Documentation for the Groundswell Spatial Population and Migration Projections at One-Eighth Degree According to SSPs and RCPs, 2010-2050

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Abstract

This document outlines the data and methods used to construct the Groundswell Spatial Population and Migration Projections at One-Eighth Degree According to SSPs and RCPs, 2010-2050, along with use cases, limitations, and use constraints. The data set provides spatial population projections with and without climate impacts according to different scenarios, together with projections of climate migration and identification of climate migration hotspots for 112 countries.

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We appreciate feedback regarding this data set, such as suggestions, discovery of errors, difficulties in using the data, and format preferences. Please contact:

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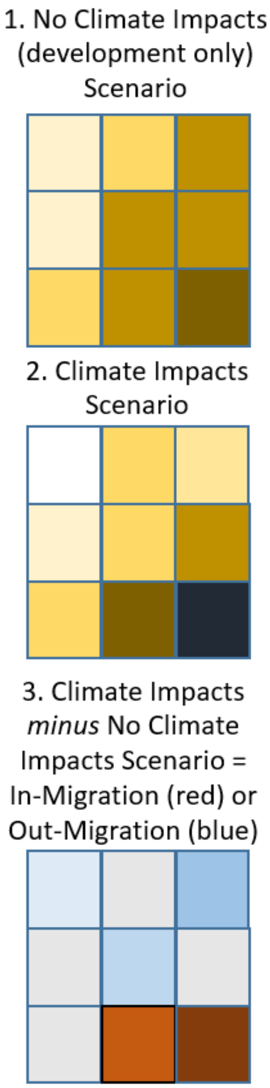
Contents

I. Introduction

The Groundswell data set provides projections of future population distribution and migration on a one-eighth degree grid (or 7.5 arc-minute which are approximately 15 kilometer grid cells at the equator) for 112 countries. The data were produced under the *Groundswell* project of The World Bank, which deployed a novel population gravity modeling approach based on gridded population data (Clement et al., 2021, Rigaud et al., 2018). The *Groundswell* methodology, led by Bryan Jones at the CUNY Institute for Demographic Research (CIDR), relies on spatial population projections with and without climate impacts using a combination of Shared Socioeconomic Pathways (SSPs) only, for the former, and SSPs and Representative Concentration Pathways (RCPs) for the latter.

The modeling work is conducted using gridded population distributions at 15 kilometer resolution projected out to 2050. The diagrams below depict a hypothetical 45km x 45km grid for a portion of a country, illustrating the modeling process for a single model run of one scenario in three steps. In steps 1 and 2, higher population densities in 2050 are represented by darker shades and lower population densities are represented in lighter shades.



In the first step, a population gravity model is used to project future population distribution for each country based on two development scenarios that are framed by the widely used SSPs: a moderate development scenario (SSP2) and an unequal development scenario (SSP4). Step 1 in the diagram presents a hypothetical population distribution for one development scenario.

In the second step, climate impacts on water availability, crops, and pasturage for two potential climate futures – low and high emissions as found in Representative Concentration Pathways (RCPs) 2.6 and 8.5 – are added to the two development scenarios, which affect the relative attractiveness of regions within countries. Areas projected to see higher water availability and productivity attract people (or retain people in place); areas projected to see lower water availability and productivity tend to repel people (or reduce their attractiveness). Areas impacted by sea level rise or storm surge are progressively "masked" out in a way that people cannot move into them in future time steps, reducing the area of inhabitable land. Step 2 in the diagram presents a hypothetical population distribution for one climate impact scenario.

In the final step, future population projections without climate impacts are subtracted from population projections with climate impacts in order to yield a map of population differences. In Step 3, positive differences are assumed to reflect net in-migration and negative differences are assumed to reflect net out-migration due to climate change impacts. It is possible to sum all positive grid cells in a country to obtain a total number of climate migrants; it is also possible to obtain net migration figures for different areas of a country (e.g. urban areas, coastal zones, etc.) by summing the positive and negative grid cells.

Using similar methods, the model can capture what is called "development migration"–that is migration that is likely to occur under the SSPs. To do that, the spatial distribution of the population is projected forward using a proportional allocation method such that each grid cell contains the same proportion of population in 2050 as it did in 2010. The principle of this scaled population is that everyone in a country stays in place, and that natural increase (births *minus* deaths) is the only mechanism driving growth in each grid cell. This, then, is subtracted from the population per grid cell projected to 2050 using the development scenarios described in step 1 above. Grid cells where there are positive differences represent areas projected to receive development migrants, and grid cells where there are negative differences represent sending areas.

The climate impacts scenarios are calibrated by looking at the relationship between past climate impacts and changes in historical population distributions between 1990 and 2015 (in five five-year increments), which generates parameter estimates used to project future changes. Multiple model runs are combined to create an average (or ensemble mean) for each scenario. Details on the methods are provided in the following sections.

The resulting data set includes the following variables for each 7.5 arc-minute grid cell:

- Baseline 2010 population counts and density per square kilometer.
- Projected population counts and densities for each time slice (2020, 2030, 2040, 2050) for the SSP only "no climate" projections, the individual model runs that include climate impacts, and ensembles for the four scenarios (SSP-RCP combinations).
- Projected climate migration for each time slice (2020, 2030, 2040, 2050) for each model run and scenario.
- Hotspots of climate migration (2030, 2040, 2050), indicating agreement among the scenarios for the areas with greatest in- or out-migration owing to climate impacts.

II. Data and Methodology

Methods here are slightly amended from those provided in Appendix B of *Groundswell Part 2: Acting on Internal Climate Migration* (Clement et al., 2021). Data users are encouraged to review this and the first report, *Groundswell: Preparing for Internal Climate Migration* (Rigaud et al., 2018), for a more complete understanding of the data inputs and results.

Input data

Three input data layers were used for this work:

1. The baseline population data used for this work is the Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals, Revision 11 (CIESIN, 2018). The gravity model was calibrated based on population change estimates for 1990-2010 derived from Gridded Population of the World, Version 3 (GPWv3): Population Count Grid (CIESIN et al., 2005) and for 2000-2010 from GPWv4.

2. Crop and water sectoral impacts data were developed under the Inter-sectoral Impacts Model Intercomparison Project (ISIMIP), managed by the Potsdam Institute for Climate Impacts Research (PIK) (https://www.isimip.org/). Further details on the models used are provided below.

3. Sea-level rise and storm surge projections were developed using NASA Shuttle Radar Topography Mission (SRTM) data for the Low Elevation Coastal Zone (LECZ) Urban-Rural Population and Land Area Estimates, Version 2 data set (CIESIN, 2013).

Additional background on inputs to the modeling are provided here.

Representative Concentration Pathways

The magnitude of future global warming can be framed through Representative Concentration Pathways (RCPs). Developed in advance of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, RCPs represent the latest generation of global scenarios for climate change research (van Vuuren at al., 2014). RCPs are trajectories of greenhouse gas concentrations resulting from human activity corresponding to a specific level of radiative forcing in 2100.[1] For example, the low greenhouse gas concentration RCP2.6 and the high greenhouse gas concentration of RCP8.5 employed in this analysis imply futures where radiative forcing of 2.6 and 8.5 watts/m², respectively, are achieved by the end of the century.[2] The additional warming implied by these RCPs is 0.3°C (RCP2.6) to 2.5ºC (RCP8.5) by 2050, with far more warming anticipated (about 4ºC) by 2100 under RCP8.5.

RCPs do not rely on a fixed set of scenario-specific assumptions on economic development, technological change, or population growth. Many different socioeconomic futures or pathways may lead to the same level of radiative forcing. This framework allows researchers to consider alternative policy decisions with combinations of social, economic, and technological change. A future with high population growth but rapid development of clean technology may achieve the same level of radiative forcing as a world characterized by low population growth but continued reliance on fossil fuels. This framework allows researchers to specify certain levels of temperature change and then explore alternative policy options to achieve greenhouse gas concentration levels consistent with the goal. A previous process (The Special Report on Emissions Scenarios [SRES]) specified the socioeconomic conditions that drove the climate change models, from which impacts were then calculated.

Low (RCP2.6) and high (RCP8.5) emissions scenarios were chosen.[3] They drive the indicators of water and agriculture sector change, which are incorporated in projections of future population distributions.

Under RCP2.6, greenhouse gas emissions begin to decline by 2020, and radiative forcing peaks by midcentury before declining to near current levels by 2100. This scenario is consistent with

[1] Radiative forcing is the measurement of the capacity of a gas or other forcing agent to affect that energy balance, thereby contributing to climate change.

[2] These RCPs are sometimes referred to in this report as “emissions scenarios.” They are actually “warming scenarios,” as they reflect the radiative forcing (in watts per square meter) associated with various emissions levels. Technically, low to moderate emissions could produce RCP8.5 should the climate system prove to be more sensitive to emissions than anticipated. Climate sensitivity reflects the degree of warming associated with a doubling of atmospheric CO_2 from pre-industrial levels. The potential range is 1.5º-4.5ºC.

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the extremely rapid adoption of cleaner technologies, slower population growth, and strong environmental policies. To achieve RCP2.6, new technologies would need to be widely deployed over the next 5-10 years. The extended RCP2.6 scenario assumes "negative emissions" by 2070, meaning that humans remove more Carbon Dioxide (CO_2) and Methane (CH_4) from the atmosphere than they release. RCP2.6 is thus consistent with the Paris Agreement, which seeks to limit temperature rise to 2°C.

RCP8.5 is characterized by increasing greenhouse gas emissions, leading to high atmospheric concentrations. It is a future consistent with scenarios of energy-intense development, continued reliance on fossil fuels, and a slow rate of technological development. Pathways characterized by rapid population growth and land use intensification (croplands and grasslands) are also consistent with this scenario. RCP8.5 implies little to no climate policy. It is characterized by significant increases in CO_2 and CH_4 emissions. Some have characterized it as at the high end of business-as-usual scenarios, and maybe even unrealistic, since it implies both larger future populations and a heavy dependence of the energy sector on coal (Hausfather & Peters, 2020). Yet this is an area of active debate within the climate community, and there are valid reasons to see RCP8.5, which tracks closely to historic emissions, as a realistic scenario out to 2050, even if beyond mid-century there are increasing uncertainties (Schwalm et al., 2020).

Shared Socioeconomic Pathways
To create scenarios illuminating different possible development pathways, this analysis builds on spatial population projections by Jones and O'Neill (2016) that are based on Shared Socioeconomic Pathways (SSPs). SSPs represent a set of scenarios—or plausible future worlds—that underpin climate change research and permit the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (Ebi et al., 2014). They can be categorized by the degree to which the different scenarios represent challenges to mitigation (greenhouse gas emissions reductions) and societal adaptation to climate change.

The analysis uses SSPs as story lines to guide the development of spatial population projections at 7.5 arc-minute resolution (grid cells of about 15 square kilometers at the equator). The five SSPs developed by Jones and O'Neill span a wide range of possible future development pathways and describe trends in demographics, human development, economy, lifestyles, policies, institutions, technology, the environment, and natural resources. They are the scenario benchmarks used for adaptation planning purposes. Table 1 summarizes the SSP narratives; Figure 1 relates the SSPs to one another. National-level estimates of population, urbanization, and Gross Domestic Product (GDP) have been released for each SSP and are available through the SSP database.[4]

The model used in this report builds on SSP2 and SSP4. Under SSP4, only low-income countries experience high population growth, coupled with substantial inequality leading to adaptation challenges. Middle income countries experience low population growth much like high income countries. SSP2 is a moderate development scenario between SSP1 ("sustainability") and SSP3

[4] See IIASA's website https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

("fragmentation"), with a slow reduction in inequalities among world regions and more moderate trends in population growth, urbanization, income, and education. These scenarios were chosen because they represent divergent development pathways. They were also selected for consistency, or the ability to be paired, with the high and low emissions scenarios (RCPs) used in this report. The high emissions scenario (RCP8.5) can be paired with both SSP4 and SSP2; the low emissions scenario (RCP2.6) can be paired with SSP4.

The SSP population projections include cross-border movements, but these do not include climate change as a potential driver of future migration flows. As this study builds on the SSPs, by definition it also includes the bilateral migration flows included in the national-level population projections that correspond to each SSP (K.C. and Lutz, 2014). For both SSP2 and SSP4, these flows are in the middle of the range.[5] They are based on an existing global-level matrix of in- and out-migration (Abel and Sander, 2014) that is adjusted to reflect assumptions regarding, for example, conflict and political changes and the degree of openness of national borders in each SSP (O'Neill et al., 2014).

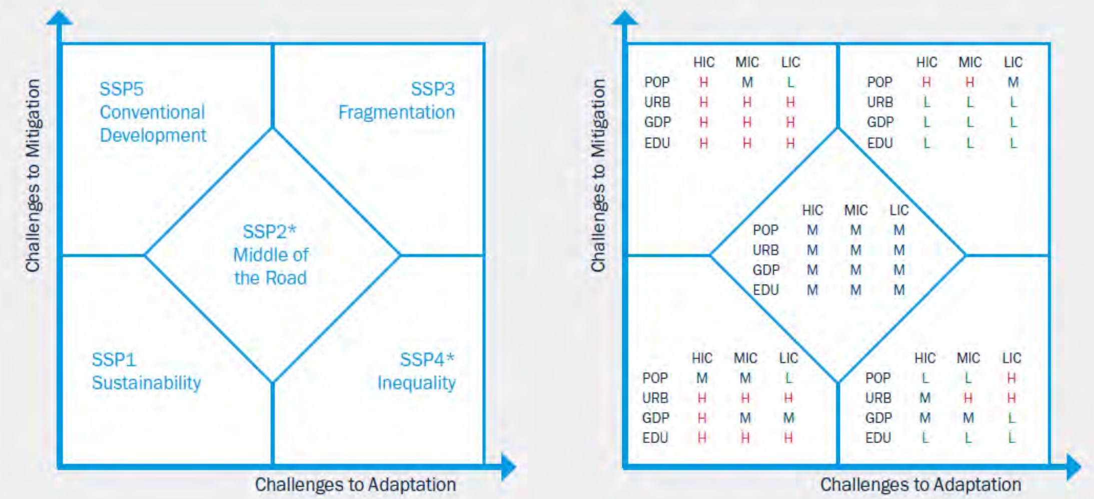
Table 1. Shared Socioeconomic Pathway (SSP) narratives

SSP	Illustrative starting points for narrative	Level of challenge
SSP1	Sustainable development proceeds at a reasonably rapid pace, inequalities are reduced, and technological change is rapid and directed toward environmentally friendly processes, including lower carbon energy sources and higher productivity of land.	Low for mitigation and adaptation
SSP2*	Intermediate case between SSP1 and SSP3.	Moderate
SSP3	Unmitigated emissions are high, as a result of moderate economic growth, rapid population growth, and slow technological change in the energy sector, making mitigation difficult. Investments in human capital are low, inequality is high, a regionalized world leads to reduced trade flows, and institutional development is unfavorable, leaving large numbers of people vulnerable to climate change and many parts of the world with low adaptive capacity.	High for mitigation and adaptation
SSP4*	A mixed world, with relatively rapid technological development in low-carbon energy sources in key emitting regions, leading to relatively large mitigative capacity in places where it matters most to global emissions. However, in other regions, development proceeds slowly, inequality remains high, and economies are relatively isolated, leaving them highly vulnerable to climate change with limited adaptive capacity.	High for adaptation, low for mitigation
SSP5	In the absence of climate policies, energy demand is high and most of this demand is met with carbon-based fuels. Investments in alternative energy technologies are low, and there are few readily available options for mitigation. Economic development is relatively rapid, driven by high investments in human capital. Improved human capital also produces a more equitable distribution of resources, stronger institutions, and slower population growth, leading to a less vulnerable world better able to adapt to climate impacts.	High for mitigation, low for adaptation

Source: Based on O'Neill and others (2014).
Note: * SSP2 and SSP4 used in the model for this report.

[5] Migration flows are considered medium across all SSPs except SSP3 ("fragmentation"), where they are low, and SSP5 ("conventional development"), where they are high. A more sophisticated set of SSP projections is under development.

Figure 1. Qualitative SSP narratives (left) and underlying assumptions (right) on various indicators by country income group



Source: Jiang (2014).
Note: H = high, M = medium, L = low, POP = population, URB = urbanization, GDP = gross domestic product, EDU = education, HIC = high income countries, MIC = medium income countries, LIC = low income countries; * = SSPs used in the model for this report.

Scenario combinations used in the model

Three plausible future internal climate migration scenario combinations are examined:

- A pessimistic reference scenario (SSP4 and RCP8.5), in which low-income countries are characterized by high population growth, high rates of urbanization, low GDP growth, and low education levels. High emissions drive greater climate impacts. This scenario poses high barriers to adaptation because of the slow pace of development and isolation of regional economies.
- A more inclusive development scenario (SSP2 and RCP8.5), which holds emissions as they are in the pessimistic reference scenario but combines them with reduced inequalities among world regions and more moderate trends in population growth, urbanization, income, and education than under SSP4. Population growth is lower than in SSP4 for low income countries and higher for middle income countries.
- A more climate-friendly scenario (SSP4 and RCP2.6), which has a lower emissions pathway, but holds the development scenario as it is in the pessimistic reference scenario.

Note that at the time of the first Groundswell report, these combinations were considered plausible. Some now argue that only SSP5 (not included here) can be combined with RCP8.5.[6] Notwithstanding the evolving knowledge base regarding the plausibility of certain SSP-RCP

[6] See Benefits of Reduced Anthropogenic Climate Change (BRACE) project, at https://www.cgd.ucar.edu/projects/chsp/brace.html.

combinations, a significant value of the approach taken in this report lies in the observed differences relative to the pessimistic scenario along the constant development and constant emissions pathways, each of which allows us to assess the impact of improved climate and socio-economic futures independently and relative to one another.

Climate impact scenarios

Many studies seeking to understand the effects of climate change on mobility have used climate variables such as temperature and precipitation rather than actual climate impacts on different sectors. The key innovation of this research project is that, rather than simply incorporating likely future climate trajectories, it incorporates actual impacts on two critical sectors: water and agriculture, as well as sea-level rise in coastal zones, augmented by storm surge.

Inter-Sectoral Impact Model Intercomparison Project

The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) is a climate-impact modeling initiative aimed at contributing to a quantitative and cross-sectoral synthesis of the differential impacts of climate change, including uncertainties. ISIMIP uses a subset of the general circulation models used in the IPCC AR5 process. This leads to slight variations in the projected temperature range associated with RCP2.6 and RCP8.5 used in this report. ISIMIP has compiled a database of state-of-the-art computer model simulations of biophysical climate impacts. It offers a framework for consistently projecting the impacts of climate change across affected sectors and spatial scales.

The analysis for this study used outputs of the ISIMIP Fast Track modeling effort, which covers 1970–2010, as well as projections for 2010-2050 (Piontek et al., 2013).[7] Under the Fast Track, future sectoral impact models are driven by a range of general circulation models. This project used two general circulation models that provide a good spread for the temperature and precipitation parameters of interest: the Hadley Centre Global Environment Model version 2 (HadGEM2-ES) climate model developed by the Met Office Hadley Centre for Climate Science and Services (in the United Kingdom) and the Institut Pierre Simon Laplace Climate Modeling Center Low-Resolution (IPSL-CM5A-LR) climate model (in France) (see Appendix A of Rigaud et al., 2018 for details).

Climate impacts addressed in the model

The ISIMIP collection of sectoral models includes a range of systems and sectors, such as health, coastal infrastructure, forests, and other ecosystems. The focus of this study is on water availability and crop productivity, as well as sea-level rise scenarios that were developed outside the ISIMIP framework. The global simulations, at a relatively coarse spatial scale (0.5 degrees or

[7] See https://www.isimip.org/protocol/fast-track/. Note that only the Fast Track model runs were available in 2017, at the time of the original preparation of the original *Groundswell* report. Since that time, new impact model runs are available under ISIMIP2b.

roughly 55 kilometers at the equator), are an advance over purely climate model-based indicators of rainfall and temperature, because they represent actual resources of relevance to development. These climate impacts were selected because the literature shows that water scarcity and declining yields, along with sea-level rise, are among the major potential climate impacts facing low-income countries and these impacts will also be very important drivers of migration. In the ISIMIP models, water availability is influenced by rainfall, rising temperatures, dams and reservoirs, and management practices, while crop productivity is a function of rainfall, temperature, CO_2 concentrations, irrigation, and management practices. These technologies and management practices have been held static since 2005; in other words, technologies remain fixed, and there is no adaptation to future climate impacts in either the water or agricultural sectors.

The model leaves out many important impacts, including the impacts of flood, drought, and cyclones (except to the extent that they affect water availability and crop yields). As devastating as they may be for rural livelihoods, short-duration fast-onset events are not directly included. The full range of environmental factors that could influence livelihoods and mobility are also not directly included and some of these may be important for particular localities (e.g., urban heat stress effects, salination expanding the area affected by sea-level rise and related effects on surface and groundwater used for irrigation). These factors are difficult to capture in global models, and therefore require more localized study. This work starts with the most important sectoral impacts on migration as a first step (future efforts could also incorporate more sectoral models). For these reasons, the results should be seen as a lower-bound estimate of the likely impact of climate change on migration.

The focus of this work is not on short-term climate variability or extremes—which are not as well captured by the impact models—but on deviations from baseline conditions over decades. There are compelling theoretical reasons to focus on trends rather than extremes.

- Extremes are more likely to result in short-term displacement (followed by population return to affected areas) (Kälin, 2010; Brzoska and Fröhlich, 2015; Black et al., 2011)
- Longer-term trends in crop yields or water availability are more likely to contribute to out-migration (Nawrotzki et al., 2017; Bohra-Mishra, Oppenheimer, and Hsiang, 2014).
- The impact of successive climate shocks may erode household assets and therefore the ability to adapt locally, eventually affecting decisions to migrate (IDMC, 2016; Warner et al., 2012).
- Successive shocks over several years will affect the index values described below, because they represent more prolonged deviations from the mean.

The modeling work also considers sea-level rise projections from the IPCC Fifth Assessment Report, augmented by an increment for storm surges. The figures in Table 2 represent the lower-, middle-, and upper-bound sea-level rise by 2030 and 2050, as reported by the IPCC (Church et al., 2013) but do not take storm surge into account. According to Dasgupta et al., (2007, 6), “Even a small increase in sea level can significantly magnify the impact of storm surges, which occur regularly and with devastating consequences in some coastal areas." A comprehensive assessment of the likely levels of storm surge for all the coastal areas covered by this report was beyond the scope of this project.

Two scenarios meant to be representative of changes in sea-level by 2050 associated with RCP2.6 and RCP8.5 were adapted by adding an increment to account for storm surge on top of the estimates in Table 2. Under RCP2.6, the increment was 0.85-0.9 meters, for a total of 1 meter; under RCP8.5, the increment was 1.68-1.85 meters, for a total of 2 meters. These assumptions are applied to all coastlines for 2050; they represent the loss of habitable land as a result of sea level rise plus storm surge in each coastal grid cell. Both the 1- and 2-meter sea level rises are based on NASA SRTM data, as modified by the Center for International Earth Science Information Network (CIESIN, 2013). Although the addition of the increments is technically sound and based on past work (Hallegatte et al., 2011; Dasgupta et al., 2007), the 1- and 2-meter bands were chosen partly as an expedient (the global sea level rise layers were developed in earlier work) and partly because at the 15-kilometer modeling resolution, smaller sea level rise increments would have barely registered.

Table 2. Projected rise in sea level under low and high Representative Concentration Pathways (meters above current mean sea level)

	RCP 2.6			*RCP 8.5*		
Year	*Lower*	*Middle*	*Upper*	*Lower*	*Mid*	*Upper*
2030	0.092	0.127	0.161	0.098	0.132	0.166
2050	0.157	0.218	0.281	0.188	0.254	0.322

Source: Church et al., 2013. *Note: Sea level rise was augmented with storm surge increments under RCP 2.6 (0.85-0.9m); and RCP 8.5 (1.68-1.85m).*

Water and crop models used in the gravity model

Data on water availability and crop productivity were integrated into the gravity model using the following approach. The water sector model outputs represent river discharge, measured in cubic meters per second in daily/monthly time increments. The crop sector model outputs represent crop yield in tons per hectare on an annual time step at a 0.5° x 0.5° grid cell resolution. Crops include maize, wheat, rice, and soy beans; for regions with multiple cropping cycles, yield reflects only the major crop production period.[8] The data were converted to decadal average water availability and crop production (in tons) per grid cell.[9] An index was then calculated that compares those values with the 40-year average for water availability and crop production for 1970–2010:

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[8] The ISIMIP models seek to assess the risk that climate change will affect the potential for agriculture in a given location. For this purpose, the relative changes in average yield potential are useful.

[9] The models report "pure crop yields" in tons per hectare (that is, they assume that a given crop is grown everywhere, irrespective of growing conditions or the location where crops are actually grown). These yields were multiplied by observations-based growing areas (in 2005), separately for rainfed and irrigated yields, to obtain grid cell-level production (in metric tons) (Portmann, Siebert, and Döll, 2010).

$$Index = (D_{avg} - B_{avg}) / B_{avg} \qquad \text{(Equation 2.1)}$$

where D_{avg} is the decadal average crop production/water availability and B_{avg} is the baseline average crop production/water availability for the 40-year period 1970-2010. The indexes for water availability and crop production represent deviations from the long-term averages (0.2 indicates 20 percent above the baseline average, -0.6 indicates 60 percent below the baseline average).

The ISIMIP models are based on different combinations of climate, crop, and water models. Applying the combinations—two global climate models driven by two different emissions scenarios, which in turn drive two sets of sectoral impact models (described below)—provides a range of plausible population projections. It also gives a sense of the level of agreement across scenarios. Because the population modeling process is time consuming and computationally intensive, it was important to work with a reduced set of ISIMIP inputs.[10] The modeling employed the HadGEM2-ES and IPSL-CM5A-LR global climate models, which drive combinations of the two water models and two crop models: the Lund-Potsdam-Jena managed Land (LPJmL) water and crop models, the Water Global Assessment and Prognosis version 2 (WaterGAP2) water model, and the GIS-based Environmental Policy Integrated Climate (GEPIC) crop model (Table 3). Appendix A in Rigaud et al. (2018) provides detailed information on model selection.

The crop and water models were selected based on several criteria, including model performance over the historical period, diversity of model structure, diversity of signals of future change, and availability of both observationally driven historical (ISIMIP2a) and global climate model-driven historical and future (ISIMIP Fast-Track) simulations. Table 3 presents the combinations of models used.

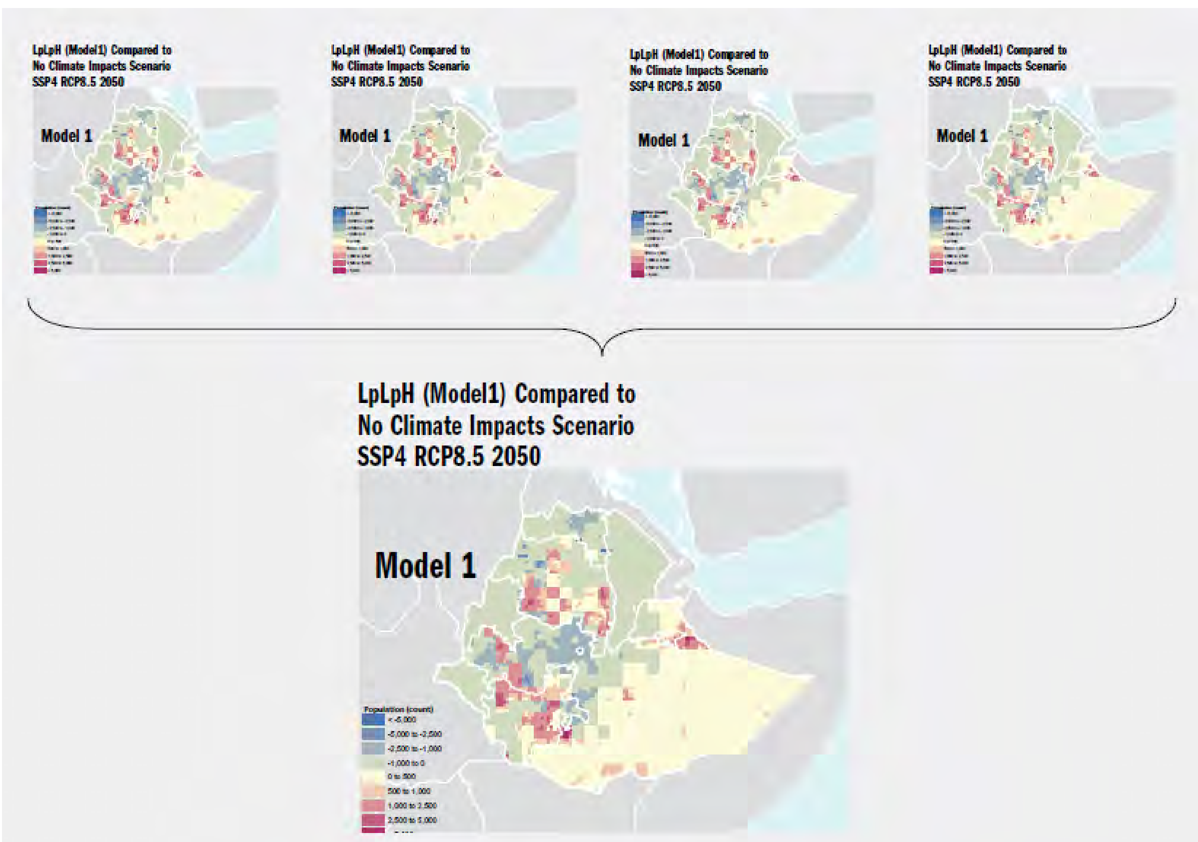
For each of the three climate migration scenarios (pessimistic reference, more inclusive development, and more climate-friendly model) outputs were averaged to generate a mean or "ensemble." Figure 2 shows how the four model results for the pessimistic reference scenario (SSP4-RCP8.5) were averaged to create an ensemble for Ethiopia.

[10] Feeding all potential ISIMIP water and crop model outputs into the gravity model would have yielded 12,500 model runs: 2 RCPs * 5 GCMs * 25 crop model outputs * 50 water model outputs = 12,500.

Table 3. Matrix of global climate models and crop and water model combinations used in this report

	Crop Simulation			
Water Simulation	*GCM1, LPJmL (crop)*	*GCM1, GEPIC*	*GCM2, LPJmL (crop)*	*GCM2, GEPIC*
HadGEM2-ES, LPJmL (water)	Model 1			
HadGEM2-ES, WaterGAP2		Model 2		
IPSL-CM5A-LR, LPJmL (water)			Model 3	
IPSL-CM5A-LR, WaterGAP2				Model 4

Figure 2. Illustrative example for Ethiopia: Combining four model outputs into one ensemble



ISIMIP water and crop model results

Climate impacts on water availability and crop production have important impacts on the population potential of locations in the gravity model. Appendix B of Groundswell I (Rigaud et al., 2018) and Appendix A of Groundswell II (Clement et al., 2021) present the water and crop productivity indexes in the context of climate trends and projections for each of the regions of focus. The climate impacts are an input to the gravity model; when combined with parameters derived from the development scenarios (the SSPs), they directly affect the population potential of regions within countries.

Population data

The population gravity model used to project future climate migration is calibrated based on the historical sensitivity of past shifts in population distribution to the effects of deviations in water availability and crop productivity from long-term baselines. These relationships are then assumed to hold into the future, such that changes in each of the sectoral impacts will result in increasing or decreasing attractiveness of areas for human settlement in the future. The calibration process, carried out on changes in actual population distribution in two decadal increments–between 1990 to 2000 and between 2000 and 2010–revealed that populations are most sensitive to historical deviations in water availability (in both rural and urban areas) followed by historical deviations in crop productivity, although the relative influence of each varies from region to region. This means that positive deviations in water availability and crop productivity are associated with increases in population density in the past, and negative deviations are associated with decreases. Crop productivity is not used to calibrate urban grid cells since populations in these areas are assumed not to be as dependent on agriculture for livelihoods. In any given grid cell, the drivers may either act in concert, reinforcing one another (e.g., rural grid cells with crop productivity and water availability declines), or they may offset each other (e.g., flood risk may increase but water availability declines).

The population baseline used is the 2010 baseline in the Center for International Earth Science Information Network (CIESIN) Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals, Revision 11 (CIESIN, 2018) (Figure 3). The gravity model was calibrated based on population change estimates for 1990-2010 derived from Gridded Population of the World, Version 3 (GPWv3): Population Count Grid (CIESIN et al., 2005) and for 2000-2010 from GPWv4. GPW versions 3 and 4 model the distribution of the population on a continuous global surface based on the highest spatial resolution census data available from the 2000 and 2010 rounds of censuses, respectively. In this work, population count grids were used that were adjusted to national-level estimates from the United Nations World Population Prospects reports. GPWv3 and v4 are gridded data products with output resolutions of 2.5 arc-minutes (a square approximately 4 kilometers on a side at the equator) and 30 arc-seconds (a square approximately 1 kilometer on a side at the equator), respectively. For model calibration and the baseline population for the future projections, the data were aggregated to 7.5 arc-minutes (a square approximately 15 kilometers on a side at the equator [i.e. grid cells with an area of 196 square kilometers]). Uncertainties about these data are discussed in Appendix A of Rigaud et al. (2018).

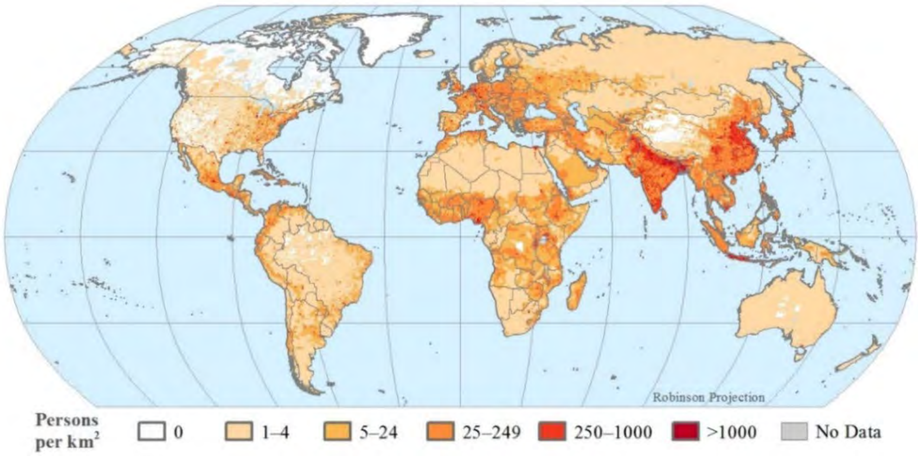
A decision was taken not to model climate migration in the countries of the Middle East owing to the high degrees of uncertainty in baseline (2010) populations, the conflict that continues to affect Syria and Yemen, and, in the case of Syria, resulting refugee flows to neighboring countries. Out of an estimated population of 21.4 million in 2010 (UNDESA, 2019), 5.6 million people have fled Syria since 2011, and 6.6 million are internally displaced (UNHCR, undated). Yemen, in turn, has 1 million internally displaced people out of a 2010 estimated population of 23.2 million (UNHCR, undated). These conflicts have had the effect of calling into question any baseline within these countries, as well as in neighboring countries such as Lebanon and Jordan. The decision to model Libya, which has similarly suffered conflicts since 2011, was made on the basis of the fact that the population of 6.2 million people (less than the total internally displaced population of Syria) is concentrated in a few coastal urban areas. Given that displacement levels of 217,000 (UNCHR, undated) are modest in comparison to the other countries, one can argue that the population distribution has not changed significantly since the onset of the conflict. For other North African countries, while these are also hosting refugees from Syria and other countries, inflows are more modest than in some of the countries of the Middle East and do not affect baseline population distribution in a substantial way. In no country in the region did refugees count for more than 0.5 percent of the population between 2004 and 2020, and for most the refugee population was well under 0.25 percent.

For Eastern Europe and Central Asia, a decision was also taken not to model certain countries, namely the Russian Federation as well as certain former republics of the Soviet Union, namely Belarus, Moldova, and the Ukraine, because the climate sensitivity of past changes in population distribution in these temperate, higher latitude countries is low.[11] For the same reason, and because they are high income countries, other International Bank for Reconstruction and Development (IBRD) countries in Eastern Europe, namely Poland and Croatia, were not modeled.

Finally, given the coarse resolution of the ISIMIP inputs (0.5 degree grid cells or 55 kilometers on a side), Small Island Developing States (SIDS) were too small to model successfully. Although an attempt was made to model larger SIDS (e.g., Fiji), there was very little meaningful variation in population distribution between the no climate impact and climate impact scenarios, and sea-level rise had only negligible impacts on future population distributions at the scale mapped, especially where land rises steeply from the shoreline.

[11] Belarus was modeled as a test case and it was found that climate factors had very low predictive power in terms of past movements.

Figure 3. Global population density, 2010



Source: Gridded Population of the World, Version 4 (CIESIN, 2018).

Methods

The modeling work is based on a modified version of the National Center for Atmospheric Research-CUNY Institute for Demographic Research (NCAR-CIDR) gravity model (Jones and O'Neill, 2016).[12] Technical details on the model specification are in Appendix C of *Groundswell II* (Clement et al., 2021).

The gravity model

The original NCAR-CIDR model is a gravity-based approach that downscales national population projections to subnational raster grids (Jones and O'Neill, 2013, 2016) as a function of geographic, socioeconomic, and demographic characteristics of the landscape and existing population distribution. Gravity-type approaches are commonly used in geographic models of spatial allocation and accessibility. They take advantage of spatial regularities in the relationship between population agglomeration and spatial patterns of population change. These relationships can be described as a function of the characteristics known to correlate with spatial patterns of population change.

The NCAR-CIDR model uses a modified form of population potential, a distance-weighted measure of the population taken at any point in space that represents the relative accessibility of that point. For example, higher values indicate a point more easily accessible by a larger number of people. Summed over all points within an area, population potential represents an index of the relative influence that the population at a point within a region exerts on each point within that region, and can be considered an indicator of the potential for interaction between the population at a given point in space and all other populations (Rich, 1980). This potential will be higher at

[12] Data for the original SSP-only population projections are available for download via the NASA Socioeconomic Data and Applications Center (SEDAC) at https://doi.org/10.7927/H4RF5S0P. These projections are produced using a baseline 2010 population of GPWv3 rather than GPWv4, as used here.

points closer to large populations; potential is thus also an indicator of the relative proximity of the existing population to each point within an area (Warntz and Wolff, 1971). Such metrics are often used as a proxy for attractiveness, under the assumption that agglomeration is indicative of the various socioeconomic, geographic, political, and physical characteristics that make a place attractive.

Adding climate impacts

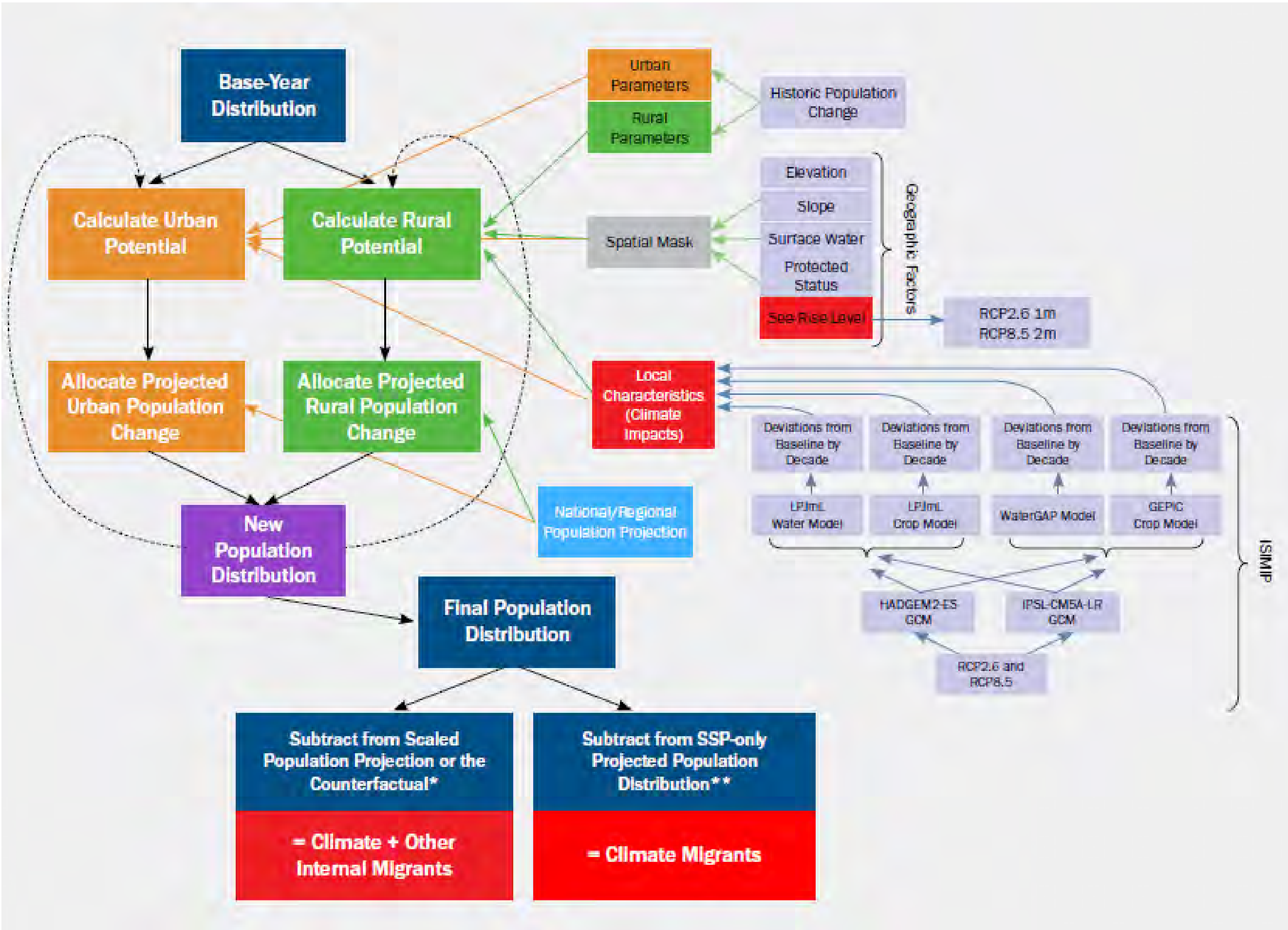
The calculation of potential was modified by adding local characteristics, including climate impacts. Figure 4 is a flowchart of the modeling steps; boxes in red show the addition of climate impacts or results incorporating climate impacts. Population potential is a relative measure of agglomeration, indicating the degree to which amenities and services are available. In the original model, this value shifts over time as a function of the population; of assumptions regarding spatial development patterns (for example, sprawl vs. concentration); and of certain geographic characteristics of the landscape.

Beginning with the 2010 gridded urban/rural population distribution for each country, the modeling done for this report incorporated the influence of climate impacts on relative attractiveness in the following manner:

1. Calculate an urban population potential surface (a distribution of values reflecting the relative attractiveness of each grid cell).
2. Calculate a rural population potential surface.
3. Allocate projected urban population change to grid cells proportionally based on their urban potentials.
4. Allocate changes in the projected rural population to grid cells proportionally based on their rural potential.
5. Because the allocation procedure can lead to some redefinition of population from rural to urban (e.g., rural population allocated to a cell with an entirely urban population is redefined as urban), this step entails redefining population as urban or rural as a function of density and contiguity of fully urban/rural grid cells to match projected national-level totals.

These steps are then repeated for each decadal time interval. Figure 5 illustrates steps 3 and 4 for a hypothetical population distribution. Note that population potential surfaces, urban and rural, are continuous across all grid cells; each grid cell may thus contain urban and rural populations.

Figure 4. Flowchart of modeling steps

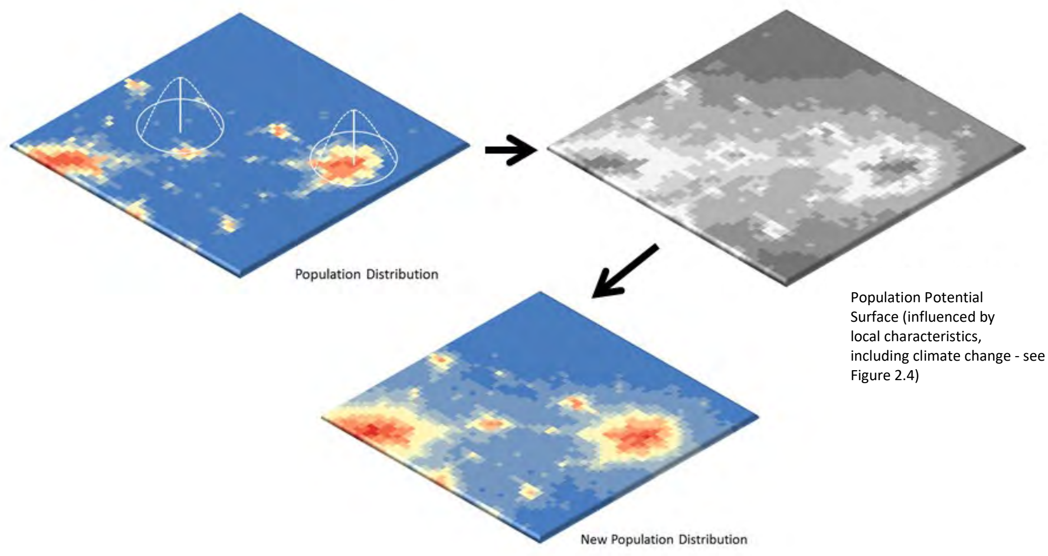


Note: Boxes in red represent the addition of climate impacts into the modeling framework or results that reflect climate impacts.

* The counterfactual population projection simply scales the population distribution in 2010 to country-level population totals appropriate to each SSP.

** The SSP-only population projection represents the population projection without climate impacts (i.e., based only on the development trajectories embodied in the SSPs).

Figure 5. Hypothetical example of gravity-based population projection model for single time step



Based on the modified NCAR-CIDR model, population potential (v_i) is calculated as a parametrized negative exponential function:

$$v_i = A_i l_i \sum_{j=1}^{m} P_j^{\alpha} e^{-\beta d_{ij}} \qquad \text{(Equation 2.2)}$$

Where:
Ai = Local characteristics
li = Spatial mask
a = Population parameter etc.
P = Population
ß = Distance parameter
d = Distance

It is weighted by a spatial mask[13] (*l*) that prevents population from being allocated to areas that are protected from development or unsuitable for human habitation, including areas that will likely be affected by sea-level rise between 2010 and 2050. P_j is the population of grid cell *j*; *d* is the distance between two grid cells. The distance and population parameters (α and β) are estimated from observed patterns of historical population change. The β parameter is indicative of the shape of the distance–density gradient describing the broad pattern of the population distribution (for example, sprawl versus concentration). The α parameter captures returns on agglomeration externality, interpreted as an indicator of the socioeconomic, demographic, and political characteristics that make a place more or less attractive.

[13] Spatial masks are used in geospatial processing to exclude areas from consideration. The effect is that the algorithm is not applied in these areas. Examples in this instance would include protected areas or places where the terrain is too rugged to inhabit.

The primary reason for relying on the agglomeration effect, characterized by the population and friction-of-distance parameters, as opposed to some of the known drivers of migrations, such as employment opportunity and wage rates, is the difficulty associated with gathering historic data in a consistent fashion over a large portion of the globe, and projecting these indicators (that theoretically, drive the agglomeration effect) forward over time at fairly high resolution. By correlating population change trends to population potential, the need to project these variables individually is negated. This decision reflects a desire to (1) limit uncertainty where possible, and (2) ground results in observed historical relationships paying particular attention to broad trends that can be characterized over space.

The SSPs include no climate impacts on aggregate total population, urbanization, or the subnational spatial distribution of the population. The NCAR-CIDR approach was modified by incorporating additional spatial data in the form of the ISIMIP sectoral impacts likely to affect population outcomes. The index A_i is a weight on population potential that is calibrated to represent the influence of the crop and water sectoral impact indicators on spatial patterns of population change. The ISIMIP data, which represent decadal deviation from long-term baseline conditions, are incorporated into the model as gridded spatial layers. The value A_i is calculated as a function of these indicators; it represents an adjustment to the relative attractiveness of (or aversion to) specific locations (grid cells), reflecting current water availability and crop yields relative to “normal” conditions. The model is calibrated over two decadal periods (1990-2000 and 2000-2010) of observed population change relative to deviations of water availability and crop production from the 1970-2010 average for a subset of representative countries in each region.[14] Table 4 provides the countries that were used to calibrate each sub-region for the *Groundswell* model. Where more than one country was used to calibrate a sub-region, the resulting coefficients were averaged.

Details on the modeling methodology, including the methods used for calibration, are in Appendix C of *Groundswell II* (Clement et al., 2021). The model was validated using Mexico and Ethiopia, the process and results for which can also be found in Appendix C.3 of *Groundswell II*.[15]

[14] Accurate spatial data from censuses on the location of populations or the change in population over time are not available for most developing countries before 1990.
[15] The results of these validation exercises were quite similar despite very dissimilar geographies and economic contexts. Because validation is a time-consuming process it was determined that further validation would not be undertaken.

Table 4. Countries used to calibrate each sub-region modeled (from east to west)

Sub-Region	Countries
China and Mongolia	China
Southeast Asia (including Lower Mekong)	Thailand and Vietnam
South Asia	India and Bangladesh
Central Asia	Kyrgyz Republic
Caucuses	Georgia
Eastern Europe	Bulgaria
Turkey	Turkey
North Africa	Morocco
East Africa	Ethiopia, Mozambique and Tanzania
Southern Africa	Botswana
Central Africa	Democratic Republic of Congo
West Africa	Guinea and Mauritania
South America	Argentina and Brazil
Central America and Mexico	Mexico

Characterizing the model

This modeling provides transparent, spatially explicit estimates of changes in the population distribution (and indirectly migration) as a function of climate and development trends. It is important to understand what the model does and does not do.

Gravity models can be used to model past evolutions of population distributions based on observed agglomeration effects over large geographic regions, under varying conditions, and at alternative spatial scales. They can also be refined to incorporate additional details, such as environmental parameters that affect the relative attractiveness of locations.

Gravity models do not directly model internal migration. Instead, deviations between the population distributions in model runs that include the crop and water impacts and the development-only (also referred to as the SSP or "no climate") model runs are assumed to be driven primarily by differences in climate change–induced internal migration. Migration is a "fast" demographic variable compared with fertility and mortality; it is responsible for much of the decadal-scale redistributions of population. Without significant variation in fertility/mortality rates between climate-migrant populations and non-migrant populations, it is fair to assume that differential population change between the climate impact scenarios and the development-only scenarios occur as a function of migration. Another way of saying this is that the model assumes that fertility and mortality rates are relatively consistent across populations in a locale.

For each climate migration scenario, the model produces a range of estimates that reflect variation in the underlying inputs to the model, which in turn reflect scientific uncertainty over likely future climate projections and impacts and development trajectories. In any scenario, outcomes are a function of the global climate models and the sectoral impact models that drive climate impacts on population change. For each of the three scenarios, there are four models, consisting of different global climate model/ISIMIP combinations. The ensemble mean (or average) of the four models is reported as the primary result for each scenario. Uncertainty is reflected in the range of outcomes (across the four models) for each grid cell and at different levels of aggregation. While some may prefer to have just one figure, in a complex issue like climate-related migration, a scenario-based approach is preferable. It would be desirable to have even more scenarios, to better assess the uncertainty (or conversely confidence) in the results (see section below on Limitations). However, time and resource constraints prevented more than four realizations for the model per climate-development combination.

In the model, cross-border mobility is not affected by the climate drivers. Rather, the SSP assumptions are applied to cross-border movements. The model thus builds on the SSPs, which include cross-border migration, following a limited set of assumptions about the potential for international movements across scenarios.

This “top-down” model shows the results of household-level decisions that influence migration, but it does not build directly on the evidence (or data) from micro-level studies. It considers such factors only at an aggregate level. In an effort to connect this work to household-level migration research, subsequent chapters provide case study narratives for Morocco, Vietnam, and the Kyrgyz Republic. Those case studies situate, and to some degree validate, this work in the context of the household dimension.

The model is run at spatial and temporal scales that capture migration well. With grid cells of about 15 square kilometers at the equator, population shift can be considered a form of short-distance migration. The temporal scale of decadal increments from 2010 to 2050 is adequate to capture the longer-term shifts in population caused by slow-onset changes in water availability, crop conditions, and sea-level rise. The model does not capture movements over shorter time periods.

The model cannot forecast all future adaptation efforts or conflict, cultural, political, institutional, or technological changes. Discontinuities are likely to arise as a result of political events and upheavals that can heavily influence migration behavior. Armed conflict itself may have links to climate variability and change, but models have generally failed to forecast armed conflict or state failure with any precision. The scenario framework is not designed to predict shocks to any socioeconomic or political system, such as war or market collapse. The models can also not anticipate new technologies that may dramatically affect adaptation efforts to the degree that climate impacts become negligible. They also do not include long-term national strategic planning efforts across key sectors such as water or agriculture that may influence future sector resilience and that of associated livelihoods to projected climate impacts. The SSPs, as well as output from the global climate model and ISIMIP, reflect plausible futures that span a wide range of global trajectories, with the caveat that extremely unpredictable or unprecedented events are explicitly excluded.

III. Data Set Description

The Groundswell Spatial Population and Migration Projections at One-Eighth Degree According to SSPs and RCPs, 2010-2050, data set provides a baseline population distribution for 2010 and projections from 2020 to 2050, in ten-year increments, of population distribution and internal climate-related and other migration. The projections are produced using the NCAR-CIDR Spatial Population Downscaling Model developed by the CUNY Institute for Demographic Research (CIDR) and the National Center for Atmospheric Research (NCAR). The model incorporates assumptions based on future development scenarios (Shared Socioeconomic Pathways or SSPs) and emissions trajectories (Representative Concentration Pathways or RCPs). The SSPs include SSP2, representing a middle-of-the road future, and SSP4, representing an unequal development future. Climate models using low and high emissions scenarios, RCP2.6 and RCP8.5, then drive climate impact models on crop productivity and water availability from the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP). Sea-level rise impacts in the coastal zone are estimated to be 1 meter under RCP2.6 and 2 meters under RCP8.5, to account for potential storm surge or coastal flooding. Three scenarios are generated, a pessimistic reference scenario combining SSP4 and RCP8.5, a more climate-friendly scenario combining SSP4 and RCP2.6, and a more inclusive development scenario combining SSP2 and RCP8.5, and each scenario represents an ensemble of four model runs combining different climate impact models. The modeling work was funded and developed jointly with The World Bank, and covers most World Bank client countries, with reports released in 2018 and 2021 that address different regions and provide full methodological details.

Data set web page:
SEDAC URL: https://sedac.ciesin.columbia.edu/data/set/climmig-groundswell-pop-mig-proj-1-8-ssps-rcps-2010-2050
Permanent URL: https://doi.org/10.7927/c5kq-fb78

Data set format:
The data are available in GeoPackage (GPKG) and Esri File Geodatabase (GDB) formats for each of the 112 countries modeled. The countries are listed in Table 5. Each file includes the ISO3 code listed in the table. The data dictionary includes field names and descriptors for 204 variables found in each file. This is packaged with each download as a separate Excel file. Each downloadable is a compressed zip file, containing: 1) the GPKG or GDB file, 2) Microsoft Excel file (XLSX) data dictionary, and 3) PDF documentation.

Data set downloads:
- climmig-groundswell-pop-mig-proj-1-8-ssps-rcps-2010-2050-country-gdb.zip
- climmig-groundswell-pop-mig-proj-1-8-ssps-rcps-2010-2050-country-gpkg.zip

Table 5. List of countries modeled, grouped by World Bank region

ISO3	Country	World Bank Region		ISO3	Country	World Bank Region
KHM	Cambodia	East Asia & Pacific		AFG	Afghanistan	South Asia
CHN	China	East Asia & Pacific		BGD	Bangladesh	South Asia
IDN	Indonesia	East Asia & Pacific		BTN	Bhutan	South Asia
LAO	Lao PDR	East Asia & Pacific		IND	India	South Asia
MYS	Malaysia	East Asia & Pacific		MDV	Maldives	South Asia
MNG	Mongolia	East Asia & Pacific		NPL	Nepal	South Asia
MMR	Myanmar	East Asia & Pacific		PAK	Pakistan	South Asia
PNG	Papua New Guinea	East Asia & Pacific		LKA	Sri Lanka	South Asia
PHL	Philippines	East Asia & Pacific		AGO	Angola	Sub-Saharan Africa
THA	Thailand	East Asia & Pacific		BEN	Benin	Sub-Saharan Africa
TLS	Timor-Leste	East Asia & Pacific		BWA	Botswana	Sub-Saharan Africa
VNM	Vietnam	East Asia & Pacific		BFA	Burkina Faso	Sub-Saharan Africa
ALB	Albania	Europe & Central Asia		BDI	Burundi	Sub-Saharan Africa
ARM	Armenia	Europe & Central Asia		CPV	Cabo Verde	Sub-Saharan Africa
AZE	Azerbaijan	Europe & Central Asia		CMR	Cameroon	Sub-Saharan Africa
BIH	Bosnia and Herz.	Europe & Central Asia		CAF	Central African Rep.	Sub-Saharan Africa
BGR	Bulgaria	Europe & Central Asia		TCD	Chad	Sub-Saharan Africa
HRV	Croatia	Europe & Central Asia		COM	Comoros	Sub-Saharan Africa
GEO	Georgia	Europe & Central Asia		COD	Congo, Dem. Rep.	Sub-Saharan Africa
KAZ	Kazakhstan	Europe & Central Asia		COG	Congo, Rep.	Sub-Saharan Africa
KOS	Kosovo	Europe & Central Asia		CIV	Cote d'Ivoire	Sub-Saharan Africa
KGZ	Kyrgyz Republic	Europe & Central Asia		GNQ	Equatorial Guinea	Sub-Saharan Africa
MNE	Montenegro	Europe & Central Asia		ERI	Eritrea	Sub-Saharan Africa
MKD	North Macedonia	Europe & Central Asia		SWZ	Eswatini	Sub-Saharan Africa
ROU	Romania	Europe & Central Asia		ETH	Ethiopia	Sub-Saharan Africa
SRB	Serbia	Europe & Central Asia		GAB	Gabon	Sub-Saharan Africa
TJK	Tajikistan	Europe & Central Asia		GMB	Gambia, The	Sub-Saharan Africa
TUR	Turkey	Europe & Central Asia		GHA	Ghana	Sub-Saharan Africa
TKM	Turkmenistan	Europe & Central Asia		GIN	Guinea	Sub-Saharan Africa
UZB	Uzbekistan	Europe & Central Asia		GNB	Guinea-Bissau	Sub-Saharan Africa

ISO3	Country	World Bank Region		ISO3	Country	World Bank Region
ARG	Argentina	Latin America & Caribbean		KEN	Kenya	Sub-Saharan Africa
BLZ	Belize	Latin America & Caribbean		LSO	Lesotho	Sub-Saharan Africa
BOL	Bolivia	Latin America & Caribbean		LBR	Liberia	Sub-Saharan Africa
BRA	Brazil	Latin America & Caribbean		MDG	Madagascar	Sub-Saharan Africa
CHL	Chile	Latin America & Caribbean		MWI	Malawi	Sub-Saharan Africa
COL	Colombia	Latin America & Caribbean		MLI	Mali	Sub-Saharan Africa
CRI	Costa Rica	Latin America & Caribbean		MRT	Mauritania	Sub-Saharan Africa
ECU	Ecuador	Latin America & Caribbean		MUS	Mauritius	Sub-Saharan Africa
SLV	El Salvador	Latin America & Caribbean		MOZ	Mozambique	Sub-Saharan Africa
GUF	French Guiana	Latin America & Caribbean		NAM	Namibia	Sub-Saharan Africa
GTM	Guatemala	Latin America & Caribbean		NER	Niger	Sub-Saharan Africa
GUY	Guyana	Latin America & Caribbean		NGA	Nigeria	Sub-Saharan Africa
HND	Honduras	Latin America & Caribbean		RWA	Rwanda	Sub-Saharan Africa
MEX	Mexico	Latin America & Caribbean		STP	Sao Tome & Principe	Sub-Saharan Africa
NIC	Nicaragua	Latin America & Caribbean		SEN	Senegal	Sub-Saharan Africa
PAN	Panama	Latin America & Caribbean		SLE	Sierra Leone	Sub-Saharan Africa
PRY	Paraguay	Latin America & Caribbean		SOM	Somalia	Sub-Saharan Africa
PER	Peru	Latin America & Caribbean		ZAF	South Africa	Sub-Saharan Africa
SUR	Suriname	Latin America & Caribbean		SSD	South Sudan	Sub-Saharan Africa
URY	Uruguay	Latin America & Caribbean		SDN	Sudan	Sub-Saharan Africa
VEN	Venezuela, RB	Latin America & Caribbean		TZA	Tanzania	Sub-Saharan Africa
DZA	Algeria	Middle East & North Africa		TGO	Togo	Sub-Saharan Africa
DJI	Djibouti	Middle East & North Africa		UGA	Uganda	Sub-Saharan Africa
EGY	Egypt, Arab Rep.	Middle East & North Africa		ZMB	Zambia	Sub-Saharan Africa
LBY	Libya	Middle East & North Africa		ZWE	Zimbabwe	Sub-Saharan Africa
MAR	Morocco	Middle East & North Africa				
TUN	Tunisia	Middle East & North Africa				

IV. How to Use the Data

The data set is useful both for its multiple population projections under climate and no-climate impacts scenarios, and for the projections of climate migration, which was the focus of the *Groundswell* reports. Users may apply zonal statistics to assess net climate migration within different biophysical or administrative units. Users are cautioned against using only one model run or scenario ensemble, but should seek to use multiple model runs per scenario (or multiple scenarios) in order to characterize the uncertainty across model runs/scenarios. In the event that only one model run/scenario is used, it should be made clear to end-users that the results do not take into account uncertainties in the underlying model outputs.

R processing scripts for post-processing of model outputs (e.g., to produce the graphs presented in the *Groundswell* reports) are available on request from ciesin.info@ciesin.columbia.edu.

V. Potential Use Cases

The projections of future population distributions with and without climate impacts, along with future estimates of climate migration, have already been used by The World Bank for country consultations related to development planning. Anticipating the potential scale of population shifts as a result of climate impacts can be useful for service provision and infrastructure development. The fundamental reasons for projecting population, and by implication the most common application areas, can be boiled down to the following:

- Demographers have always projected populations to meet needs for planning purposes, since population is fundamental
- The humanitarian community wants projections of likely displacement for humanitarian response
- Development actors are grappling with potential limits to adaptation for rural livelihoods, and how population may be redistributed as a result
- Cities want to understand the magnitude of future flows from rural areas
- Policy makers want “what if?” scenarios based on alternative futures–providing both projections with and without climate impacts fulfills a demand

VI. Limitations

Limitations of the input data are covered elsewhere–e.g., the GPWv4 documentation, Jones and O’Neill, 2016 for the gravity model, and the ISIMIP web site and accompanying data documentation. In addition to these, the modeling results incorporate nine main sources of uncertainty that can affect the estimated number of climate migrants or the differences between the three scenarios and the development-only scenario.

1. ISIMIP impacts vary across models. In Central America, for example, the combined LPJmL water and crop models have generally lower impacts than the WaterGAP-GEPIC combination of water and crop models, though these differences vary across the region. The differences result in different effects in the gravity model; models with the highest impacts repel more people from affected areas in the former set of outputs than in the latter set.
2. Variations between the two global climate models—HadGEM2-ES and IPSL-CM5A-LR—can amplify the ISIMIP differences. The global climate models were selected in part because their future precipitation trends differ substantially in magnitude, and partly even in sign, for the focus regions (see Appendix A of Rigaud et al., 2018). This variance in precipitation has an impact on both the water and crop models.
3. The modeling has a temporal component that can influence population distribution trajectories. Stronger sectoral impacts early in the 40-year projection period will have greater influence than the same impacts later in that period, because those early impacts affect the gravitational pull of locations, creating "temporal" momentum over which later climate impacts may have less influence. Similarly, the timing of population change (growth or decline) projected by the SSPs relative to the development of sectoral impacts can influence outcomes. For example, for most countries in the study, projected population growth is greatest during the first decade; if conditions are also predicted to deteriorate severely during that period, the impact on migration will be greater than if the deterioration took place during a more demographically stable period.
4. If the SSP-only model finds a place that is relatively attractive and the sectoral climate impacts are positive or neutral (relative to other areas that see negative impacts), it will have the effect of reinforcing the attractiveness of that area. Conversely, in remote areas experiencing population decline and negative climate impacts, "push" factors will be reinforced. This phenomenon creates spatial momentum.
5. The climate in-migration results can be interpreted as population levels above what would otherwise occur in the absence of climate impacts on livelihoods due to the increased viability of livelihoods, and climate out-migration results can be interpreted as population declines that would not otherwise occur in the absence of climate impacts. There may be situations in which the development-only (SSP or "no climate") model runs project higher rates of population decline in rural areas than the model runs that include climate impacts–i.e., that more benign or favorable climate conditions in the future put a brake on rural out-migration. In those relatively rare cases, it is not so much "climate migration" that is being measured as reductions in out-migration that otherwise would have occurred.
6. Model parameterization affects the results. The model was calibrated using actual population changes in association with actual climate impacts (represented by ISIMIP model outputs) for two periods, 1990-2000 and 2000-2010. This calibration was done using the two separate sets of model combinations: the LPJmL water and crop models and the WaterGAP water and GEPIC crop models. Different parameters correspond to the different models. If the parameter estimates are close together across the different crop or water models, there will be less variation in the population distribution projected by each model; the uncertainty around the ensemble mean (measured using the

coefficient of variation) will therefore be lower. Conversely, if parameter estimates are not close together, there will be greater uncertainty around the ensemble mean.

7. Because the historical population data for a country have to meet certain stringent criteria to be used for calibration, one or more representative countries from each sub-region that meet those criteria are selected for calibration (Table 4), and the coefficients derived from that calibration are applied to all countries in the region. If those countries are not representative from a climatological or geographical standpoint, or in terms of level of development, that will affect the degree to which those coefficients are applicable in the other countries, thus increasing the uncertainty of model outputs in those countries.
8. Countries within regions are at different stages of economic development, which can have a significant impact on the population totals by 2050 for the two groups.
9. Cross-border migration is included in the socioeconomic scenarios underlying this work, insofar as population totals by country include an cross-border migration component. However, the modeling was carried out separately for each country and the modeling work does not include cross-border movements as a consequence of climate impacts. Climate change can be an inhibitor or a driver of cross-border migration, depending on a range of factors that propel individuals to decide to move and would need to be considered on a case by case basis. If in the future climate change impacts do result in higher or lower levels of bilateral flows between countries, then this will also lead to different results than those modeled here

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XI. Source Code

No source code is provided.

XII. References

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Appendix 1. Data Revision History

No revisions to date.

Appendix 2. Contributing Authors & Documentation Revision History

Revision Date	ORCID	Contributors	Revisions
July 5, 2022	0000-0002-8875-4864	Alex de Sherbinin, Bryan Jones	This document is the 1st instance of documentation.