability with respect to the independent regions for small risk pools, while larger risk pools provide an increase of the solvency probability with respect to the case of independent regions. Full cross-regional cooperation results in an improvement of the solvency probability by 3.3 percentage points in the low-pressure development scenario, and by 15.4 percentage points in the high-pressure development scenario (Fig. 5c). Despite these improvements, risk pooling cannot achieve the fiscal sustainability of contingency funds even under full cross-

regional cooperation. The results confirm the understanding that hardly any agricultural insurance scheme can cover costs exclusively based on premiums⁴⁷. Combined with limited willingness to pay for insurance products⁵¹, this finding restates the necessity of additional financing mechanisms and the support from the public sector to ensure the viability of agricultural insurance.

The total allocated land does not present a clear trend over different levels of cooperation (Fig. 5e). Cross-regional cooperation encourages the relocation of agricultural production towards more efficient regions to compensate for shortages in the least productive areas. For small risk pools, the compensation of shortages leads to a higher total cultivated area, while larger risk pools can achieve efficiency gains in total cultivated area. Under the low-pressure development scenario a slight decrease of allocated land can be noticed in case of full cooperation. Under the high-pressure development scenario, an increase of the allocated land can be observed in line with the increasing population. As to cultivation costs, inter-regional cooperation helps to overcome the food shortages of a struggling region (Fig. 5f). However, small risk pools do not have the ability to fully exploit cost efficiencies and therefore the total cultivation cost increases. Larger risk pools can take advantage of the most cost-efficient regions to increase production, with positive effects for the total cultivation costs. This effect illustrates that risk pooling requires a minimum size of the pool to avoid additional cultivation costs. Note that we consider here only cultivation costs, and that the cost of public investment to facilitate inter-regional cooperation is not included. The results of the cooperation analysis

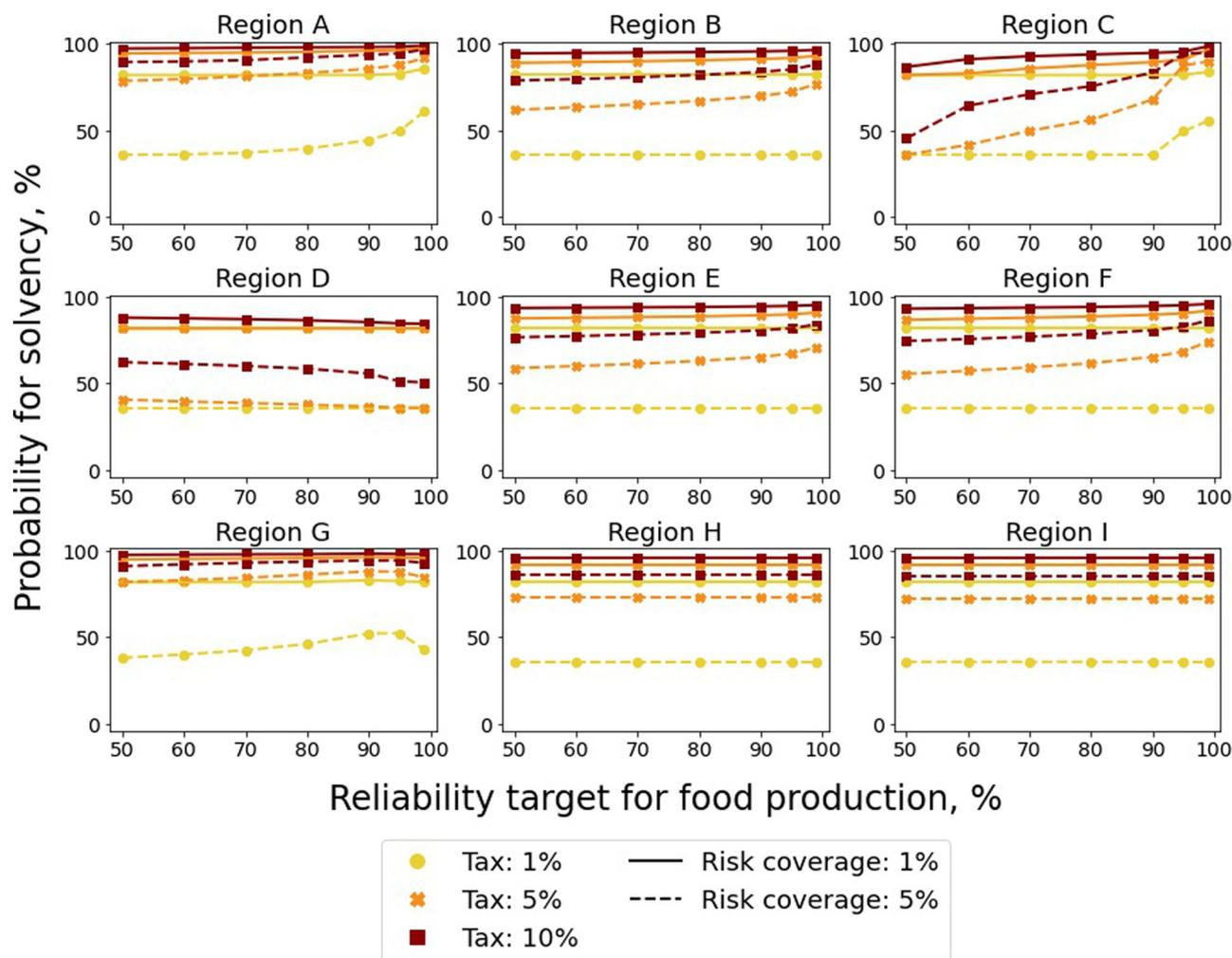


Fig. 4 | Fund solvency for different policy levers. The solvency probability of the contingency fund is depicted as a function of the reliability target for food production. Increasing the reliability target results in a growing food production, and the corresponding growing contributions to the fund can be observed as a main trend of increasing solvency probabilities with higher reliability targets. However, when the available arable land is entirely cultivated, substitution from more profitable crops to less profitable but higher yielding crops can result in decreasing contributions into the fund, and correspondingly lower solvency probabilities, as for instance in region G. The risk coverage level has an important effect on the solvency,

with less frequent risks leading to higher solvency, notwithstanding the higher payouts necessary to achieve the regional guaranteed income. Annual contributions to the fund also have a sizeable effect on the fund solvency, although solvency probabilities above 90% are mainly achievable for infrequent events (1%) and for annual contributions above 5%. Under these conditions, a solvency probability of 90% can be reached in eight of the nine regions. When annual contributions are below 5% and the covered risk level is higher (5%), the fund solvency probability shows large variations between 36% and 61%.

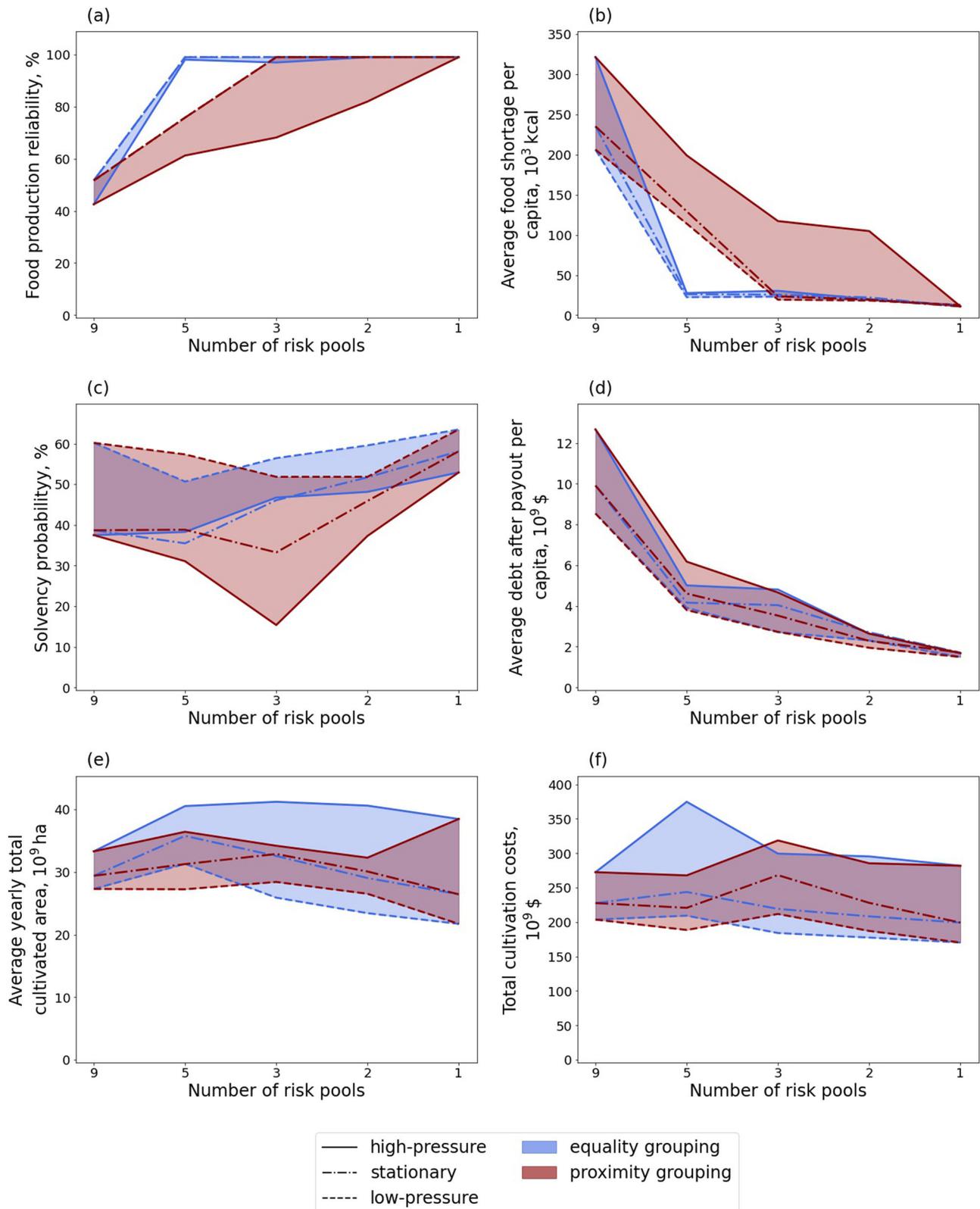
demonstrate that the substantial gains of full regional cooperation in the reliability of food supply and debt reduction are not at the expense of higher cultivation cost or a large expansion of cultivated area. This is relevant both from an economic and environmental perspective.

Discussion

Increasingly frequent and severe droughts in conjunction with demographic developments in West Africa are likely to put food security and livelihoods of farmers under growing pressure. To address these problems, it is essential to get a better understanding how crop production decisions by farmers affect the reliability of food production and the stability of their livelihoods. By integrating crop yield uncertainty in the decision-making, the risk-adjusted food production model offers the possibility to integrate risk considerations into regional crop allocation guidelines and assess the corresponding impacts on production costs and cultivation area, which can help determine an acceptable level of residual risk^{37,52}. In addition to integrating risk, the model examines risk pooling and contingency funds as two approaches to increase the reliability of food production and livelihoods of farmers. Regional cooperation through risk pooling can strengthen the

reliability of food supply to very high levels (i.e., 99%), and allows to reduce external financing to guarantee farmer livelihoods by a considerable factor (i.e., between 5.7 and 7.5 for the low-pressure and high-pressure development scenarios). Since the contingency fund is capitalized through an annual tax on farmer incomes, the most productive regions, rather than the most risk-prone regions, bear the largest cost within the risk pool of the risk management scheme.

The results of this study contribute to the broader context of agricultural risk management in three main ways. First, we demonstrate that there is a strong trade-off between cultivation costs and food security at the regional level. For high levels of food security, a small further increase in the reliability of food supply requires a big increase in production costs. The characterization of this trade-off can be very useful for policymakers who are interested to better understand the role of extensification and crop substitution in increasing the reliability of food production. Second, we add nuance to the benefits of risk pooling. We show that risk pooling is always beneficial to reduce the risk for food insecurity and the magnitude of food shortages, but the risk pool features a critical mass behavior in terms of solvency probability and total cultivation cost:



Below a certain critical size of the risk pool, the solvency probability can go down albeit for considerably lower debt levels, while reducing the risk of food insecurity and the amount of food shortages might require an increase of the cultivation costs. Only beyond the critical mass level, risk pooling has unambiguously the desired effect in improving the resilience of food security in the region and the livelihoods of farmers. Third, our

analysis highlights that the composition of the risk pool affects its performance, and that the presence of regions with good performance can reduce the critical mass of the risk pool. That is why participation rates need to be bolstered also among regions that do not directly suffer from catastrophic yields, but who can be the victim of externalities of these events in neighboring regions.

Fig. 5 | Potential of risk pooling for risk management. Cooperation levels are indicated by the number of risk pools, where nine risk pools stand for independent regions, and a single risk pool represents full cooperation. For (a–d), averages are taken over risk pools with population as weight. **a** Actual reliability for food production. Due to the highly populated regions H and I in Nigeria who feature an actual reliability for food production of 0%, the reliability for food production is low at the cross-regional scale in the absence of risk pooling. Risk pooling has the ability to completely resolve the reliability problem for food production, even under the high-pressure scenario. **b** Average food shortage per capita under deficit conditions. The average food shortage can virtually be eliminated through risk pooling, even under the high-pressure development scenario. **c** Solvency probability of the contingency fund. Cooperation in small risk pools initially aggravates the solvency probability due to the earlier occurrence of catastrophic yields over multiple independent regions and the resulting lack of time to capitalize the contingency fund. In larger risk

pools, the earlier occurrence of catastrophic yields is compensated by the saving capacity of multiple regions, resulting in moderate improvements. **d** Average debt per capita over risk pools after payouts under conditions of insolvency (i.e., debt level of contingency fund after payouts translated in debt per capita to facilitate comparison). Risk pooling can reduce the debt levels substantially, which improves the practical implementability of external aid mechanisms in large risk pools. **e** Average yearly total cultivated area (average over all years). The cultivated area is reasonably stable over the different cooperation levels. Although risk pooling has important benefits in terms of food security and debt reduction, this is not at the expense of farmland expansion and the corresponding environmental cost, under scenarios with a constant population. **f** Total cultivation cost (summed over all years). The total cultivation cost is reasonably stable over different cooperation levels. The improvements in food security and debt reduction are not at the expense of growing cultivation costs at the cross-regional scale.

Due to the stylized nature of the food production model, several aspects of food security were outside the scope of this study. For instance, considerations regarding balanced diets, nutritional value, or the impacts of climate change on nutritional value are not accounted for⁵³, and other crops that are equally important in the region, such as millet and sorghum, were not considered in the crop selection. Furthermore, past climate variability might not be an accurate predictor of future climate risk, and therefore, our simple yield projections do not capture the effects of increasing duration and intensity of extreme weather⁶. This might have made the yield projections overly optimistic. In terms of climate adaptation, actions to alleviate the pressure on the food system, including buffer stocks⁵⁴, improved water management⁵⁵, further sustainable intensification to close the yield gap⁵⁶, and emergency response, were not examined here. Although there currently exist substantial food imports into West Africa, they have not been considered in this work, since we wished to focus on long-term food security which needs to build on domestic production⁵⁷. With regard to the contingency fund, the protection of farmer livelihoods covers all losses beyond the risk coverage level. Since the fund is often not solvent after payouts, the proposed livelihood protection could be complemented with risk-layering⁵⁸, so that farmer income losses are covered by the fund up to a predetermined level, after which excess losses can be ceded to a co-insurer through reinsurance or catastrophe deferred drawdown options⁵⁹. Finally, food security also depends on other sources of uncertainty apart from weather uncertainty and population growth, such as conflict^{23,60}, global economic conditions²³, fluctuations of the commodity markets⁶¹, and migration^{1,60}, some of which are hard to quantify. The presented modeling framework can be adjusted to incorporate multiple probabilistic and scenario-based uncertainties, including correlated and compound risks, and this constitutes a promising direction for future research. However, we note that the actual design of crop allocations and tax rates requires a model that captures all elements of the food system listed above.

Notwithstanding these limitations, the insights presented in this paper indicate that risk-targeting combined with regional cooperation and contingency funds can considerably improve the reliability of food production and provide guarantees for farmer livelihoods. The implementation of this combined risk mitigation strategy in real life requires certain conditions. While this paper does not address the complexity of the implementation challenge, here we point at the most obvious factors. Trade liberalization is a prerequisite to obtain the benefits of risk pooling, and therefore further economic integration in the region is required^{1,37,62}. In order to sell food surpluses in good years and optimally allocate crop production over a larger area, appropriate investment in the distribution infrastructure is necessary⁶³. In terms of fiscal sustainability, the success of the contingency fund depends on the willingness of countries to participate in risk pools and the availability of fiscal space in the participating countries²³. The studied regions in West Africa are diverse in their ability to meet the food demand, and both surplus and deficit regions are added to the risk pool. In real risk pools such as the ARC²⁶, initially only weaker regions were partnering. By making the downstream effects of food insecurity in the region more observable, regions with a more robust agricultural performance could be convinced of the

benefits of participation in the risk pool. Moreover, the societal relevance of food security could also justify to mobilize fund contributions from society as a whole and not rely exclusively on farmer contributions. Multi-sectorial cooperation mechanisms could further reduce the reliance on external financing of the contingency fund, contingent credit, or reinsurance.

Finally, the relevance of risk-adjusted decision-making and regional cooperation is not limited to the challenge of food security within SDG 2 - Zero Hunger. The results of this paper underscore that ignoring uncertainty can result in solution pathways that contain excessive residual risk, as demonstrated through the ex-post accounting for uncertainties in the risk-neutral strategy. This insight applies to multiple systems relevant to sustainability, ranging from energy to transport to industrial production, which are all subject to multiple uncertainties.

Methods

Clustering West Africa

For the selection of the study area in Fig. 1, we pruned the area between -19 and 10.5° longitude, and between 3 and 18.5° latitude, based on available data on expected yields⁴⁸. Only those cells are retained where the expected yields are profitable in 2016 for one of the considered crops, thus excluding the non-arable land at the edge of the Saharan desert. The resulting set of yield cells is large (750 cells), and makes a stochastic analysis including that many locations numerically intractable. Furthermore, the limited amount of historical data would limit the statistical significance of a yield regression at the scale of each cell. Finally, targets for food security are typically defined at a larger, regional scale. For these reasons, we group yield cells into regions. Since this study focuses on the risk of low yields as a result of weather variability, we define regions as areas that exhibit similar weather patterns. The clustering into regions is therefore based on SPEI data, which has widely been used to monitor droughts^{64,65}, and the partitioning clustering algorithm k -medoids⁶⁶. The SPEI gridded data set covers the period from January 1901 to December 2018 with monthly frequency and coverage at a $0.5^\circ \times 0.5^\circ$ resolution. In the clustering algorithm, the Pearson distance between the SPEI time series of any two cells is used as the distance metric to be minimized in the clustering procedure. An optimal number of regions is found by maximizing the intra-cluster similarity and minimizing the inter-cluster similarity, which results in an optimal number of nine regions (see Supplementary Methods, section 1.1 for more details). Using the regions defined by the k -medoids algorithm allows us to assume similar weather patterns in all cells belonging to a region, as well as to make use of average yields for each region. However, we ignore the residual spatial correlation between clusters and do not consider temporal autocorrelation for each cluster. This assumption implies that the reported benefits of risk pooling in this work represent an upper performance bound.

We use five different degrees of cooperation: nine independent regions, four risk pools of two regions (with one remaining, independent region), three risk pools of three regions each, one risk pool of four regions combined with a risk pool of five cooperating regions, and full cooperation in a single risk pool of nine regions. There are many ways to define the risk pools of cooperating regions, but we consider here two strategies. In the proximity-

Table 1 | Yield projections for rice and maize

Region	rice yield projection	maize yield projection
Region A	$5.15 + 0.082 \times t$	$1.67 + 0.025 \times t$
Region B	$3.88 + 0.072 \times t$	$1.98 + 0.033 \times t$
Region C	$2.87 + 0.057 \times t$	$1.31 + 0.016 \times t$
Region D	$2.25 - 0.002 \times t$	$1.53 + 0.013 \times t$
Region E	$2.20 + 0.014 \times t$	$1.57 + 0.013 \times t$
Region F	$2.21 + 0.035 \times t$	$2.33 + 0.043 \times t$
Region G	$2.83 + 0.047 \times t$	$2.28 + 0.035 \times t$
Region H	$2.23 - 0.010 \times t$	$2.24 + 0.021 \times t$
Region I	$1.69 - 0.034 \times t$	$2.20 + 0.020 \times t$

Yield projections [t/ha] for Regions A-I under the non-stationary assumption, where t is the number of years since 2016. The yield projections are used in the low-pressure scenario.

based cooperation strategy, adjacent regions are clustered by minimizing the sum of Pearson distances between the medoids within the respective risk pool, while in the inequality-reducing cooperation strategy the maximum difference between the expected surplus food supply of the risk pools is minimized while adjacency is not considered.

Yield projection model

The computation of crop yield projections in the nine regions is based on the GDHY dataset, which provides gridded yield data for maize, wheat, rice, and soybean. The GDHY data set is based on downscaled FAO yield data at the country scale with a spatial resolution of $0.5^\circ \times 0.5^\circ$ and annual temporal resolution from 1981 to 2016⁴⁸. Of the four major crops in the world, we restrict our analysis to maize and rice, which are widely cultivated in West Africa. Time series of average crop yields are computed for each region over the period 1981–2016, and linear trends are extrapolated into the future for a time window of 20 years (2017–2036). The residuals of the linear regression model can be approximated by a normal distribution, as confirmed by the Shapiro-Wilk normality test with alpha level equal to 0.5 for 15 out of 18 crop-region combinations, notwithstanding the small sample size. We therefore assume yields to follow a time-dependent Gaussian distribution, with mean equal to the linear trend and constant variance equal to the variance of the residuals. The crop yield data and the corresponding linear regression, the crop yield projections, and modeled crop yield distributions are depicted in Supplementary Figs. 2–5 (Section 1.2 of the Supplementary Methods), and a summery overview is given in Table 1. Note that the yield projection model captures the combined effects of agricultural intensification and climate change. From the linear regression in Supplementary Fig. 2 of the SI, we observe that intensification dominated the effect of climate change over the period 1981–2016. Since this trend is also projected over the period 2017–2036, our model does not capture specific temperature thresholds that could be breached over the considered time interval, nor an increase in drought events, or a potential reduction of the calorie content under heat stress⁶⁷.

Data sources to operationalize the modeling framework

Farm gate prices are based on producer prices provided by the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT)³⁸. For data on cultivation costs, we rely on regional case studies to find a single cultivation cost per crop, valid for all regions and all years in the considered time window^{39–43}. For the parameterization of the arable land in West Africa, we make use of a land use study indicating that 22.4% of the land surface is cultivated⁶⁸, which we assume to be constant over time. Food demand is based on population data and a daily energy intake of 2360 kcal per person, which is an estimate for 2015 Sub-Saharan Africa according to the FAO⁶⁹. We use the high fertility scenario of the United Nations World Population Prospects (UN WPP) to model the high pressure demographic development scenario⁴⁴. In the high fertility scenario, the population in the considered area of West Africa is projected to grow from 251 million in 2017 to

417 million in 2036. More details on the parameterization of the modeling framework can be found below and in the Supplementary Methods (Section 1.3).

Decision-making framework of West-African food system

In order to account for diversity in crop yields, West Africa is divided into \mathcal{K} regions and we consider \mathcal{J} crops that can be cultivated in each region. We consider maize and rice, where maize is cheaper to cultivate, and where maize and rice have comparable calorie content, but distinct yield performance depending on the region (Table 1 and Supplementary Fig. 4 in Supplementary Methods). Decisions need to be made concerning the land allocation x (ha) to the different crops j in each region k for each year t from the initial year t_0 to a final year T . We define a catastrophic yield event as an event where the yield is below an agreed upon percentile r of the yield distribution, which we refer to as the risk coverage level. We assume that weather, i.e., droughts or heat waves, drive catastrophic yields, and that there exists full correlation between catastrophic yields of different crops within the same region. We use therefore a multi-dimensional random vector M of \mathcal{K} independent and identically distributed Bernoulli random variables to indicate the occurrence of catastrophic yields at time t in the \mathcal{K} regions. The Bernoulli random variables take value 1 with probability r , the risk level of a catastrophic yield event. According to the realization of the random vector $M_{k,t}$, yield samples [t/ha] are drawn for the yield vector Y for each crop j , region k , and time t , from above or below the r -percentile of the corresponding yield distribution. For each realization of yields, simulation is cut off after the first catastrophic yield event in the year $T_{\text{fin}}(M)$ based on the realization of M .

Contingency fund. The capital accumulation in the contingency fund for a risk pool \mathcal{P} consisting of a subset of regions is described as follows

$$F_{\mathcal{P}}(x, t, M, Y) = F_{\text{ini}} + \tau \sum_{t'=t_0}^t \sum_{k \in \mathcal{P}} I_k(x, t', Y) - \sum_{t'=t_0}^t L_{\mathcal{P}}(x, t', M, Y). \tag{1}$$

The capital in the fund at time t is determined by the initial capital F_{ini} at t_0 (set to zero in this work), the annual contributions from farmers (second term), and the payouts in case of catastrophic yields (third term). The annual contributions are proportional to the total value of the produced crops with a contribution rate τ . The total value of the produced crops I_k represents the profit that can be realized in region k , which can be written as follows

$$I_k(x, t, Y) = \sum_{j=1}^{\mathcal{J}} Y_{j,k,t} \cdot x_{j,k,t} \cdot p_j - \sum_{j=1}^{\mathcal{J}} x_{j,k,t} \cdot c_j, \tag{2}$$

with the first term describing revenue and the second term describing cultivation costs. Farm gate prices for crop j are represented by p_j [\$/t], and c_j is the cultivation cost of crop j (see Section 1.3 in Supplementary Methods). Payouts to farmers are made during a year of catastrophic yields according to

$$L_{\mathcal{P}}(x, t, M, Y) = \sum_{k \in \mathcal{P}} M_{k,t} \cdot (1 - \tau) \cdot \max\{0, I_k^{\text{gov}}(t) - I_k(x, t, Y)\}, \tag{3}$$

compensating for losses with respect to $I_k^{\text{gov}}(t)$, the guaranteed regional income for farmers. The guaranteed regional income is a fraction g of the expected regional profit at $t_0 - 1$, which grows over time proportional to the population of each region; here, we use a baseline value of $g = 0.9$.

Note that we assume in this study that the contingency fund is launched with zero initial capital stock. Accumulated debt calls for foreign aid or other financing channels to cover incurred losses in case of insolvency of the fund. Conversely, if the fund capital after payouts is positive, this could be accounted for by a positive initial fund capital F_{ini} .

Risk-neutral strategy. In the risk-neutral strategy, the focus is on the cost-efficiency of the food production while ensuring that the expected food production meets the food demand⁵⁰. In this strategy, best estimates of the food system parameters are used, in particular for the crop yields, to determine the land allocation over the different crops. Land allocation x of the different crops is determined in each region in order to minimize the cultivation cost, with the constraint that the land allocation does not exceed the available arable land \bar{x}_k and that the expected food production meets the food demand at all times. The problem can be formalized for each region k as follows

$$\min_x \sum_{t=t_0}^T \sum_{j=1}^{\mathcal{J}} x_{j,k,t} \cdot c_j \quad (4a)$$

$$\text{s.t. } x_{j,k,t} \geq 0 \quad \forall j \in \{1, \dots, \mathcal{J}\}, \forall t \in \{t_0, \dots, T\} \quad (4b)$$

$$\sum_{j=1}^{\mathcal{J}} x_{j,k,t} \leq \bar{x}_k \quad \forall t \in \{t_0, \dots, T\} \quad (4c)$$

$$\sum_{j=1}^{\mathcal{J}} \mathbb{E}[Y_{j,k,t}] \cdot x_{j,k,t} \cdot a_j \geq d_{k,t} \quad \forall t \in \{t_0, \dots, T\} \quad (4d)$$

where a_j is represents the calorie content of crop j in [kcal/t], and $d_{k,t}$ is the food demand at time t for region k [kcal]. The food demand grows proportionally with the growth of population in each region. As to the land constraints in Eq. (4b, 4c), we assume that agricultural area is evenly spread over West Africa, and we ignore trends in agricultural area over time. Crop yields can be subject to large variations, but the risk-neutral decision-maker relies on the best estimate of the crop yields $\mathbb{E}[Y_{j,k,t}]$ to calculate the calorie supply (left-hand side in Eq. (4d)). Finally, since the risk-neutral decision-maker utilizes expected yield values, there are no occurrences of catastrophic yields and the cultivation costs in Eq. (4a) are calculated from t_0 to T , where the terminal time is 20 years after the initial time.

Risk-target strategy. In systems that operate under uncertainties, decisions based on expected parameter values can result in bad policies as different types of risks and their impacts are ignored⁷⁰. In the risk-target strategy, the goal is to improve the reliability of the food production in the presence of natural hazards, in addition to pursuing cost-efficiency^{71,72}. Improving the reliability of the food production requires to add risk constraints for food security and to internalize the available distributional information on crop yields in the decision making framework. We define risk and reliability here as the likelihood of a negative event (food shortage) versus a positive event (food surplus). Adding food security risk targets allows decision-makers to balance the reliability of the food production with the cost of achieving this. In particular, decision-makers can define an acceptable residual risk for events where the food supply does not meet the food demand. Relaxing the food security constraint allows finding solutions that are permissive for rare, yet consequential events, and by doing so, a region can limit consistent over-cultivation.

In the risk-target strategy, the food production needs to meet the food demand with a selected level of reliability. In the modeling framework, this reliability target is captured by a probabilistic constraint in a chance-constrained problem with reliability level α . The optimization problem can be formulated for each region k as

$$\min_x \mathbb{E} \left[\sum_{t=t_0}^{T_{\text{fin}}(M)} \sum_{j=1}^{\mathcal{J}} x_{j,k,t} \cdot c_j \right] \quad (5a)$$

$$\text{s.t. } x_{j,k,t} \geq 0, \quad \forall j \in \{1, \dots, \mathcal{J}\}, \forall t \in \{t_0, \dots, T\} \quad (5b)$$

$$\sum_{j=1}^{\mathcal{J}} x_{j,k,t} \leq \bar{x}_k, \quad \forall t \in \{t_0, \dots, T\} \quad (5c)$$

$$\mathbb{P} \left[\sum_{j=1}^{\mathcal{J}} Y_{j,k,t} \cdot x_{j,k,t} \cdot a_j \geq d_{k,t} \mid t \in \{t_0, \dots, T_{\text{fin}}(M)\} \right] \geq \alpha \quad (5d)$$

Here, the expected cultivation cost for each region k is minimized depending on the random terminal time $T_{\text{fin}}(M)$. The constraints in Eq. (5b) and (5c) need to be fulfilled independent of the yield sample, and therefore cover the full time frame from t_0 to T . The food security constraint in Eq. (5d) needs to be met with reliability level α over the period until the first catastrophic yield event (instead of at each time t).

We evaluate the solvency of the contingency fund after the payouts relative to the first catastrophic yield event, which occurs at random time $T_{\text{fin}}(M) \in \{t_0, \dots, T\}$. Note that we study the fund solvency as a model output, and do not integrate a dedicated solvency constraint in the optimization problem. This logic is motivated by two main arguments. First, if catastrophic yields happen early after the launch of the contingency fund, the fund solvency is practically unattainable without a high degree of prior capitalization. Second, in case of an insolvent fund, regional decision-makers often make use of alternative financing instruments such as international aid or contingency credit. The analysis of the fund solvency should therefore be considered as an evaluation of emergency preparedness.

Chance-constrained problems involving multiple empirical distribution functions are typically numerically intractable. In order to solve the optimization problem, we make use of the equivalence between chance-constrained problems and two-stage stochastic optimization problems⁷³, and reformulate the problem for each region k as a penalty-function problem with deterministic constraints

$$\begin{aligned} \min_x \quad & \mathbb{E} \left[\sum_{t=t_0}^{T_{\text{fin}}(M)} \sum_{j=1}^{\mathcal{J}} x_{j,k,t} \cdot c_j + \sum_{t=t_0}^{T_{\text{fin}}(M)} \left(\rho \cdot \max \left\{ 0, d_{k,t} - \sum_{j=1}^{\mathcal{J}} Y_{j,k,t} \cdot x_{j,k,t} \cdot a_j \right\} \right) \right] \\ \text{s.t. } \quad & x_{j,k,t} \geq 0, \quad \forall j \in \{1, \dots, \mathcal{J}\}, \forall t \in \{t_0, \dots, T\} \\ & \sum_{j=1}^{\mathcal{J}} x_{j,k,t} \leq \bar{x}_k, \quad \forall t \in \{t_0, \dots, T\} \end{aligned} \quad (6)$$

In the two-stage optimization problem, the cultivation costs are adjusted by a penalty proportional to the food shortage indicated by $\max\{0, d_{k,t} - \sum_{j=1}^{\mathcal{J}} Y_{j,k,t} \cdot x_{j,k,t} \cdot a_j\}$, and the resulting penalty function is minimized. Crop allocations x are first-stage, strategic decisions that are taken without any knowledge of the actual crop yields that will materialize. In case these decisions result in a food shortage, the second-stage or recourse actions account for the direct cost of the food shortage through food imports and indirect costs in terms of the corresponding socio-economic impacts. In other words, the two-stage stochastic optimization framework enables us to account for the externalities of food insecurity⁷⁴. A higher penalty ρ per unit of food shortage increases the incentive to expand the strategic land allocation and prevent potential shortages. The relationship between the required reliability level α and the penalty ρ can be found numerically. An economic interpretation of the penalty ρ can be obtained by considering the equivalence between the chance-constrained problem and the two-stage stochastic optimization problem. Indeed, it can be demonstrated that the penalty ρ represents the shadow price or marginal cost of strengthening the food supply constraint at a target reliability level⁷⁵. As high reliability levels α result in very high values of ρ , this indicates that the economic cost of food shortages needs to be sufficiently high so as to increase crop production.

By endogenizing risk evaluations and converting them in monetary values, we can avoid the difficulties of probabilistic risk assessments⁷⁶. The two-stage stochastic programming framework can benefit decision-makers to decide upon an acceptable risk level by considering the dollar values of the corresponding costs. This framework allows us to endogenize a price for the

reliability of the food system by translating the probabilistic food security target into a price tag for the risk of food insecurity.

Risk-sharing strategy. The risk-sharing strategy seeks to reduce risk exposure through cooperation⁷¹. Extreme weather events such as droughts generate high losses with high correlation over space. A possible solution is to aggregate statistically uncorrelated risk exposures into a risk pool to reduce the variance of the aggregated agricultural profits⁷⁷. For that reason, cross-regional cooperation is often considered as it enables the pooling of uncorrelated catastrophic risks, which can in turn result in financial resilience for the pool members with respect to natural disasters.

Cooperation via risk pooling elevates the problem of land allocation to the cross-regional level. In the risk-sharing strategy, cooperation scenarios are defined where the cultivation cost of joint production within the risk pool is minimized while ensuring the reliability of the food production, again at the risk pool level. When multiple regions share the risks of food insecurity, a year is called catastrophic if at least one region has catastrophic yields below the risk coverage level. The food security problem under a partial or full risk-sharing strategy can then be formulated as follows for each risk pool $\mathcal{P}_i \subset \{1, \dots, \mathcal{K}\}$ with $\bigcup_i \mathcal{P}_i = \{1, \dots, \mathcal{K}\}$

$$\begin{aligned} \min_x \quad & \mathbb{E} \left[\sum_{t=t_0}^{T_{\text{fin}}(M)} \sum_{k \in \mathcal{P}_i} \sum_{j=1}^{\mathcal{J}} x_{j,k,t} \cdot c_j + \sum_{t=t_0}^{T_{\text{fin}}(M)} \left(\rho \cdot \max \left\{ 0, d_{\mathcal{P}_i,t} - \sum_{k \in \mathcal{P}_i} \sum_{j=1}^{\mathcal{J}} Y_{j,k,t} \cdot x_{j,k,t} \cdot a_j \right\} \right) \right] \\ \text{s.t.} \quad & x_{j,k,t} \geq 0 \quad \forall j \in \{1, \dots, \mathcal{J}\}, \forall t \in \{t_0, \dots, T\}, \forall k \in \mathcal{P}_i \\ & \sum_{j=1}^{\mathcal{J}} x_{j,k,t} \leq \bar{x}_k \quad \forall t \in \{t_0, \dots, T\}, \forall k \in \mathcal{P}_i \end{aligned} \tag{7}$$

with $d_{\mathcal{P}_i,t} = \sum_{k \in \mathcal{P}_i} d_{k,t}$.

Numerical complexity. To calculate the expectation of the objective function over a random terminal time and random crop yields, we approximate the expected value by a sample mean. For details, we refer to section 1.4 in the Supplementary Methods. The sample mean is calculated using 50000, 100000, 150000, 150000, and 200000 generations of yield samples in case of nine, five, three, two, or one risk pools, respectively. Using generic Monte Carlo sampling of the multivariate yield distribution, the numerical complexity suffers from the curse of dimensionality, and requires in turn to limit the number of regions that can be considered. Other techniques such as Markov Chain Monte Carlo methods could further ease the requirement to consider a small set of regions.

Data availability

All results and output data can be reproduced using the code and data publicly available at <https://github.com/deleip/FoodSecurityWestAfrica/tree/master/RiskFoodSupply>. Other data sources used to support the analysis include: Standardized Precipitation-Evapotranspiration Index (SPEI): <https://hdl.handle.net/10261/202305>. Population data from UN World Population Prospects: <https://population.un.org/wpp/>. Gridded Population of the World (SEDAC): <https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-adjusted-to-2015-unwpp-country-totals-rev11/data-download>. GDHY yield data: <https://doi.org/10.1594/PANGAEA.909132>. Farm gate prices: <https://www.fao.org/faostat/en/#data/PP>.

Code availability

The food security optimization framework was implemented in Python using the Gurobi solver environment. The code is publicly available at the following GitHub Repository: <https://github.com/deleip/FoodSecurityWestAfrica/tree/master/RiskFoodSupply>.

Received: 6 October 2023; Accepted: 25 January 2024;
Published online: 24 February 2024

References

1. FAO and ECA. Africa regional overview of food security and nutrition. Addressing the threat from climate variability and extremes for food security and nutrition. (Food and Agriculture Organization of the United Nations, Accra, 2018).
2. Hall, C., Dawson, T., Macdiarmid, J., Matthews, R. & Smith, P. The impact of population growth and climate change on food security in Africa: Looking ahead to 2050. *Int. J. Agric. Sustain.* **15**, 124–135 (2017).
3. Delgado, C., Tshunkert, K. & Smith, D. Food insecurity in Africa: Drivers and solutions. *SIPRI Research Policy Paper* (2023).
4. United Nations, Sustainable Development Goal 2: Zero hunger. <https://www.un.org/sustainabledevelopment/hunger/>. accessed 16 Nov 2021.
5. HLPE. Food security and nutrition: Building a global narrative towards 2030. *Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security* (2020).
6. Stott, P. How climate change affects extreme weather events. *Science* **352**, 1517–1518 (2016).
7. Niang, I., Ruppel, O.C., Abdrabo, M.A., A. Essel., C. Lennard., J. Padgham & P. Urquhart. Africa. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [V.R. Barros., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199–1265. (2014).
8. Trisos, C. et al. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change: Africa* (Cambridge university press, 2022).
9. Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso. Food security and food production systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485–533. (2014).
10. Richardson, K. J. et al. Food security outcomes under a changing climate: Impacts of mitigation and adaptation on vulnerability to food insecurity. *Climatic change* **147**, 327–341 (2018).
11. Food and nutrition situation in the context of the COVID-19 pandemic in the Sahel and West Africa – press release. *CILSS* (June 2020). <https://go.nature.com/3kWdmf6>.
12. Lobell, D. B., Schlenker, W. & Costa-Roberts, J. Climate trends and global crop production since 1980. *Science* **333**, 616–620 (2011).
13. Choquette-Levy, N., Wildemeersch, M., Oppenheimer, M. & Levin, S. A. Risk transfer policies and climate-induced immobility among smallholder farmers. *Nat. Clim. Change* **11**, 1046–1054 (2021).
14. Dercon, S. Risk, crop choice, and savings: evidence from tanzania. *Econ. Dev. Cultural Change* **44**, 485–513 (1996).
15. Ali, Z. et al. Long-term impact of West African food system responses to COVID-19. *Nat. Food* **1**, 768–770 (2020).
16. Barrett, C. B. Covariate catastrophic risk management in the developing world: Discussion. *Am. J. Agric. Econ.* **93**, 512–513 (2011).
17. Trærup, S. L. Informal networks and resilience to climate change impacts: a collective approach to index insurance. *Global Environ. Change* **22**, 255–267 (2012).

18. UN report. Disasters cost billions in agricultural losses, poor farmers bear brunt. Accessed 17 November 2021 <https://news.un.org/en/story/2018/03/1005012> (2018).
19. Laborde, D., Lallemand, T., McDougal, K., Smaller, C. & Traore, F. Transforming agriculture in africa & asia: What are the policy priorities. *International Institute for Sustainable Development* (2019).
20. Steiner, A. et al. Actions to transform food systems under climate change. *CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)* (Wageningen, The Netherlands, 2020).
21. Nguyen, T. Insurability of catastrophe risks and government participation in insurance solutions. *Background Paper prepared for the Global Assessment Report on Disaster Risk Reduction 2013* (United Nations Office for Disaster Risk Reduction (UNISDR), Geneva, Switzerland, 2013).
22. Premand, P. & Stoeffler, Q. Do cash transfers foster resilience? Evidence from rural Niger. *Policy Research Working Paper; No. 9473. World Bank, Washington, DC* (2020).
23. FAO, IFAD, UNICEF, WFP & WHO. State of food security and nutrition in the world 2019: Safeguarding against economic slowdowns and downturns. Vol. 2019. Food & Agriculture Org. (2019).
24. African Union Commission. Africa–Regional Overview of Food Security and Nutrition 2019: Containing the damage of economic slowdowns and downturns to food security in Africa. Vol. 1. Food & Agriculture Org. (2020).
25. Bank, W. The Caribbean catastrophe risk insurance facility: providing immediate funding after natural disasters. *Operat. Innov. Latin Am. Caribbean* **2**, 1–23 (2008).
26. Jones, S. Independent Evaluation of the African Risk Capacity. Pilot Impact Country Study: Senegal. *e-Pact* (2021).
27. Linnerooth-Bayer, J. & Hochrainer-Stigler, S. Financial instruments for disaster risk management and climate change adaptation. *Clim. Change* **133**, 85–100 (2015).
28. Clarke, D. J., Mahul, O., Poulter, R. & Teh, T.-L. Evaluating sovereign disaster risk finance strategies: a framework. *Geneva Papers Risk Insurance-Issues Pract.* **42**, 565–584 (2017).
29. Clarke, D. & Mahul, O. Disaster risk financing and contingent credit: a dynamic analysis. *World Bank Policy Research Working Paper No. 5693*, Available at SSRN: <https://ssrn.com/abstract=1871589> (2011).
30. Ghesquiere, F. & Mahul, O. Financial protection of the state against natural disasters: A primer. *World Bank Policy Research Working Paper No. 5429*, Available at SSRN: <https://ssrn.com/abstract=1680722> (2010).
31. OECD and World Bank. *Fiscal Resilience to Natural Disasters: Lessons from Country Experiences*, <https://doi.org/10.1787/27a4198a-en> (OECD Publishing, Paris, 2019).
32. Gaupp, F., Pflug, G., Hochrainer-Stigler, S., Hall, J. & Dadson, S. Dependency of crop production between global breadbaskets: a copula approach for the assessment of global and regional risk pools. *Risk Anal.* **37**, 2212–2228 (2017).
33. Anshah, I. G. K., Gardebreek, C. & Ihle, R. Shock interactions, coping strategy choices and household food security. *Clim. Dev.* **13**, 414–426 (2021).
34. Capano, G. & Woo, J. J. Designing policy robustness: outputs and processes. *Policy Soc.* **37**, 422–440 (2018).
35. Hall, J. W. et al. Robust climate policies under uncertainty: A comparison of robust decision making and info-gap methods. *Risk Ana.: Int. J.* **32**, 1657–1672 (2012).
36. Ben-Tal, A., El Ghaoui, L. & Nemirovski, A. *Robust optimization*, vol. 28 (Princeton university press, 2009).
37. Fuss, S. et al. Global food security & adaptation under crop yield volatility. *Technol. Forecast. Soc. Change* **98**, 223–233 (2015).
38. FAOSTAT. Producer prices. Accessed 01 November 2022. <https://www.fao.org/faostat/en/#data/PP>.
39. Ministry of Agriculture (Liberia), M. Liberia: Invest agriculture, Accessed 01 November 2022. <https://ekmsliberia.info/document/liberia-invest-agriculture/> (2019).
40. Ben-Chendo, G., Lawal, N. & Osuji, M. Cost and returns of paddy rice production in Kaduna state. *Eur. J. Agric. For. Res.* **5**, 41–48 (2017).
41. Fall, A. A. Synthèse des études sur l'état des lieux chaîne de valeur riz en Afrique de l'ouest: Bénin, Burkina Faso, Mali, Niger et Sénégal. *Rapport final, ROPPA*, 83p (2016).
42. Sadiq, M., Yakasai, M., Ahmad, M., Lapkene, T. & Abubakar, M. Profitability and production efficiency of small-scale maize production in Niger State, Nigeria. *IOSR J. Appl. Phys.* **3**, 19–23 (2013).
43. Ba, M. N. Competitiveness of maize value chains for smallholders in West Africa: Case of Benin, Ghana and Cote D'Ivoire. *Agric. Sci.* **8**, 1372–1401 (2017).
44. United Nations, Department of Economic and Social Affairs, Population Division. World population prospects 2019: Methodology of the United Nations population estimates and projections (ST/ESA/SER.A/425) (2019).
45. Benso, M. R. et al. Design and evaluation of weather index insurance for multi-hazard resilience and food insecurity. *Nat. Hazards Earth Syst. Sci.* **23**, 1335–1354 (2023).
46. Bucheli, J., Dalhaus, T. & Finger, R. The optimal drought index for designing weather index insurance. *Eur. Rev. Agric. Econ.* **48**, 573–597 (2021).
47. Mahul, O. & Stutley, C. J. *Government support to agricultural insurance: Challenges and options for developing countries* (World Bank Publications, 2010).
48. Iizumi, T. & Sakai, T. The global dataset of historical yields for major crops 1981–2016. *Sci. Data* **7**, 1–7 (2020).
49. FAO. World food and agriculture-statistical yearbook 2020. *World Food and Agriculture-Statistical Yearbook* (2020).
50. Vittis, Y., Folberth, C., Bundle, S.-C. & Obersteiner, M. Restoring nature at lower food production costs. *Front. Environ. Sci.* **9**, 672663 (2021).
51. Ghosh, R. K., Gupta, S., Singh, V. & Ward, P. S. Demand for crop insurance in developing countries: New evidence from india. *J. Agric. Econ.* **72**, 293–320 (2021).
52. Ermolieva, T. et al. Integrated management of land use systems under systemic risks and security targets: a stochastic global biosphere management model. *J. Agric. Econ.* **67**, 584–601 (2016).
53. Leisner, C. P. Climate change impacts on food security-focus on perennial cropping systems and nutritional value. *Plant Sci.* **293**, 110412 (2020).
54. Devereux, S. Social protection for enhanced food security in sub-saharan africa. *Food Policy* **60**, 52–62 (2016).
55. Nhamo, L. et al. Cereal production trends under climate change: Impacts and adaptation strategies in southern africa. *Agriculture* **9**, 30 (2019).
56. Lal, R. Sustainable intensification for adaptation and mitigation of climate change and advancement of food security in Africa. In *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa* (eds Lal, R. et al.) (2015).
57. Dupraz, C. L. & Postolle, A. Food sovereignty and agricultural trade policy commitments: how much leeway do west african nations have? *Food Policy* **38**, 115–125 (2013).
58. Hochrainer-Stigler, S. & Reiter, K. Risk-layering for indirect effects. *In. J. Disaster Risk Sci.* **12**, 770–778 (2021).
59. Cordero, L., 2021. Appraisal Program Information Document (PID) - Fourth Disaster Risk Management Development Policy Loan with a Catastrophe-Deferred Drawdown Option - P177125 (English), *World Bank Group. United States of America*. Retrieved from <https://policycommons.net/artifacts/1819581/appraisal-program-information-document-pid/2557426/> (2021).
60. Puma, M. J. et al. A developing food crisis and potential refugee movements. *Nat. Sustain.* **1**, 380–382 (2018).

61. Zhang, D. & Broadstock, D. C. Global financial crisis and rising connectedness in the international commodity markets. *Int. Rev. Financial Anal.* **68**, 101239 (2020).
62. Janssens, C. et al. A sustainable future for Africa through continental free trade and agricultural development. *Nat. Food* **3**, 608–618 (2022).
63. Balineau, G., Bauer, A., Kessler, M. & Madariaga, N. *Food Systems in Africa: Rethinking the Role of Markets* (World Bank Publications, 2021).
64. Miah, M., Abdullah, H. & Jeong, C. Exploring standardized precipitation evapotranspiration index for drought assessment in Bangladesh. *Environ. Monit. Assess.* **189**, 1–16 (2017).
65. Tam, B. et al. CMIP5 drought projections in Canada based on the standardized precipitation evapotranspiration index. *Can. Water Resour. J./Revue Canadienne des ressources hydriques* **44**, 90–107 (2018).
66. Kaufmann, L. & Rousseeuw, P. Clustering by Means of Medoids. In *Proc. Statistical Data Analysis Based on the L1 Norm Conference*, 405–416 (Neuchatel, 1987).
67. El-Sappah, A. H. et al. Heat stress-mediated constraints in maize (zea mays) production: challenges and solutions. *Front. Plant Sci.* **13**, 879366 (2022).
68. CILSS. *Landscapes of West Africa – A Window on a Changing World*. (U.S. Geological Survey, 2016).
69. Harrison, P. World agriculture: towards 2015/2030: Summary report. *Food and Agriculture Organization of the United Nations* (2002).
70. Savage, S. The flaw of averages. *Harvard Bus. Rev.* **80**, 20–21 (2002).
71. Gitz, V., Meybeck, A., Lipper, L., Young, C. D. & Braatz, S. Climate change and food security: Risks and responses. *Food and Agriculture Organization of the United Nations (FAO) Report* **110** (2016).
72. OECD, Food, and Agriculture Organization of the United Nations *Building Agricultural Resilience to Natural Hazard-induced Disasters* (2021). <https://www.oecd-ilibrary.org/content/publication/49eefdd7-en>.
73. Ermoliev, Y. M., Ermolieva, T. Y., MacDonald, G. J. & Norkin, V. I. Stochastic optimization of insurance portfolios for managing exposure to catastrophic risks. *Annal. Oper. Res.* **99**, 207–225 (2000).
74. Van den Bergh, J. C. Externality or sustainability economics? *Ecol. Econ.* **69**, 2047–2052 (2010).
75. Birge, J. R. & Louveaux, F. *Introduction to stochastic programming* (Springer Science & Business Media, 2011).
76. Nickerson, R. S. *Cognition and chance: The psychology of probabilistic reasoning* (Psychology Press, 2004).
77. Embrechts, P., Klüppelberg, C. & Mikosch, T. *Modelling extremal events: for insurance and finance*, vol. 33 (Springer Science & Business Media, 2013).
78. Beguería, S., Vicente-Serrano, S. M. & Angulo-Martínez, M. A multiscalar global drought dataset: the SPEIbase: a new gridded product for the analysis of drought variability and impacts. *Bull. Am. Meteorol. Soc.* **91**, 1351–1354 (2010).

Acknowledgements

M.W. acknowledges funding received from the Oxford Martin Programme on Systemic Resilience.

Author contributions

D.L. was involved in the conception of the study, development of the optimization framework, model coding and simulation, analysis of the results, and revising of the paper draft. E.R. was involved in the conception of the study, development of the optimization framework, analysis of the results, and revising of the paper draft. M.W. was involved in the conception of the study, development of the optimization framework, analysis of the results, writing of the first paper draft, and revising of the paper. Correspondence and requests for materials should be addressed to M.W. (matthias.wildemeersch@eci.ox.ac.uk).

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43247-024-01242-9>.

Correspondence and requests for materials should be addressed to Matthias Wildemeersch.

Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Martina Grecequet. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024