

Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways

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Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways

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B Jones¹ and B C O'Neill²¹ City University of New York Institute for Demographic Research, 135 East 22nd Street, NY 10010, USA² National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307, USAE-mail: bryan.jones@baruch.cuny.edu**Keywords:** spatial population, population projections, Shared Socioeconomic PathwaysSupplementary material for this article is available [online](#)**Abstract**

The projected size and spatial distribution of the future population are important drivers of global change and key determinants of exposure and vulnerability to hazards. Spatial demographic projections are widely used as inputs to spatial projections of land use, energy use, and emissions, as well as to assessments of the impacts of extreme events, sea level rise, and other climate-related outcomes. To date, however, there are very few global-scale, spatially explicit population projections, and those that do exist are often based on simple scaling or trend extrapolation. Here we present a new set of global, spatially explicit population scenarios that are consistent with the new Shared Socioeconomic Pathways (SSPs) developed to facilitate global change research. We use a parameterized gravity-based downscaling model to produce projections of spatial population change that are quantitatively consistent with national population and urbanization projections for the SSPs and qualitatively consistent with assumptions in the SSP narratives regarding spatial development patterns. We show that the five SSPs lead to substantially different spatial population outcomes at the continental, national, and sub-national scale. In general, grid cell-level outcomes are most influenced by national-level population change, second by urbanization rate, and third by assumptions about the spatial style of development. However, the relative importance of these factors is a function of the magnitude of the projected change in total population and urbanization for each country and across SSPs. We also demonstrate variation in outcomes considering the example of population existing in a low-elevation coastal zone under alternative scenarios.

Introduction

Spatially explicit projections of population are important factors in climate and global environmental change research. Population dynamics are important drivers of emissions and land use, and in determining mitigation opportunities. For example, spatial projections are commonly used as one determinant of future projections of urban land cover [1], agricultural land use [2] and spatial distributions of short lived pollutants such as SO₂ emissions [3], important to both regional climate effects and air quality. They are perhaps even more important in determining the potential exposure and vulnerability of the population to impacts. Population distribution near coastlines or

in cities can determine the risks of sea level rise and coastal storms [4, 5] and of exposure to heat waves [6, 7]. They are also a determinant of wildfire incidence [8], habitat fragmentation [9], and exposure to vector borne disease [10], all of which are also affected by climate change.

Local or regional scale spatial projections are frequently used for planning purposes, but large-scale (continental to global) spatial projections are less common, despite the demand for them in studies of global change. Global spatial population projections were developed that were consistent with the greenhouse gas emissions scenarios developed by the Intergovernmental Panel on Climate Change as part of the Special Report on Emissions Scenarios (SRES, [11, 12]). Other

Table 1. Summary of assumptions about demographic factors for five SSPs. Country groupings for factors affecting population growth outcomes (fertility, mortality, migration) are made according to current fertility and income conditions [17], while groupings for urbanization assumptions are made according to current income alone [18].

	SSP1 Sustainability	SSP2 Middle of the road	SSP3 Regional rivalry	SSP4 Inequality	SSP5 Fossil-fueled development
Population Growth					
High fertility	Low	Medium	High	High	Low
Other low fertility	Low	Medium	High	Medium low	Low
Rich low fertility	Medium	Medium	Low	Medium low	High
Urbanization level					
High income	Fast	Central	Slow	Central	Fast
Medium income	Fast	Central	Slow	Fast	Fast
Low income	Fast	Central	Slow	Fast	Fast
Spatial pattern					
	Concentrated	Historical patterns	Mixed	Mixed	Sprawl

efforts to produce such global-scale projections focused on urban populations alone [13] or maintained current distributional patterns [14].

Recently, a new set of future pathways of societal development have been developed for use in climate and global change research [15]. These Shared Socioeconomic Pathways (SSPs) describe five alternative outcomes for trends in demographics, economics, technological development, lifestyles, governance, and other societal factors. The SSPs consist of qualitative narratives of future development [16] and quantitative projections of key elements including national level population growth and educational composition [17], urbanization [18], and economic growth [19]. They describe futures that are intended to span uncertainty in two dimensions: challenges that societal conditions would present to adaptation to climate change, and challenges they would present to mitigation of climate change.

While the SSPs contain a wide range of information on possible future trends in societal development, a number of additional types of outcomes have been identified that would greatly facilitate studies of future impacts, adaptation, and vulnerability [20]. Chief among them is a set of projections of future spatial distribution of the population that is consistent with the five SSPs. Studies have already begun to use the SSPs in climate change impact assessments, but generally make ad hoc assumptions about future spatial population distributions. Approaches include using population fixed at the current levels and spatial distribution [21], scaling an existing spatial projection for a SRES scenario to match SSP aggregate population totals [22], applying uniform national level growth rates across cities [23], and scaling the existing spatial distribution of the population by aggregate national projections for the SSPs ([10] for malaria risk; [24] for exposure to record heat; [25] for heat wave risk; [26] for flood risk). This last approach is taken in several studies that are part of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; see <https://pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip/for-modellers/isi-mip>

[fast-track/input-data/ssp-data](#)). Thus there is a clear need for plausible alternative projections of the spatial distribution of the population that can represent different patterns of development and that are consistent with the different SSPs.

In this paper we present a new set of global spatial population projections at a resolution of $1/8^\circ$ for urban and rural population consistent, both quantitatively and qualitatively, with the SSPs. Quantitatively, the spatial projections are consistent with the total, urban, and rural populations at the national level in the SSPs themselves [17, 18]. Qualitatively, we interpret the SSP narratives [16] for characteristics related to the style of urban and suburban development envisioned in each SSP, and produce SSPs that share those characteristics. Methodologically, we build on a gravity model-based approach first applied in Gruebler *et al* [12] and extended in Jones and O'Neill [27] for projections of the US population. As in Jones and O'Neill, we calibrate the model to historical data on spatial population so that parameter values are grounded in observed patterns of development. Parameter values that produce spatial patterns of development judged to be consistent with particular SSPs are then used to produce projections.

In the next section, we present demographic elements of the SSPs. The methods section includes a description of the projection process, historical data, and relationship to SSPs. Projections for each SSP are presented in the results section, highlighting broad differences across SSPs in spatial patterns of projected change, the primary forces driving change and their impacts, and an example of population density in low-elevation coastal zones. Finally, the discussion section includes conclusions, caveats, and directions for future work.

Demographic elements of the SSPs

The SSPs are summarized more fully in the supplementary information (SI); here, we summarize the demographic elements (table 1), drawing on

assumptions in O'Neill *et al* [16], KC and Lutz [17], and Jiang and O'Neill [18]. General trends are applied to three broad country groups over the period 2010–2100. For the demographic factors driving population change countries are categorized as a function of current fertility and income into the following groups: high fertility, low fertility with high incomes (i.e., in the OECD), and low fertility. The high/medium/low assumptions relating to fertility are with respect to the full range of outcomes for each country group (e.g., 'high-fertility' in the currently low fertility countries is just above replacement level, and is not the equivalent of high-fertility elsewhere). For assumptions about urbanization levels, country groups are defined by current income levels alone. Finally, international migration is explicitly included in the national-level population projections that correspond to each SSP [17]. Rates are based on an existing global-level matrix of in- and out-migration [28] and are adjusted to reflect assumptions regarding, for example, conflict and political changes in each SSP [16].

SSP1 (sustainability) and SSP5 (fossil-fueled development) both envision a development path with increased investment in education and health and relatively high income growth, leading to a relatively rapid demographic transition and therefore low population growth in the high fertility countries. In contrast, in currently low fertility countries, optimism about economic prospects sustains fertility at medium (SSP1) or high levels (SSP5). Migration is substantial in both pathways, and urbanization is rapid, although it is less well managed in SSP5.

SSP3 (regional rivalry) and SSP4 (inequality) both envision relatively low investments in human capital and low income growth, leading to relatively high fertility and population growth rates in the currently high fertility countries. In contrast, economic uncertainty leads to relatively low fertility rates and low population growth (or decline) in the currently low fertility countries. Migration is relatively low in both pathways (especially SSP3), while urbanization differs: it proceeds slowly in SSP3, and rapidly in SSP4, with mixed spatial patterns of sprawl in some areas and more concentrated development in others.

SSP2 (middle of the road) describes a world in which demographic outcomes are consistent with middle of the road expectations about population growth, urbanization, and spatial patterns of development.

Methods

We produced scenario-based spatial projections for each of the five SSPs by downscaling national-level projections of urban and rural population change corresponding to each scenario to $1/8^\circ$ (7.5 arc minutes) for 232 countries and territories (see SI)

using a gravity-type model parameterized to reflect the spatial patterns of change prescribed by each SSP. The choice of resolution reflects earlier work [12, 27] and is an attempt to balance the uncertainty associated with very small-area projections against the benefits of subnational resolution. The process involves (1) calibrating the model to historic data to estimate urban and rural parameters indicative of certain patterns of spatial change, (2) selecting regionally representative parameters for each SSP, and (3) applying the downscaling procedure on a country-by-country basis for each SSP. Cells that straddle national boundaries are allowed to contain population from multiple countries. However, when the model is applied to any given country, only the population corresponding to that country is included in procedure. The downscaling model and parameterization processes are explained in more detail below, beginning with the downscaling procedure as it is necessary to understand the calibration procedure used to estimate parameters.

To downscale projected national-level urban and rural population change we use the NCAR gravity-based approach [27]. Beginning with a gridded distribution of the base-year population the model consists of five basic steps: (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 according to their respective urban potentials, and (4) allocate projected rural population change to grid-cells proportionally according to rural potential. Population potential surfaces, both urban and rural, are continuous across all cells, and as such each cell may contain urban and rural population. Because the allocation procedure can lead to some redefinition of population from rural to urban (e.g., rural population allocated to a cells with an entirely urban population is redefined as urban), a final step is to (5) redefine population as urban or rural as a function of density and contiguity with fully urban/rural cells to match projected national-level totals. These steps are then repeated for each 10 year time interval (see SI for illustrated example).

For the base-year population we use the 2000 2.5' Gridded Population of the World [29]. We define each grid cell, and the population therein, as urban or rural using the urban extent grids produced as part of the Global Urban-Rural Mapping Project (GRUMP [30]). Any grid cell with a center point falling within an urban extent is defined as urban. To ensure consistency with the national-level urbanization rate we then add to or subtract from cells defined as urban using a simple population density and contiguity algorithm until the total population of cells defined as urban matches the observed national total. The data are then aggregated to $1/8^\circ$ grid cells to carry out the modeling. As such, each grid-cell can contain both urban and rural populations in the base-year.

In steps (2)–(3) we construct separate population potential surfaces for the urban and rural populations that are used to allocate projected urban/rural change in steps (4)–(5). However, urban and rural population potential are both calculated using the total population in each grid-cell. Potential for each cell is calculated as:

$$v_i = a_i l_i \sum_{j=1}^m P_j^\alpha e^{-\beta d_{ij}}, \quad (1)$$

where v_i is potential of cell i , a_i is a cell-specific adjustment factor that removes boundary effects from the calculation of potential, l_i is the portion of each cell that falls within the country in question (in the case of border cells) and is suitable for human habitation, P is population within a grid-cell, d is geographic distance between two grid-cells, α and β are parameters, and j is an index of the m cells within a 100 km window around cell i (see SI). Urban and rural potential are both calculated using equation (1), however the values of α and β for urban and rural population differ from one another, reflecting the different patterns of spatial change assumed for these two different components of the population. Habitable land is calculated as the difference in the total area of each grid cell and the portion of the cell covered by a geospatial mask (l) that accounts for elevation, slope, surface water, and mandate for protection (see SI).

To produce estimates of α and β parameters for urban and rural populations that are indicative of observed patterns of historic spatial change, we fit the model to observed change in the 1990–2000 urban/rural GPW population distributions for a representative set of countries. We selected countries from 20 regions of the world (see SI) for which the 1990/2000 GPW distributions are based on two separate population censuses (avoiding cases in which GPW 2000 is a scaled version of 1990 owing to the lack of two separate census periods from which to compile gridded distributions). For each SSP, we specify urban/rural α and β parameters for each of the 20 world regions from the historic estimates that reflect the pattern of spatial change prescribed by the corresponding narratives. These parameters determine the pattern of, for example, spatial change in the urban population distribution (e.g., sprawl or concentration), however the overall level of urbanization is prescribed by the SSPs.

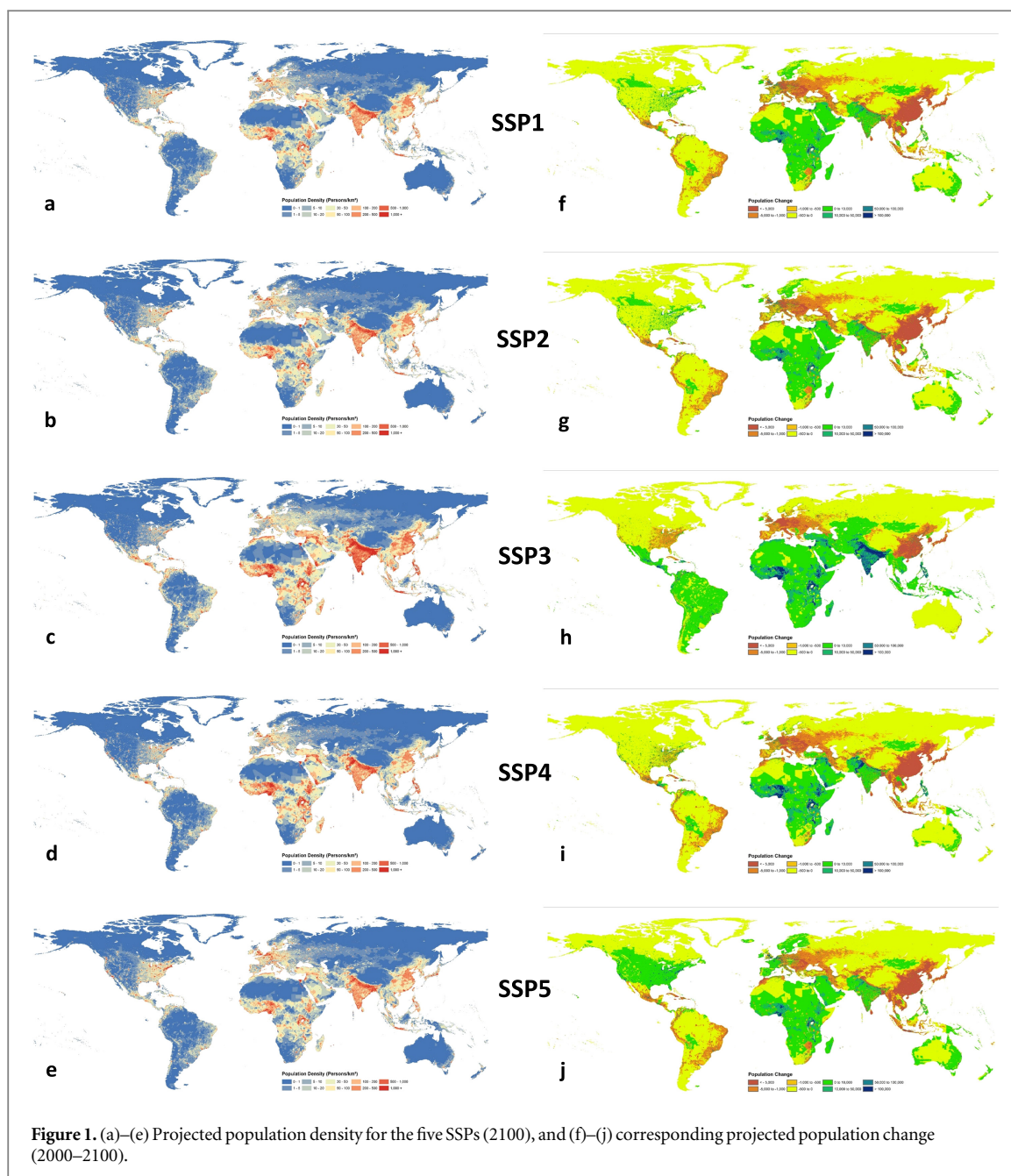
Results

Figure 1 includes outcomes for all five SSPs for population density in 2100 (figures 1(a)–(e)) and population change over the century (figures 1(f)–(j)). At the global scale variation in broad patterns of change are evident. For example, in SSP3, high fertility across the developing world leads to rapid population growth (figure 1(h)) which, coupled with slower urbanization, leads to very dense urban and rural

settlement patterns across sub-Saharan Africa, the Middle East, India, and Southeast Asia (figure 1(c)). In contrast, in this same scenario projected low fertility and lower rates of in-migration lead to widespread areas of population loss across much of the developed world, with only limited growth projected in urban areas (figure 1(h)). In SSP5, higher fertility rates driven by economic optimism in Europe, North America, and Australia, combined with international migration, lead to growth across these regions (figure 1(j)), while rapid development across Asia and Africa leads to low fertility and slower population growth relative to SSP3 (figure 1(e)). Similarly, the slower growth SSP1 scenario, coupled with its spatial pattern of urban concentration, leads to locally concentrated areas of urban growth across most of the world, along with substantial rural decline in developed regions such as Europe (figure 1(f)). Note that in all SSPs China is projected to experience substantial rural population decline, and a relatively stable urban population, a projection in line with the observed pattern of Chinese ‘rural hollowing’ [31]. Thus in stark contrast to India, demographic momentum leads to widespread population loss across most of China in all five SSPs.

Another means of summarizing global results is to plot distributions of land area and population by population density, as is done in figure 2 for 2100 for each of the five SSPs. The land area distribution indicates how much land is densely (versus sparsely) populated, while the population distribution indicates how much of the population lives in densely (versus sparsely) populated areas. In all cases the percentage of the global population in low to medium density areas (<1000 persons km^{-2}) declines relative to the base-year, while the proportion residing in higher density areas increases significantly. However there are substantial differences across SSPs. The percentage of people living in high density areas is largest in SSP3, driven by its high population growth (despite its slower urbanization assumptions), and smallest in the slower growth SSP1 and SSP5 scenarios (especially in SSP1 in which growth in industrialized countries is slower than in SSP5). The proportion of land area containing relatively low population density declines in all SSPs with the exception of the lowest density areas (<1 person km^{-2}) and zero population cells which actually increase in number (a function of rural population decline across most countries). Conversely, very densely populated land increases relative to the base-period. The aggregate patterns depicted in figure 2 vary substantially on a country-by-country basis.

To illustrate the types of outcomes that occur across SSPs within a single country, we show results for Nigeria in figure 3. High population growth in SSP3 and SSP4 is evident in figures 3(c) and (d), however the lower urbanization rate in SSP3 (63% versus 93%) leads to a much larger rural population, manifest in the more dispersed pattern of change (figures 3(h) and (i)). The projected urbanization rate is the same

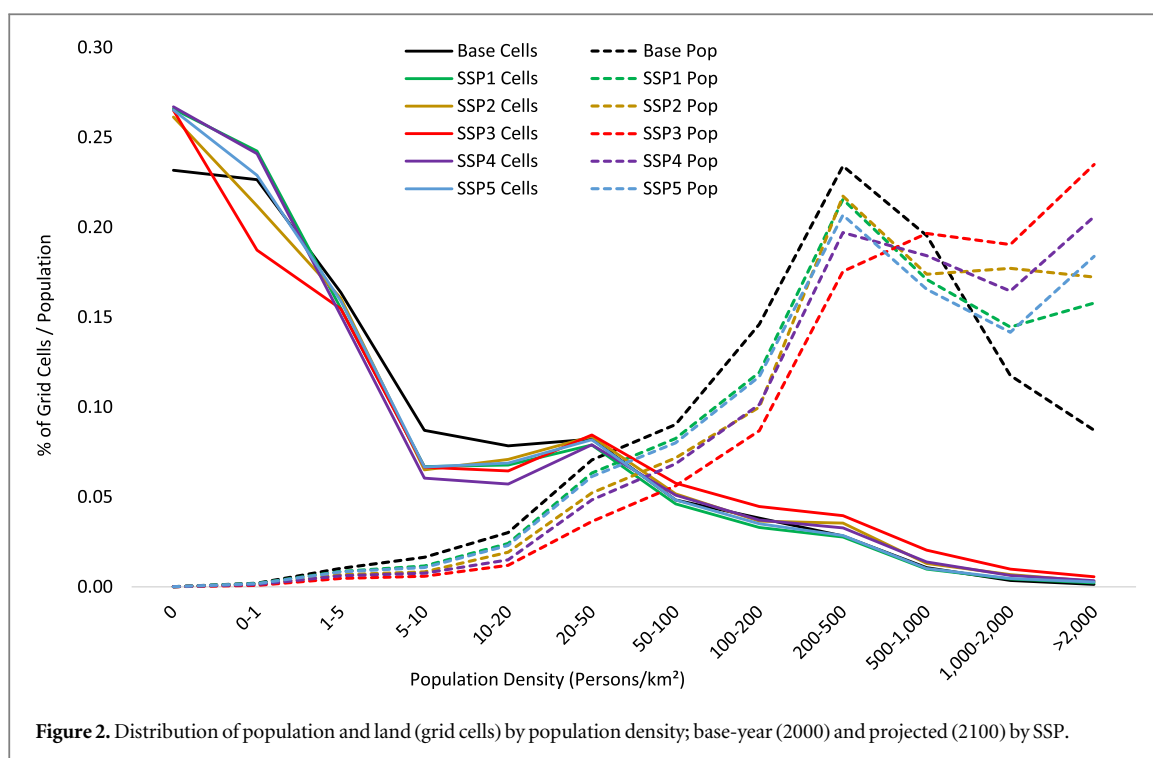


for SSPs 1, 4, and 5, however the projected total population for SSP4 is nearly double the other two, evident in figure 3(i) relative to figures 3(f) and (j). SSP1 and SSP5 are both slower growth, high urbanization scenarios, however small differences arise as a result of the implied pattern of spatial change (concentration and sprawl, respectively). Finally, SSP2 represents a middle-of-the-road outcome with moderate population density and change relative to the other scenarios (figures 3(b) and (g)).

Outcomes for Nigeria can also be used to address the question of which factors are most important in driving spatial population change in the SSPs. Projected spatial population change across each of the SSPs is driven by three factors: (1) aggregate national-level population change, (2) national-level

urbanization, and (3) the style of spatial development (reflected in parameter values assumed in the down-scaling model). Spatial variation resulting from the first factor is purely a function of the presence of a larger or smaller number of people within sub-national grid cells resulting from the aggregate projection. National-level urbanization leads to more people located near existing urban areas, since the gravity model generally allocates new urban population in or near existing urban areas. Finally, the style of spatial development affects the degree to which populations tends towards sprawl or concentration.

We are able to assess the relative contribution of each factor to spatial population change in Nigeria by comparing outcomes from SSPs in which two of the three factors are similar, and differences in outcomes



are due mainly to the remaining factor. That analysis (see SI for full details) shows that in terms of relative importance, measured by the effect on average percent difference in population density across grid cells, aggregate national-level change is the most influential (66.1%), followed by urbanization rate (20%), and finally the spatial pattern of development (9.7%). All three factors impact spatial outcomes in each country/territory for which projections were carried out in a somewhat similar fashion, however the relative importance of aggregate level population change and urbanization are dictated to a degree by the magnitude of those changes (e.g., in highly urbanized, slow-growth nations, aggregate growth and urbanization rate contribute less to overall change).

To illustrate how outcomes vary across SSPs at the city level, we consider the city of Kano, Nigeria, the country's second largest city situated in the north-central region (figure 4(b)). Here we present normalized distance density gradients over a 50 km radius from the center of Kano (figure 4(c)) for the base-year (2000) and each SSP (2100). The high-population, high-urbanization SSP4 scenario produces the steepest gradient, indicating the highest city-center density relative to the surrounding urban fringe. SSP1, the high-urbanization, concentrated growth scenario with much lower population growth than SSP4 also produces a steep gradient relative to the other scenarios. SSP 3 (high-population, low-urbanization) and SSP5 (low-population, high-urbanization, sprawling-growth) produce similar gradients, while the middle-of-the-road SSP2 scenarios produces results that most resemble the base-year.

Future exposure: sea-level rise

Population scenarios are crucial to the assessment of exposure and vulnerability to physical hazards under alternative future assumptions regarding both climate and demographic change. To illustrate this point we consider exposure to sea-level rise and coastal flooding as characterized by the population residing in low elevation coastal zones (LECZ, [5]). LECZs are comprised of contiguous land area under 10 m in elevation that border a major body of water (see SI). Many major world cities (e.g., Shanghai, Kolkata) lie within LECZs, and on average a larger portion of residents in the developing world reside in LECZs than in the developed world. Relative to base-year levels the largest projected global increase in LECZ population occurs in SSP3, the highest growth scenario. The numbers vary regionally however (table 2), primarily as a function of regional assumptions regarding population change. Urbanization rate and spatial patterns of change contribute to a lesser degree and are more evident on a country-by-country basis. For example, exposure is highest in SSP5 in Europe, North America, and Oceania, the highest growth scenario in these regions, whereas exposure is greatest in SSP3 for Latin America, Asia, and Africa. Outcomes for individual regions vary widely across SSPs. In North America, exposure in 2100 ranges from similar to today's level of just above 30 million people (SSP3, a low growth pathway for this region), to more than doubling to nearly 80 million (in SSP5, in which regional population growth is high). In Asia, population in LECZs actually declines in SSPs 1, 4, and 5, a function of total population decline in China and slower growth throughout India and Southeast Asia, while it increases

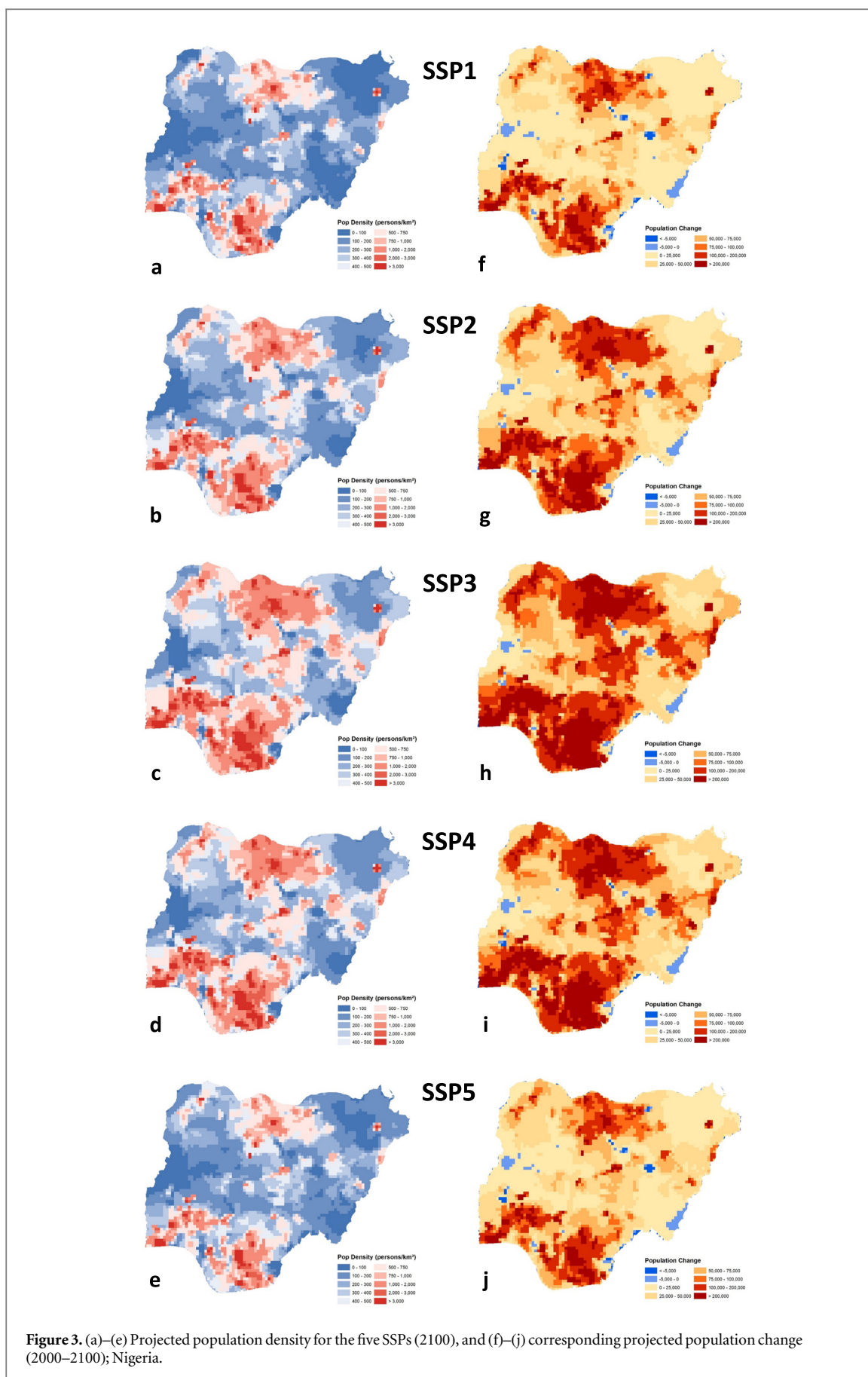


Figure 3. (a)–(e) Projected population density for the five SSPs (2100), and (f)–(j) corresponding projected population change (2000–2100); Nigeria.

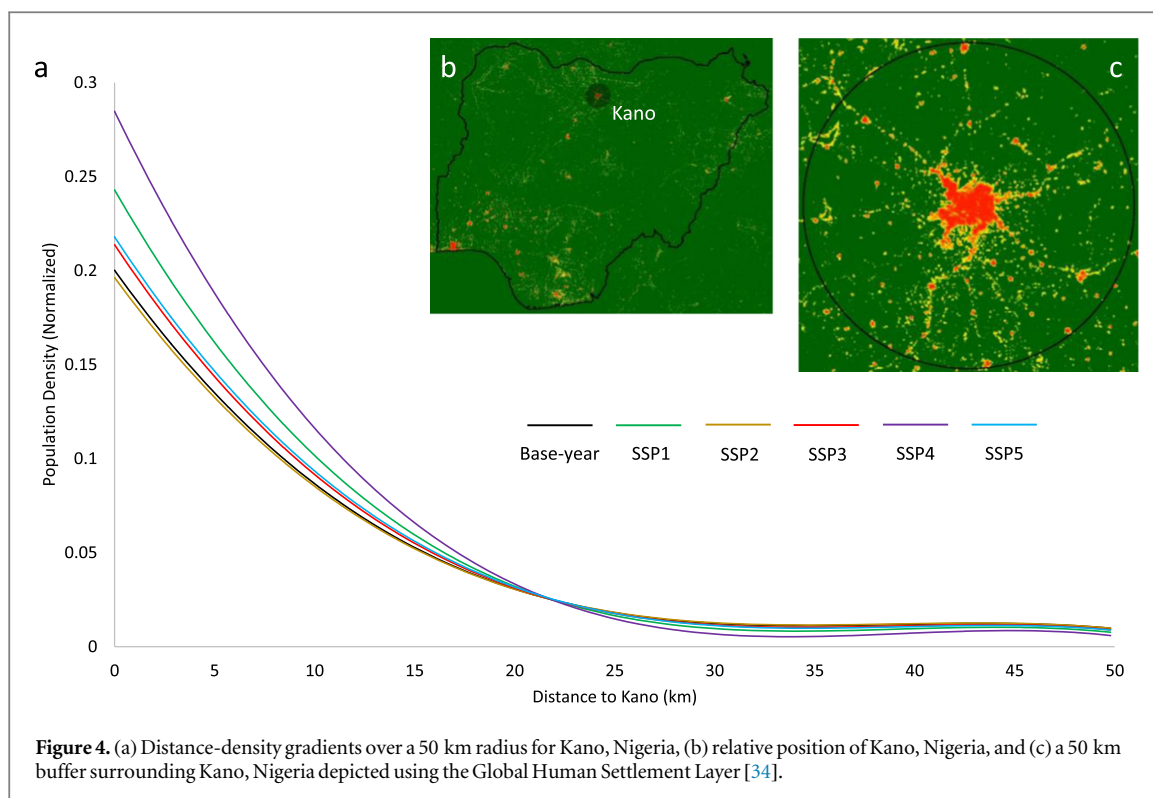


Table 2. Population (millions) living in low-elevation coastal zones, base-year (2000) and projected (2100).

Region	Base	Scenario				
		SSP1	SSP2	SSP3	SSP4	SSP5
North America	31.247	53.607	52.885	31.32	42.742	78.874
Latin America	40.544	39.435	53.673	83.572	41.37	37.427
Europe	56.055	61.439	62.298	38.806	48.367	88.982
Africa	56.444	105.501	144.334	219.32	158.264	101.496
Asia	512.488	472.166	581.208	765.376	492.985	476.314
Oceania	5.39	9.953	10.576	7.553	9.011	14.712
World	702.167	742.101	904.974	1145.946	492.74	797.805

by about half in SSP3. In all scenarios exposure increases in Africa, ranging from not quite doubling (SSP1) to nearly quadrupling (SSP3).

Discussion

Global-scale spatially explicit population scenarios that can be made consistent with the qualitative narratives guiding global-change research are of increasing importance, and are a necessary component in the assessment of exposure/vulnerability to hazards. Few examples of such scenarios exist, and of those most are simple extrapolations. Here we presented a set of global-scale population scenarios that are quantitatively and qualitatively consistent with the new SSPs. A parameterized gravity-based downscaling model is used to allocate projected change in urban and rural population across sub-national grid-cells, controlling for both protected land and geographic

characteristics of the landscape. The model is calibrated to observed patterns of change in historic data to produce parameter estimates indicative of certain patterns of spatial change. We take the national-level population change and urbanization rates included in the SSPs, and parameter estimates that fit the pattern of spatial population change implied by the SSP narratives, to produce scenarios consistent with the assumptions regarding each development pathway.

Broad-scale patterns, identifiable at the global scale, are consistent with the assumptions driving each of the SSPs. For example, the substantial urban and rural growth across Africa and Asia implied by SSP3, growth in Europe and North America in an SSP5 future, fragmented urban growth and rural decline in SSP4, and the consistent population decline in China across all SSPs are all easily identifiable. At the country level we observe how relative levels of population change and urbanization, as well as different spatial

patterns of change, combine to drive different patterns of growth, illustrated using projected outcomes for Nigeria. For example, projections for the high-population scenarios (e.g., SSP3 and SSP4) vary substantial as a function of the urbanization rate. Similarly, at the city level we illustrate variation in projected distance-density gradients. We find that assumptions regarding spatial patterns of change and urbanization are important factors driving the projected population structure in urban areas.

At the national level we unpack the relative contribution of three primary drivers of spatial patterns of change in the gridded data: total population change, urbanization, and local spatial patterns. We find that, in rapid-growth/urbanization scenarios such as those commonly found in parts of Africa, it is aggregate-level change driving the largest portion of projected grid-cell level change, followed in importance by the urbanization rate and then spatial patterns of change. As the magnitude of projected change in aggregate-growth and urbanization decline, the relative importance of more local patterns of spatial change increase. These patterns, and the forces driving them, have implications for impacts as they are the primary determinants of population exposure to climate hazards (illustrated here using LECZs as a proxy for exposure to sea-level rise and coastal events).

A key caveat to this work is that neither the national-level population and urbanization projections associated with the SSPs nor the spatial projections developed here account for the potential impacts of climate change, which may lead to alternative, unanticipated population and urbanization outcomes, such as the movement of people away from potentially drought-ridden regions of East/Central Africa or coastal urban areas facing rising sea-levels and towards currently under-developed cooler areas. There is growing emphasis on anticipating the potential sources and movement of climate migrants [e.g., 32] and constructing spatial projections that include such 'what-if' scenarios should be high priority in the future.

Other limitations related to the outcomes reported here result from the underlying population distributions that serve as the base-year distribution (2000) and the calibration period (1990–2000). First, the GPW data that serve as the base-year distribution are based on population counts obtained at the highest resolution administrative units available and are assumed to be distributed uniformly within those units. As such, in some cases we observe large areas of uniform population distribution in the base-period (e.g., parts of Saharan Africa and Saudi Arabia), which upon application of the gravity model leads to a similar potential distribution and thus the allocation of future population in patterns or places that may be somewhat unrealistic. The problem is limited to a few geographic areas that tend to be very lightly populated, as such only a small portion of the population is affected, but

the results can be seen, for example, in areas of the Saudi Arabian desert in SSP3. A related problem results when we attempt to fit the model to historic data in places where the underlying population distribution is unrealistically uniform. We generate parameter estimates that tend towards maintaining uniformity in some cases, which is not a plausible outcome under any of the SSPs. In such cases we chose not to include affected parameter estimates for consideration as markers for any of the SSP narratives. Additionally, in some cases the 2000 GPW data is simply a scaled version of the 1990 distribution (when data from only one historic census was available). We also chose to exclude these countries from the calibration process. Despite the issues, GPW best served our purposes as it is the only global population data set that is constructed consistently over time and space (e.g., in 1990 and 2000, and across different countries), allowing us to calibrate our model without having to account for affects related to, for example, disparate dasymetric techniques applied at different time periods. A final limitation of note is that the historic distributions are available for only a very short time period (10 years). As such we are generating parameter estimates from a small sample. To combat this problem we carried out the procedure for a large sample of countries, and compared results to estimates generated from alternative historic data in countries where the historic record is longer.

Plans for future work include the application of refined base-year data to alleviate several of the aforementioned limitations, continued assessment of the drivers of spatial population change across multiple scales, and potential refinement and/or alternative forms of the downscaling procedure. Since the time this work was completed, GPW version 4 [33] has become available, and in some countries the gridded data reflect a higher-resolution census geography. The gravity framework presented here is particularly flexible in terms of its specification, a key feature of the model. As additional global-scale spatially explicit data becomes available we are easily able to incorporate additional spatial layers that may serve to attract or repel population. Similarly, we are exploring the correlation between patterns of spatial change, as characterized by the gravity parameters, to alternative demographic/socio-economic indicators, facilitating both additional exploration into the possible drivers of spatial change and projections guided explicitly by these indicators.

Despite the limitations discussed here the results represent a major step forward in global-scale spatially explicit population scenarios, and are potentially very useful to the global change research community. In contrast to many existing projections that are simply scaled versions of the existing population, or extrapolate current trends into the future, these scenarios are consistent with the demographic assumptions of the SSPs, and reflect the population dynamics implied

by the each of the SSP narratives. As such, they will enhance ongoing assessment of alternative demographic, socio-economic, and environmental outcomes, particularly as they relate to climate-change adaptation/mitigation.

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