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ORIGINAL PAPER

Assessing populations exposed to climate change: a focus on Africa in a global context

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Abstract

The recent debate on population dynamics and climate change has highlighted the importance of assessing and quantifying disparities in populations' vulnerability and adopting a forward-looking manner when considering the potential impacts of climate change on different communities and regions. In this article, we overlay demographic projections based on the Shared Socioeconomic Pathways and climate change projections derived from the Representative Concentration Pathways. We focus on populations that are likely to be the most exposed to climate change in the future, namely, African populations in a comparative global context. First, we estimate the share of populations living in rural areas, who would be more dependent on agriculture, as one of the economic sectors mostly affected by climate change. Second, we explore how climate change would worsen the condition of populations living below the poverty line. Finally, we account for low levels of education, as further factors limiting people's adaptation ability to increasingly adverse climate circumstances. Our contribution to the literature on population, agriculture, and environmental change is twofold. Firstly, by mapping the potential populations exposed to climate change, in terms of declining agricultural yields, we identify vulnerable areas, allowing for the development of targeted strategies and interventions to mitigate the impacts, ensure resilience, and protect the population living in the most affected areas. Secondly, we assess differentials in the vulnerability of local populations, showing how African regions would become among one of the most exposed to climate change by the end of the century. The findings support the targeting of policy measures to prevent increased vulnerability among already disadvantaged populations.

Keywords Climate change · Exposed populations · Vulnerable populations · Projections

Introduction

According to the 2023 Global Report on Food Crises, "humanity's failure to make progress toward Sustainable Development Goal 2 to end hunger" (FSIN, 2023—pp 6) must be recognised. Up to 153.4 million people are expected to

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Extended author information available on the last page of the article experience high levels of acute food insecurity in 2023, but estimates may likely increase due to a series of shocks from natural hazards, such as the unexpected tropical cyclones in Madagascar, Malawi, and Mozambique; the earthquakes in Syria; and the cumulative effects of prolonged droughts in the Horn of Africa. Although several factors determine food insecurity worldwide, such as conflict and policy instability (e.g., the war in Ukraine), economic shocks (together with the impacts of COVID-19), in 2022, weather extremes remained the main factors affecting more than 56 million people (FSIN, 2023). Below-average rainfall, along with tropical storms and persistent drought, impacted agriculture activities, including crop losses and the displacement of large rural populations, affecting food production and access to resources for a large proportion of the population.

Climate change is expected to have an increasingly significant impact on agriculture yields worldwide (IPCC, 2014). While the increase in carbon dioxide in the atmosphere could have a positive impact on crop yields, it is probable that the consequences stemming from elevated temperatures, changes in precipitation patterns, and potentially more frequent extreme events like droughts and floods will converge to reduce crop yields and heighten production risks in various regions across the globe, particularly in countries with an economic system relying substantially on agriculture, like Africa (Tubiello & Fischer, 2007). There, climate change will likely threaten the food security and livelihoods of rural populations, and contribute to an increase in the level of exposure and vulnerability to climate change in the decades to come (Serdeczny et al., 2017). O’Neill et al. (2022) provided an assessment of the key risks associated with climate change across regions and sectors, and how future developments and adaptation efforts can influence them. In line with the definitions adopted by the Intergovernmental Panel on Climate Change (IPCC), exposure is assessed by the presence of populations in places affected by climate change, while vulnerability is a measure of the ability of exposed populations to cope with the adverse consequences of climate change (IPCC, 2012; Turner et al., 2003). Risks associated with climate change are defined as “economic impacts across scales, including impacts on gross domestic product (GDP), *poverty*, and livelihoods, as well as the exacerbating effects of impacts on socio-economic inequality between and within countries” (O’Neill et al., 2022, pp. 173). The International Monetary Fund (2021) assessed that at global level, the warming of around 4 °C could have led to a ~ 3% drop in annual GDP.

Studies have demonstrated that environmental stressors are highly context specific (Piquet, 2020), recognising African populations as among the most vulnerable in the world (IPCC, 2012; UNEP, 2017). The main reasons of this primacy are thought to lie in the socio-economic conditions of populations and the high economic dependence on agriculture, which is one of the main economic sectors for population subsistence, particularly in tropical and subtropical regions, where fast-growing populations, affected by poverty and recurrent environmental shocks, may have low adaptive capacity (Zarnetske et al., 2021). Yet, few empirical analyses have been able to systematically compare the future effects of climate change on the population at global level, highlighting the disadvantage of African populations compared with the rest of the world.

Against this backdrop, our research aims to estimate how many people at global level could be exposed to climate change up to the end of the century, under hypothetical demographic and climate scenarios. We seek to fill the gaps by using harmonised datasets on population and environmental conditions at a granular level between 1975 and 2015, enabling us to assess historical trends and project potential futures for all world regions. The severity of climate change impacts is assessed based on the interactions between extreme weather events and climate hazards on the one hand, and the exposure and vulnerability of environmental systems and the population, on the other (O'Neill et al., 2020a, b). The latter is not and will not be homogenously distributed across regions, with some local areas and specific populations more affected than others, depending on their level of vulnerability. Within this framework, we quantify the differentials across populations worldwide in a comparative way. Specifically, our approach relies on the combination of two independent sets of projections: the shared socioeconomic pathways (SSPs), which forecast the socio-economic evolution of societies based on certain narratives about the future (O'Neill et al., 2017), and the representative concentration pathways (RCPs), used to model greenhouse gas concentration and land use, which translate into different future climate trajectories (van Vuuren et al., 2011). We intersect projections of socio-economic indicators from the SSPs with projections of climate change stemming from different greenhouse gas emission targets of the RCPs.

Our contribution to the *Population Environment Special Issue on Population, Food and Environment* is twofold. First, we assess the share of populations living in rural territories where agriculture represents one of the main human activities and one of the economic sectors most dependent on natural systems and most exposed to climate change. Our choice to focus on rurality is consistent with a growing body of studies that recognise agriculture as one of the main channels through which climate change may shape migration/mobility behaviours (Tubiello et al., 2002). We therefore quantify differences in impact for African regions, where agriculture makes a significant contribution to the gross domestic product (GDP)—around 20%—and is the main source of employment in most countries, comparing them to other world regions. Goedde et al. (2019) estimated that 60% of the population of sub-Saharan Africa is made up of small-scale farmers. Second, we take into account socio-economic factors that would increase the vulnerability of the population: i) *poverty*: people living below the poverty line would suffer additional burdens for climate variability and extreme conditions (Hallegatte & Rozenberg, 2017); ii) *education*: climate risks are strongly linked to inequalities generated by differential vulnerability and capacity to adapt such as education (Oppenheimer et al., 2014; Lutz et al., 2014; O'Neill et al., 2020a, b). Following these perspectives, we unravel the disadvantage of African populations in a comparative perspective.

This paper is structured as follows. The second section describes the approach used to project populations at a high geographical granularity, under the assumptions defined by the SSPs and RCPs. The third section presents the results of our analysis, describing the potential impacts of climate change on agriculture, which is one of the crucial economic sectors in many countries, and assessing the vulnerability of the population along the characteristics of place of residence, poverty, and education levels. The final section examines possible policy implications of our findings and how the limitations of the analysis can be addressed in future research.

Data and methods

To explore possible climate change trajectories over the coming decades, we adopt the RCP scenarios which provide potential future patterns of greenhouse gas emissions. Since 2011 (van Vuuren et al., 2011), RCPs have formed the basis of climate change research and impact modelling, indicating the potential changes in the energy balance of the earth system in relation to increases in anthropogenic greenhouse gas emissions.

Out of the four existing RCPs, we select two scenarios: i) the RCP2.6 scenario, which projects an increase of the global temperature below 2 °C by the end of the century (IPCC, 2014), in line with the Paris agreement,[1] the first legally binding international treaty on climate change; ii) the RCP6.0 scenario, which corresponds to a global warming of around 3.5 °C by 2100. Our methodological choice is motivated by the need to present two opposing global warming trajectories: while RCP2.6 explores the possibility of keeping global warming under control and within a stringent target, RCP6.0 represents a stabilisation pathway in the longer term.

Given that the analysis focuses on the effect of climate change on food security, for the two selected RCP scenarios, we consider the agriculture sector as the most relevant economic sector and use the datasets available from the Agricultural Model Inter-comparison and Improvement Project (AgMIP). The AgMIP project was part of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). It was initiated to improve modelling capacities based on common protocols and unified frameworks (Byers et al., 2018; Lange et al., 2020) for the modelling of habitat degradation and crop yields, enabling the comparison of simulation experiments (Müller et al., 2019).

More specifically, changes in agriculture are estimated for the four main crops that together occupy nearly 50% of the planet's agricultural land (Martin et al., 2019): soybean, rice, maize, and wheat. Although projected impacts vary widely across territories, reductions are expected for all four crops. Specifically, without adaptation to climate change, regions could lose about two-thirds of wheat productivity by the end of the twenty-first century (Adhikari et al., 2015; Natale et al., 2021). For rice, maize, and soybean, yield reductions are expected, mostly in East African regions (Adhikari et al., 2015).

Our empirical strategy is implemented in three main steps, as follows. Firstly, we consider two global climate models (GCM), the HadGEM2-ES and IPSL-CM5A-LR.[2]

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[1] The Paris Agreement was adopted by 196 Parties at the UN Climate Change Conference in Parison 12 December 2015. It entered into force on 4 November 2016.

[2] The HadGEM2-ES has been developed by the Met Office Hadley Centre for Climate Change in the United Kingdom (Collins et al., 2008), whereas the IPSL-CM5A-LR is a family of climate models developed by the Institute Pierre Simon Laplace Climate Modeming Center in France (Dufresne et al., 2013).

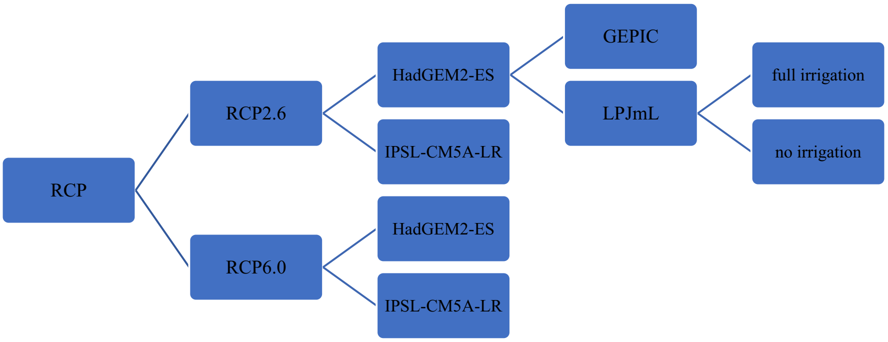

Fig. 1 RCP selected scenarios and related climate and impact models

The main reason for choosing these two models is that the trends in their precipitation forecasts differ substantially in terms of magnitude (Schewe et al., 2014). Furthermore, both models are widely recognised (Frieler et al., 2017) and adopted, due to their finer resolution (0.5 grid degree) compared to other models using a regional scale. Secondly, results derived from global climate models become inputs for two impact models (GEPIC and LPJmL[3]). Thirdly, we take account of irrigation use (full irrigation and no irrigation). For each crop and RCP, we use the mean of the eight models. The results are finally weighted based on the irrigated surfaces reported by the *Global data set of monthly irrigated and rainfed crop areas around the year 2000* (MIRCA).[4] For instance, if a grid has 100% of the rice area with irrigation, we exclude the option "no irrigation" from the simulation models; if a grid area has 50% of rice with irrigation and 50% without irrigation, results are weighted equally. It should be noted that neither change in irrigation conditions nor progress in the use of agricultural technology is considered. For the scope of the analysis, results obtained at grid level are aggregated at country/continental level, covering the past trends for the period 1975–2015, and projections for the period 2020–2100. To derive anomalies in the period 2020–2070, we calculated mean deviations from the past trends over 5-year intervals.

To explore future population dynamics, we overlay the RCPs (Fig. 1) with SSPs scenarios (Table 1). The SSPs are narratives (O'Neill et al., 2017), describing demographic and urbanisation dynamics in relation to the socio-economic challenges societies may face in mitigating climate change and adapting to its impacts. The first scenario "SSP1: sustainability: taking the green road" [SSP1 (sustainability)] identifies the path to sustainability based on optimistic scenario assumptions, where

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[3] The GEPIC (GIS-based Environmental Policy Integrated Climate) is a crop growth model (Liu et al., 2007) characterises by its high flexibility for simulating different crops under a variety of climatic conditions. The LPJmL is a global water and crop model designed by Potsdam Institute for Climate Impact Research to simulate vegetation composition and distribution as well as stocks and land–atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems (Bondeau et al., 2007).

[4] https://www.uni-frankfurt.de/45218023/MIRCA

Table 1 SSP scenario assumptions

		Demographic and urbanisation patterns			
Scenario	Definition	Urbanisation	Fertility	Mortality	Migration
SSP1	Sustainability	Fast—urban densification	Low	Low	Medium
SSP2	Middle of the road	Medium urbanisation process	Medium	Medium	Medium
SSP3	Regional rivalry	Slow—intermediate levels of agglomeration	High	High	Low
SSP4	Inequality	Fast urbanisation process	High	High	Medium
SSP5	Fossil-fueled development	Fast—sprawling new urban areas	Low	Low	High

improvements in environmental and human well-being are achieved jointly. Overall, fertility and mortality decline lead to low population growth—and decline by 2055—in a world in which humans face weak challenges in terms of climate change adaptation and mitigation. The global population is projected to remain below 9 billion for the entire century.

The second scenarios "SSP2: middle of the road" [SSP2 (middle of the road)] represents the baseline scenario, consisting mainly of a continuation of historical trends, with intermediate challenges for adaptation and mitigation. The world population would reach a peak in 2075 at 9.7 billion and start declining thereafter.

In the third scenario "SSP3: regional rivalry: a rocky road" [SSP3 (regional rivalry)] slow economic development characterised by growing inequality, rising nationalism, and weak institutions worldwide is expected. Demographic and urbanisation transitions would stagnate, limiting population's ability to mitigate and adapt to environmental degradation. Population growth would continue unabated throughout the century, leading to a population of 13.7 billion by 2100.

The fourth scenario "SSP4: inequality: a road divided" [SSP4 (inequality)] formulates different trajectories across and within countries. In middle- and high-income countries, elites control environmental policies with weak mitigation strategies. While fast urbanisation is expected at global level, adaptation remains challenging for populations living in areas with low levels of development. The resulting world population is close to that obtained in SSP2, but with higher population growth in low-income countries and lower growth in high-income countries.

In the final scenario "SSP5: fossil-fuelled development: taking the highway" [SSP5 (fossil-fuelled development)] globalisation and the economic success of industrialised and emerging countries would ensure the achievement of human development goals. However, a trade-off between relatively low adaptation challenges and high mitigation challenges would persist due to a high fossil fuel dependency. Urbanisation would be characterised by the sprawl of new urban areas. Population growth rapidly turns negative, and the population trajectory resembles that of SSP1.

Previous studies have notably used the SSPs to develop projections including population by education levels (KC & Lutz, 2017), urbanisation patterns (Jiang & O'Neill, 2017), and economic indicators, such as economic growth (Dellink et al., 2017) and income inequality (Rao et al., 2019). We use the projections that are derived from the narratives and related assumptions on the level of fertility, mortality, migration, and urbanisation patterns; the projections were carried out at national level and downscaled to the geographical granularity harmonised with the RCP scenarios (Jones & O'Neill, 2016).

The approach has the advantage of combining changes in population dynamic and the climate; thus, vulnerability levels are assessed on the development of both socio-economic adaptation and mitigation with environmental pathways. Conversely, the method has the limitation of rendering untraceable effects due exclusively to demographic and socio-economic factors, compared with impacts generated by environmental conditions. Yet, for prospective assessments, the use of downscaled projections and impact models is largely recommended (Puig, 2023), particularly when conducting analyses, whose primary objective is to identify locations where populations would potentially be exposed to increased vulnerability.

Empirical strategy

As mentioned by O'Neill et al., "SSPs and RCPs are 'completed' when combined and applied in individual studies where climate risks and adaptation or mitigation strategies are assessed" (O'Neill et al., 2020a, b, pp. 1074). We cross-reference the SSPs and RCPs to set an integrated research framework that allows us to observe the following levels of population vulnerability: exposure to climate change, rurality, poverty, and education.

Exposure to climate change is defined as the number of people living in areas where food insecurity is projected to increase since soybean, rice, maize, and wheat productivity would fall below the 20% thresholds, compared to the 5-year interval *mean* calculated for the period 1975–2015. Future changes in productivity are therefore simply linked to climate scenarios; this implies that technological and irrigation transformations are assumed to remain as observed in 2000. All calculations are carried out at grid level then summed to macro-region level. The source for the exposed population at grid level is Jones and O'Neill (2016) whose estimates are consistent with the SSPs. Figure 2 illustrates exposed populations across macro-regions in 2100, when different thresholds are adopted (according to SSP2 and RCP6.0). The vertical line represents the selected threshold in this study (20%) which lies at the inflection point of the curve between a lower exposure threshold and a higher one. If we take the case of Africa, the 10% decrease threshold is associated with a 65% share of exposed population in 2100, while the 30% decrease threshold is associated with the 10% share of exposed population, supporting the choice of a 20% decrease with about 30% of exposed population.

Rurality is defined as the number of people living in grids classified as rural areas, as resulting from modelling scenario assumptions developed by Jiang and O'Neill (2017). Although farmers can benefit to some extent from the positive effects of higher temperatures and CO^2 fertilisation on crop growth (Tubiello et al., 2002) and/or can adapt to drought by changing crops, management practices, planting seasons, and introducing new irrigation systems, these possibilities are limited in low-technology farming systems, especially in subtropical and tropical areas. Also,

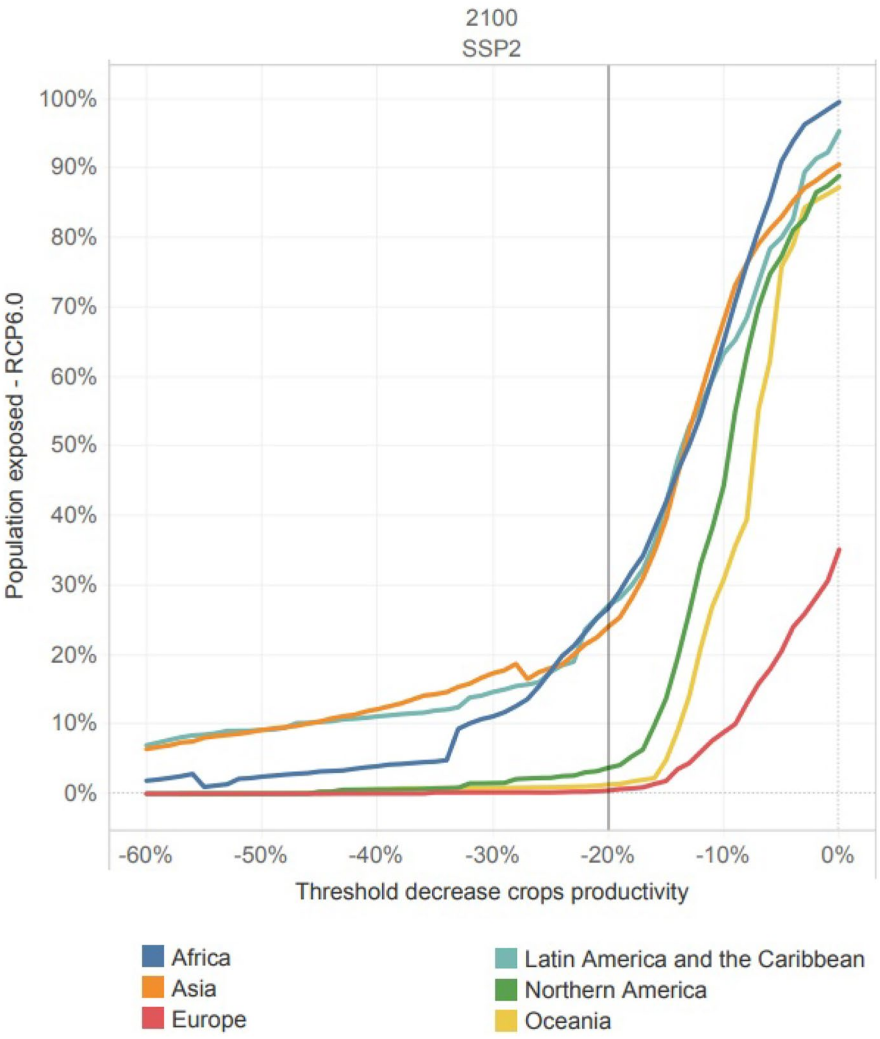

Fig. 2 Estimates of exposed population by threshold of decrease in agriculture (crops), 2100, SSP2, and RCP6.0

trade in food commodities to compensate for declining agricultural productivity will not solve local livelihood issues, especially for populations dependent on subsistence farming. For these communities, a few consecutive years of reduced harvest leave little choice but to abandon the land and move to other areas (Morton, 2007).

Poverty is measured as the percentage of the exposed population living below the poverty line of $1.9 per capita per day. By limiting the access of individuals and communities to economic resources, poverty is one of the main economic risk factors (Hallegatte & Rozenberg, 2017) to be faced in the event of climate change, limiting adaptive capacity. The poverty thresholds are presented in 2015 purchasing power parity (in $) using World Bank definitions. Grid-level poverty values correspond to national GDP estimates provided by Dellink et al. (2017) for the five SSPs.

Low education is defined as the share of populations with primary level of education or less (Oppenheimer et al., 2014). Education is recognised as one of the main factors enhancing the adaptive capacity of people to climate change (Feinstein & Mach, 2020; Striessnig & Lutz, 2016) and reducing vulnerability both at the individual and aggregate levels (Muttarak & Lutz, 2014). Conversely, lack of education can impair people's ability to adapt to climate change and counter adversities. Grid-level educational attainment values are based on estimates at national level provided by Lutz et al. (2018), following the SSPs, and available in Wittgenstein Centre for Demography and Global Human Capital (2018).

Results

We present projections of changes in agriculture according to the selected scenarios, RCP2.6 and RCP6.0, over the period 2020–2100, plotting the median change in productivity for the major crops (wheat, rice, maize, and soybean) across cells. Figure 3 shows the results aggregated by world macro-region.

Overall, we note that projected impacts on crop yields for maize and wheat are more pronounced across the regions than for soya and rice. These results are in line with Zhao et al. (2017), reporting that 1% increase in global mean temperature would, on average, reduce global yields of maize by 7.4%, wheat by 6.0%, rice by 3.2%, and soybean by 3.1%.

Under the RCP6.0 scenario, among the regions expected to experience the worst impacts in terms of crop yields, Western Africa would record a 19% decrease for maize and 13% for wheat. In Eastern Africa, both RCPs foresee a slight increase in future soybean yields, whereas no significant change is expected for rice

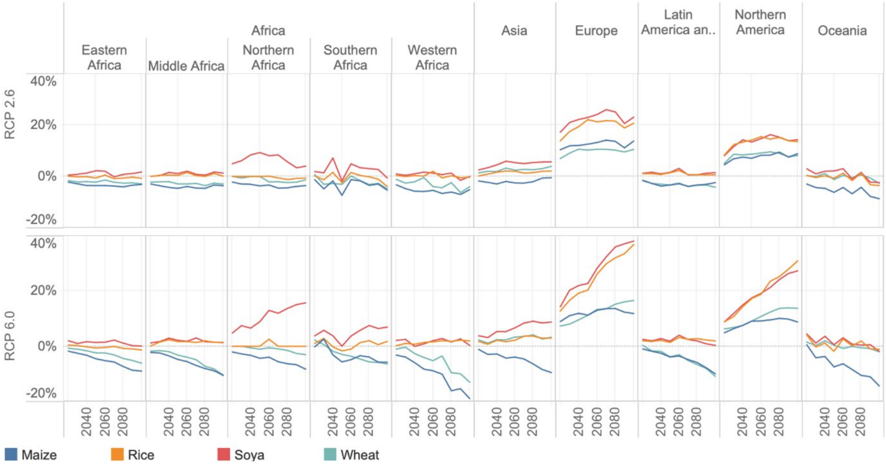

Fig. 3 Change (%) of crop productivity according to RCP2.6 and RCP6.0 scenarios for the period 2020–2100 (median values), African regions and world macro regions

productivity; on the contrary, both scenarios foresee a decrease in wheat yields, and under RCP2.6, in maize yields as well. The worst impacts are projected for maize yields (large decrease) under the RCP6.0 scenario. In Central Africa, a slight increase is foreseen for soybean yields under both RCPs, and this applies to rice under RCP6.0 scenario, whereas no significant change is predicted for rice yields under RCP2.6. A slight decrease is expected for wheat and maize yields under RCP2.6, while large decreases are projected for rice and maize under RCP6.0 scenario. In Northern Africa, a strong increase is predicted for soybean yields under RCP2.6 scenario and an even stronger increase should be anticipated for RCP6.0 scenario. Under both scenarios, no significant change is expected for rice, whereas a slight decrease is projected for wheat. Finally, a slight decrease is also forecasted for maize yields under the RCP2.6 scenario, while a larger decrease is anticipated under the RCP6.0 scenario. For Southern Africa, a slight increase is projected for soybean yields under RCP2.6, whereas an even larger increase is expected under RCP6.0. For rice, no significant change is expected under both RCP scenarios, while a slight decrease is projected for wheat in RCP2.6 scenario and an even larger decrease under RCP6.0. For maize, a large decrease is forecasted in both RCP2.6 and RCP6.0 scenarios.

Compared to the African regions, decline in yields are lesser in Latin American regions (– 4% for wheat and – 2% for maize) and Oceania (– 2% for wheat and – 9% for maize) under RCP2.6 scenario. RCP6.0 aggravates the situation for both continents (– 11% for wheat and – 10% for maize in Latin American regions and – 2% and – 14% in Oceania). By contrast, when looking at Asia and European continents, significant increases are expected in future soybean and rice yields under the RCP2.6 scenario (6% and 2% in Asia, 23% and 21% in Europe). Based on the RCP6.0 scenario, the increase is projected to raise-up in both continents (9% for soya and 3% for rice in Asia and 38% and – 37% in Europe).

These results are in line with the previous studies based on a combination of historical agricultural production and weather data (Schlenker & Lobell, 2010).

Population exposure

Table 2 summarises the results in 2100 by macro-region; population sizes by macro-region are derived from the aggregation of local populations at the level of geographic grid cells (i.e., about 56 km^2).

Compared to the other continents, by 2100, the population exposed to decrease in agricultural productivity of more than 20% would mainly live in Asia, under the more favourable RCP2.6 scenario (between 200 and 600 million depending on the SSPs) and both in Africa and Asia, under the RCP6.0 scenario.

According to the SSP1 (sustainability) and SSP5 (fossil-fuelled development) scenarios, about 500 million people in Africa and 747 million in Asia would be exposed to decrease in agricultural productivity of more than 20%. The SSP3 (regional rivalry) scenario doubles this number on both continents (1.1 billion in Africa and 1.7 billion in Asia).

Table 2 Populations (share and absolute number) exposed to decrease in crop productivity of more than 20%, all SSPs and RCP2.6 and RCP6.0, 2100, African regions and macro regions

		SSP1		SSP2		SSP3		SSP4		SSP5	
		RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0
Africa	Eastern Africa	0.52%	6.64%	0.55%	6.67%	0.61%	6.69%	0.56%	6.82%	0.49%	6.51%
		3,273,141	41,452,454	5,051,381	61,110,026	8,691,623	95,187,481	7,757,797	93,822,509	2,913,755	38,854,301
	Middle Africa	0.62%	19.55%	0.67%	20.03%	0.66%	20.21%	0.63%	19.70%	0.59%	19.31%
		1,600,398	50,454,466	2,296,964	68,677,640	3,017,079	92,839,691	2,842,666	88,578,451	1,518,415	49,474,754
	Northern Africa	3.88%	34.66%	4.19%	33.19%	4.20%	28.59%	6.37%	41.68%	4.03%	35.52%
		8,639,274	77,239,480	12,756,517	101,143,234	19,766,006	134,559,690	17,812,890	116,527,489	8,640,715	76,235,254
	Southern Africa	3.57%	8.05%	3.46%	7.95%	3.30%	7.88%	3.76%	8.24%	3.55%	8.03%
		2,022,696	4,562,552	2,353,645	5,409,943	2,741,848	6,550,910	1,849,642	4,053,159	2,136,128	4,824,373
	Western Africa	2.87%	44.57%	3.17%	46.72%	3.53%	48.18%	3.24%	47.38%	2.73%	44.22%
		20,168,079	313,600,882	31,701,780	466,557,996	53,273,888	728,149,511	47,593,324	695,729,546	18,595,446	301,271,567
Asia		7.98%	22.69%	8.26%	24.04%	8.73%	25.62%	10.85%	30.29%	7.78%	22.18%
		262,705,259	747,254,139	364,360,852	1,059,711,387	584,675,107	1,716,048,680	441,067,966	1,231,472,875	257,555,457	733,957,850
Europe		0.05%	0.47%	0.05%	0.50%	0.04%	0.63%	0.04%	0.50%	0.06%	0.43%
		326,049	3,087,094	333,079	3,533,229	212,476	3,487,232	239,552	2,673,182	513,028	3,978,091
Latin America and the Caribbean		5.06%	25.70%	4.90%	25.97%	4.54%	26.39%	4.28%	26.33%	5.32%	25.64%
		24,723,259	125,613,272	33,064,628	175,198,435	49,149,973	285,912,930	24,307,558	149,544,506	24,313,875	117,272,959
Northern America		0.08%	3.69%	0.08%	3.73%	0.07%	4.02%	0.08%	3.72%	0.08%	3.64%
		400,578	19,126,809	392,171	19,036,944	209,453	11,651,560	304,544	15,062,318	646,530	28,976,699
Oceania		0.28%	1.06%	0.27%	1.03%	0.18%	0.80%	0.23%	0.98%	0.33%	1.19%
		167,965	626,596	174,697	672,018	90,423	404,239	139,258	603,693	290,728	1,037,546

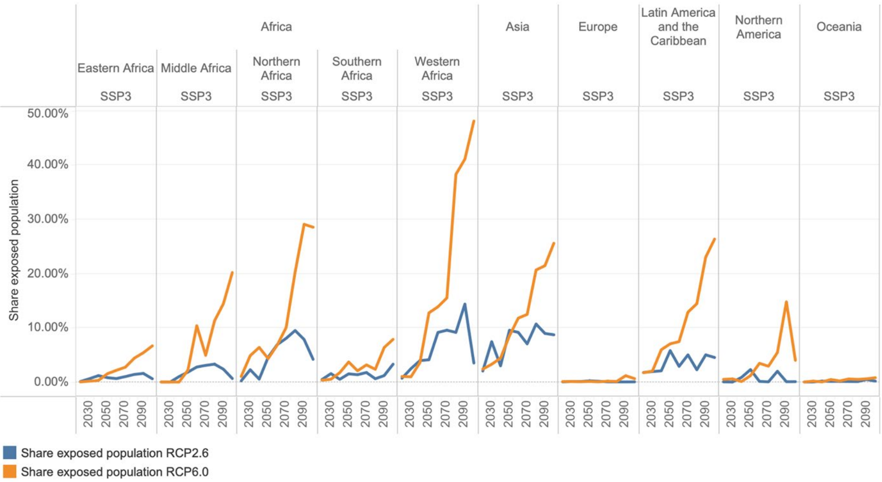

Fig. 4 Share of populations exposed to a 20% decrease in crop productivity, according to SSP3 (regional rivalry) and RCP scenarios in African sub-regions and other continents, 2020–2100

Looking at the African continent, most of the exposed population would reside in Western Africa; according to SSP3 (regional rivalry) and RCP6.0, 48% of the population in this region (728 million) would experience a decrease in agricultural productivity of more than 20%. In the case of Western Africa under SSP3 (regional rivalry), the share of exposed population would increase by 44 percentage points, under the more pessimistic RCP6.0 scenario compared to RCP2.6, the more optimistic scenario.

When examining the RPC6.0 climate scenario, the change of assumptions on socio-economic pathways between SSP1 (sustainability) and SSP3 (regional rivalry) generates an increase of 3 percentage points in the share of populations exposed to the decrease in agricultural productivity of more than 20%.

Over the entire projection period (Fig. 4), the share of population exposed to a decrease in agricultural productivity of more than 20% is projected to rise more in Western Africa than in the rest of world, expanding from less than 4% in 2040 to almost 50% in 2100. The increase would also be substantial in Northern Africa (from 4 to 28%).

Vulnerable rural populations

The share of the rural population exposed to a decrease in agricultural productivity of more than 20% would remain below 5% on all continents under most of the SSP scenarios and both RCP2.6 and RCP6.0, except in Africa and Asia under SSP3 (regional rivalry) and RCP6.0. This is most likely due to the urbanisation transition process that is foreseen at the global level. However, Table 3 shows an increased exposure under the RCP6.0 scenario, especially for SSP1 (sustainability) and SSP3 (regional rivalry), with the latter being associated with a share of populations in rural areas and exposed

Table 3 Rural populations (share and absolute number) exposed to decrease in crop productivity of more than 20%, all SSPs and RCP2.6 and RCP6.0, 2100, African regions and macro regions

		SSP1		SSP2		SSP3		SSP4		SSP5	
		RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0
Africa	Eastern Africa	0.00%	1.00%	0.00%	2.00%	0.00%	4.00%	0.00%	1.00%	0.00%	1.00%
		704,991	6,213,925	1,956,022	20,043,633	6,217,182	55,647,853	1,520,784	13,144,628	608,492	5,948,635
	Middle Africa	0.00%	2.00%	0.00%	5.00%	1.00%	11.00%	0.00%	2.00%	0.00%	2.00%
		139,604	4,763,373	753,284	18,470,798	2,722,650	49,722,984	241,413	8,191,340	132,882	4,687,123
	Northern Africa	0.00%	1.00%	1.00%	5.00%	2.00%	10.00%	0.00%	1.00%	0.00%	1.00%
		286,820	2,640,737	2,513,847	14,766,073	7,665,926	45,180,798	407,608	3,429,805	277,646	2,568,442
	Southern Africa	0.00%	1.00%	1.00%	2.00%	1.00%	3.00%	0.00%	1.00%	0.00%	1.00%
		183,746	413,300	446,522	1,037,699	905,711	2,244,605	141,114	445,495	201,154	427,104
	Western Africa	0.00%	5.00%	1.00%	14.00%	3.00%	25.00%	0.00%	5.00%	0.00%	5.00%
		2,207,808	32,604,232	13,039,808	139,737,462	38,016,507	384,853,919	5,217,304	73,149,917	2,064,961	31,299,046
Asia		0.00%	1.00%	1.00%	4.00%	3.00%	11.00%	1.00%	2.00%	0.00%	1.00%
		12,273,769	46,443,671	51,057,587	179,591,348	233,090,568	727,099,821	26,924,040	86,655,148	11,699,086	44,708,435
Europe		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
		33,635	130,430	47,156	271,031	64,324	444,179	33,167	160,500	48,190	167,045
Latin America and the Caribbean		0.00%	1.00%	0.00%	2.00%	0.00%	3.00%	0.00%	1.00%	0.00%	1.00%
		182,019	5,695,010	466,112	14,967,202	1,220,230	37,862,251	300,327	7,944,518	165,463	5,289,485
Northern America		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
		51,863	1,207,645	49,891	1,212,186	24,286	605,881	37,250	856,368	91,027	2,145,219
Oceania		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
		67,409	179,468	71,158	211,981	38,845	175,017	61,856	250,728	127,452	299,164

to a decrease in agricultural productivity of more than 20%, of around 11% in Middle Africa (50 million people) and Asia (727 million), 10% in Northern Africa (45 million), and 25% in Western Africa (385 million). These figures are consistent with the literature, which indicates that these areas, particularly those with a semi-arid Sahelian climate, are the most vulnerable to the impact of climate-change, particularly regarding food security (Defrance et al., 2020). While for the total population, most of the differences in exposure are associated with changes in climate scenarios, when considering the share of the rural population, vulnerability is also greatly influenced by assumptions about socio-economic development and urbanisation described in the SSP narratives. In the case of Western Africa, the slower urbanisation process foreseen under SSP3 (regional rivalry) scenario compared to the SSP1 (sustainability) scenario would be associated with a 20-percentage point increase in the share of the rural population exposed to the impacts of climate change. This increase is almost equivalent to the increase under the two RCPs combined with SSP3 (regional rivalry) assumptions.

Vulnerable poor populations

Extreme poverty would make people particularly vulnerable to climate change. The SSP scenarios pay special attention to the distribution of wealth within the different narratives. According to SSP3 (regional rivalry) and SSP4 (inequality), wealth inequalities remain at the level observed in the base year (2015) under SSP3 (regional rivalry) or are accentuated under SSP4 (inequality). Considering the percentage of the exposed population living below the poverty threshold of \$1.9 per capita per day, this share would be the highest in SSP4 (inequality) scenario combined with RCP6.0, particularly in Eastern Africa (1.7% corresponding to 22.8 million people) and Middle and Western Africa (1.4%, corresponding to 6.4 and 20.7 million people, respectively). Compared to the other continents (Table 4), these two African regions would stand out as having the highest share of people exposed to the risk of poverty. Nevertheless, in the case of poverty, the scenario that reports the largest impact in absolute terms of vulnerability is SSP3 (regional rivalry) scenario in Asia, representing 66 million people (1% as share).

Vulnerable low educated populations

We present results for the main relevant SSP scenarios (SSP1–SSP3) that envisage education as one of the main determining factors of population behaviours (European Commission, 2018).

Under SSP1 (sustainability) and SSP2 (middle of the road), the share of exposed population with low education would be relatively low in 2100. Specifically, it would be less than 5% in most scenarios, in all world regions (Table 5).

By contrast, the SSP3 (regional rivalry) scenario foresees a world with no education progress, the percentage of the exposed low educated population would be higher, between 5 and 10%, when the RCP6.0 assumptions are considered, especially in Asia and in Middle and Northern Africa. The exposed population in Western Africa would still account for almost 23% of the total population, meaning 345 million people in

Table 4 Populations (share and absolute number) living below the $1.9 poverty line exposed to decrease in crop productivity of more than 20%, all SSPs and RCP2.6 and RCP6.0, 2100, African regions and macro regions

		SSP1		SSP2		SSP3		SSP4		SSP5	
		RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0
Africa	Eastern Africa	0.0%	0.0%	0.0%	0.0%	0.2%	1.5%	0.2%	1.7%	0.0%	0.0%
		6	154	18,336	129,964	3,177,705	21,146,054	3,245,784	22,869,804	0	2
	Middle Africa	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.0%	1.4%	0.0%	0.0%
		0	19	7	3,066	130,433	3,328,135	178,528	6,483,618	0	0
	Northern Africa	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	1.0%	0.0%	0.0%
		0	0	0	0	182,762	826,676	578,190	2,646,596	0	0
	Southern Africa	0.0%	0.0%	0.0%	0.1%	0.3%	0.7%	0.1%	0.3%	0.0%	0.0%
		2592	5733	24,407	52,970	240,830	546,268	69,292	157,668	234	533
	Western Africa	0.0%	0.0%	0.0%	0.0%	0.1%	0.7%	0.1%	1.4%	0.0%	0.0%
		0	1	119	815	1,121,083	11,029,810	1,801,713	20,707,764	0	0
Asia		0.0%	0.0%	0.0%	0.1%	0.3%	1.0%	0.1%	0.2%	0.0%	0.0%
		0	30,026	1,099,833	3,048,761	22,237,092	66,089,104	2,284,234	6,539,136	0	5251
Europe		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		0	0	0	10	7	436	1	91	0	0
Latin America and the Caribbean		0.0%	0.0%	0.0%	0.0%	0.2%	0.8%	0.0%	0.4%	0.0%	0.0%
		0	78	52,725	153,715	2,628,496	8,205,795	197,466	2,482,536	0	134
Northern America		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		0	1	0	10	23	1346	279	14,210	0	5
Oceania		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		0	0	0	0	0	278	0	600	0	0

Table 5 Populations (share and absolute number) with low education (primary education or less) over 15 years of age exposed to decrease in crop productivity of more than 20%, SSP1-3 and RCP2.6 and RCP6.0, 2100, African regions and macro regions

		SSP1		SSP2		SSP3	
		RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0	RCP 2.6	RCP 6.0
Africa	Eastern Africa	0.000	0.000	0.001	0.010	0.003	0.035
		4482	105,151	654,817	9,114,298	4,606,315	49,207,662
	Middle Africa	0.000	0.000	0.001	0.018	0.004	0.087
		1637	36,474	379,247	6,186,787	1,821,579	39,733,755
	Northern Africa	0.000	0.001	0.001	0.003	0.012	0.061
		12,200	159,995	164,094	891,020	5,403,145	28,523,510
	Southern Africa	0.000	0.000	0.000	0.000	0.004	0.008
		647	1190	14,010	23,350	301,302	636,446
	Western Africa	0.000	0.001	0.005	0.054	0.019	0.228
		45,811	383,432	4,934,939	54,188,790	29,322,197	344,627,728
Asia		0.000	0.001	0.004	0.011	0.027	0.078
		840,003	2,194,000	16,293,536	50,225,023	179,552,663	520,439,539
Europe		0.000	0.000	0.000	0.000	0.000	0.000
		817	7,565	3,214	31,864	2,625	80,084
Latin America and the Caribbean		0.000	0.001	0.001	0.008	0.007	0.049
		116,830	641,525	800,436	5,681,262	7,889,825	53,181,434
Northern America		0.000	0.000	0.000	0.000	0.000	0.001
		1201	57,448	3960	189,145	5198	295,448
Oceania		0.000	0.000	0.000	0.000	0.000	0.000
		475	1622	2454	8871	776	16,458

2100, according to the combined SSP3 (regional rivalry) and RCP6.0 scenarios. These populations would be highly vulnerable to radical changes in their environment and likely geographically or socio-economically remote.

Discussion and conclusions

The analysis quantifies the exposed and vulnerable populations to climate change, accounting for the interactions between socio-economic and environmental conditions at local level. The figures developed in this paper should be interpreted as upper bound estimates—seen from today's perspective—of the number of people who will need to adapt to climate change impacts. Overall, results indicate that the changes in the assumptions formulated under the climate scenarios, the optimistic RCP2.6 scenario, and the pessimistic RCP6.0 scenario mainly would drive variability in the size of populations exposed to environmental conditions. Yet, the SSP scenario narratives would play a more prominent role in determining different levels of population vulnerability. SSP3 (regional rivalry) would lead to increases in both the share of exposed population living in rural areas and with low education, while the SSP4 (inequality) scenario would mainly affect the size of populations at risk of poverty.

If we consider the share of populations affected by climate change under all climate and socio-economic scenarios, the population living in African regions would reach the highest levels of vulnerability in the world, although in absolute values, the number of populations affected would be higher in Asia. The findings are in line with previous analyses on food insecurity, indicating that African populations are among the most affected by climate change (IPCC, 2012). Although over more than 50 years, cereal production and population have grown at about the same pace, since 2017 the impacts of climatic conditions contribute to increased food insecurity in many African countries (European Commission, 2018). In a long-term perspective, our results indicate that up to 48% of the total population in Western Africa, corresponding to about 728 million people, would be affected by decreases in agricultural productivity of more than 20% at the end of the century.

Moreover, some SSP scenarios indicate that the population in Africa would not only be more exposed to the impacts from climate change but also more vulnerable due to the high share of the population living in rural areas, with low levels of education and low levels of income. Comparing estimates of population vulnerability within Africa, Western Africa stands out with high levels of exposure and vulnerability in relation to population living in rural area and with low levels of education, as described by the RCP6.0 and SSP3 (regional rivalry) scenarios, while, under the assumptions of the SSP4 (inequality) scenario, Eastern Africa would produce higher shares of population exposed to the risk of poverty.

Especially in the SSP3 (regional rivalry) scenario, the high vulnerability of populations in some parts of the world could be exacerbated by the resurgence of nationalism, which would most likely constitute additional obstacles to international mobility (O'Neill et al., 2017). Given the large number of populations at risk, the needs of those who would be trapped in conditions of extreme environmental degradation and disruption must be considered. In a context of geographically differentiated impacts, the ability of populations to mitigate impacts of climate change at the global level would require change in agricultural activities, such as CO^2 fertilisation and irrigation availability to lead the increases of crop productivity, the introduction of new agricultural technologies, the diversification of the economy towards sectors less influenced by environmental conditions (Collier et al., 2008), among others.

When moving from population exposure to vulnerability, the importance of socio-economic and demographic factors in shaping future adaptive capacity should be recognised. While reducing poverty and improving education are key to enhance adaptive capacity, targeted adaptation measures are also required. This includes, for instance, addressing the specific needs and constraints of vulnerable communities, ensuring that financial resources, support mechanisms, and access to essential infrastructure and services are guaranteed.

Despite this urgent demand at the policy level, scientific results on the quantification of climate impacts are still disputed with strong criticisms (Kelman, 2019). For this reason, future research, aiming at the assessment of exposed and vulnerable populations, should face the challenge of systematic data collections at local scale—such as the lack of harmonised definitions and practices in the collection of data from communities themselves, local authorities, and relevant stakeholders—to improve the modelling ability, gauge the robustness of results, and reduce the sources of uncertainty that limit the definition of a strategical and efficient policy agenda.

The analysis developed in this paper has many limitations. First, long-range scenarios (up to 2100) are associated with high uncertainty. The uncertainty is accentuated in this case by cross-referencing several scenarios (SSP and RCP). Second, the assumption about the chosen threshold in the decline in crop yield has a large impact on the level of exposure of the population to climate change. Also, we do not allow irrigation conditions to change in the future (i.e., no adaptation of agricultural technology). While in principle with sufficient investment crops can be grown everywhere, this would however be mostly out of reach for subsistence farmers in developing countries. Third, due to the lack of detailed data, we analyse the different vulnerability factors separately, while they obviously are interlinked, e.g., poor and low educated rural populations. Additionally, for some indicators (exposure, rurality), gridded estimates are available, while for others (poverty and education), we use sources that provide data at national level, which erases some of the granularity we expect to be present. In our future research, we aim to enhance the population data by incorporating gridded spatial and socioeconomic characteristics. Although absolute figures are subject to change and highly dependent on uncertainties in population projections, climate impacts, and socio-economic conditions that are difficult to predict, we believe that our results can help in identifying present and future geographic areas of exposure and vulnerability.

Our research makes a dual contribution to the literature on population, agriculture, and environmental change. Firstly, we identify potential populations at risk of climate change impact, particularly in terms of declining agricultural yields, pinpointing vulnerable areas, enabling the development of precise strategies and interventions to mitigate the effects, enhance resilience, and safeguard the population in the most affected regions. Secondly, by assessing variations in the vulnerability of local populations, the findings underscore the importance of targeting policy measures to prevent increased vulnerability among already disadvantaged populations, particularly on the African continent which will be the most exposed to climate change at the end of the century.

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