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LETTER

Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways

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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 SO_2 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 $1/8°$ 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° (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 mulitple 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° 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 to 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

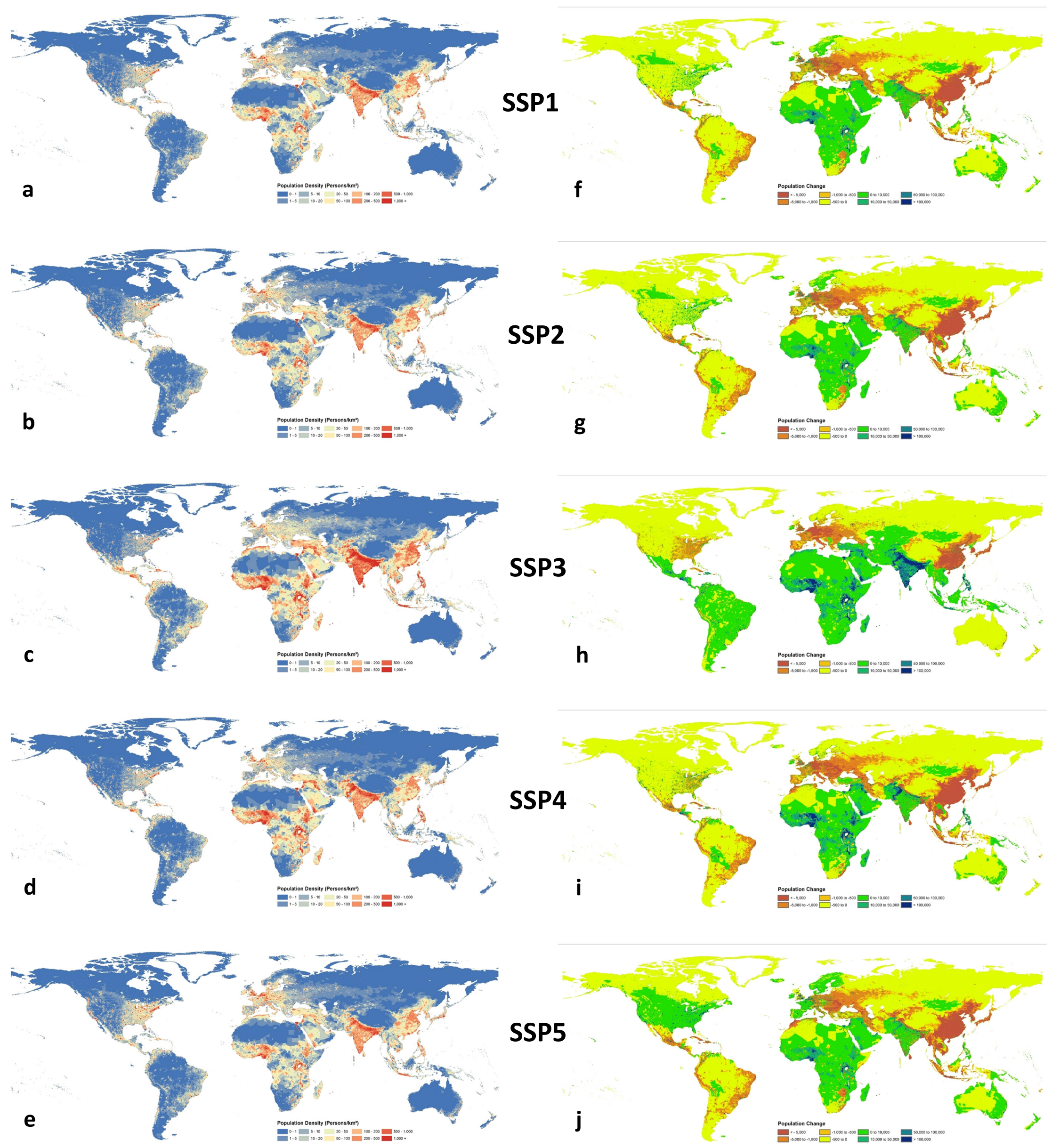

Figure 1. (a)–(e) Projected population density for the five SSPs (2100), and (f)–(j) corresponding projected population change (2000–2100).

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 downscaling 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

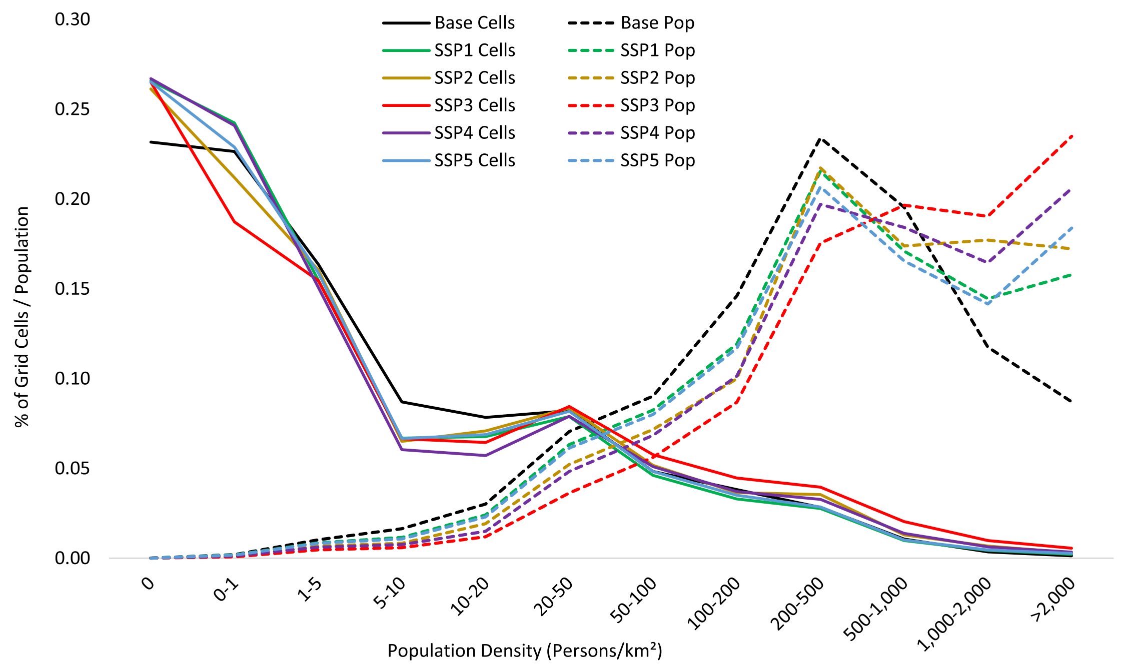

Figure 2. Distribution of population and land (grid cells) by population density; base-year (2000) and projected (2100) by SSP.

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

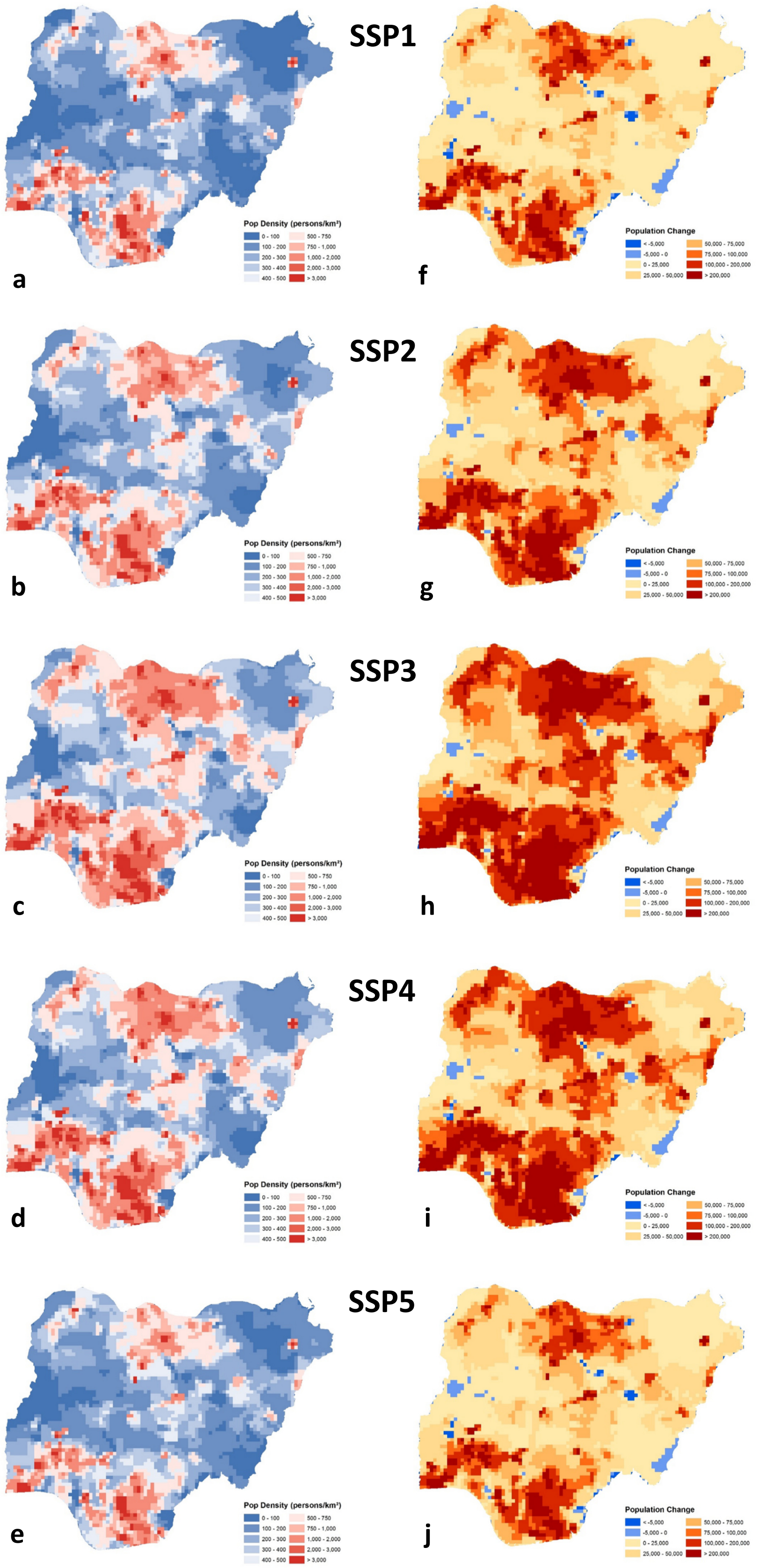

Figure 3. (a)–(e) Projected population density for the five SSPs (2100), and (f)–(j) corresponding projected population change (2000–2100); Nigeria.

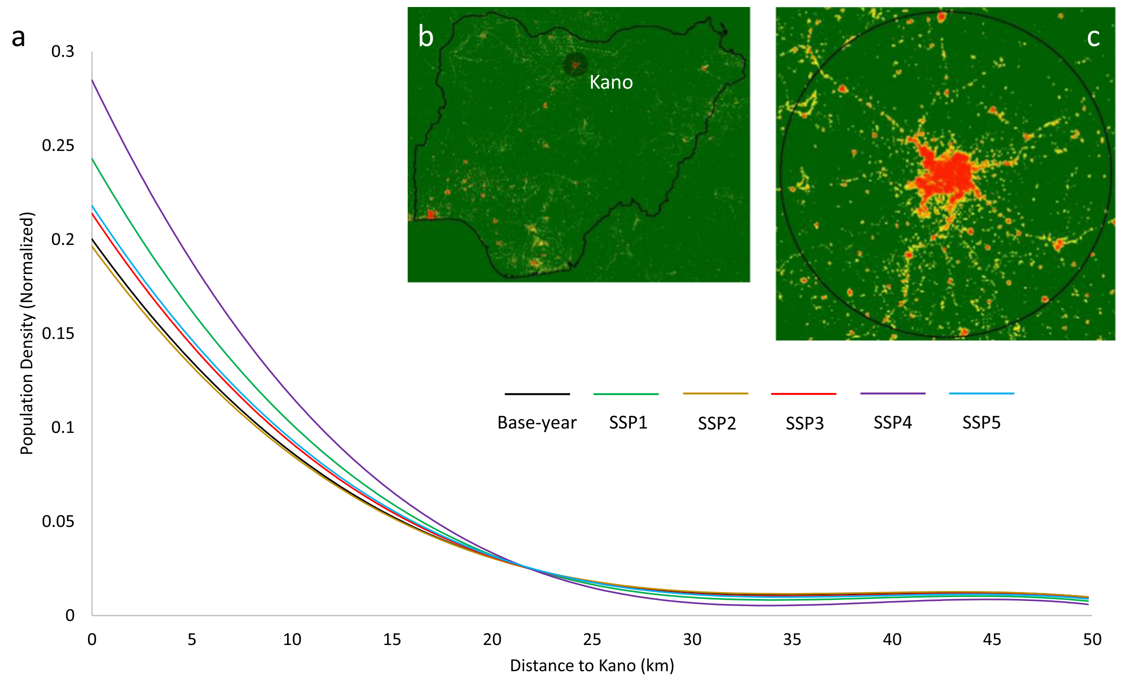

Figure 4. (a) Distance-density gradients over a 50 km radius for Kano, Nigeria, (b) relative position of Kano, Nigeria, and (c) a 50 km buffer surrounding Kano, Nigeria depicted using the Global Human Settlement Layer [34].

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

		Scenario				
Region	Base	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
Afirca	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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Supplementary Information

Jones and O'Neill, Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways

Outline

This supplementary information contains additional text and figures on four topics:

S1. Full SSP description
S2. Countries and territories, world regions, and data sources
S3. Additional methodological detail
S4. Drivers of spatial population change

S1. Full SSP Description

The five SSPs span a wide range of possible future development pathways and describe trends in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. Trends are described for three broad country groups from the present through the end of the century. For most demographic factors, those groups are the currently high fertility countries, low fertility countries with high incomes (i.e., in the OECD), and other low fertility countries. For assumptions about urbanization levels, country groups are somewhat different, defined by current income levels alone.

Two SSPs describe worlds in which societal conditions are hypothesized to present (on balance) low challenges to adaptation. SSP1 (Sustainability) envisions a development path with a gradual shift toward greater emphasis on environmental protection, reduced inequality, and enhanced cooperation internationally and among different segments of society. There is 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 levels (somewhat below replacement levels of about two children per woman). Migration is moderate and urbanization, though rapid, is well managed and sprawl and urban de-concentration is minimized. SSP5 (Fossil-fueled Development) has a greater emphasis on competitive markets, innovation and globalization than does SSP1, and also a greater reliance on fossil fuels (with less concern for global environmental consequences). But it also has several similarities in terms of human capital and demographic outcomes. Strong investments in education and even more rapid income growth than in SSP1 lead to similarly low fertility (and low population growth) in high fertility countries and even higher fertility in the currently low fertility countries (at or around replacement level). Migration levels are high, and urbanization (as in SSP1) is rapid. However, unlike SSP1, urban planning has difficulty keeping up with high urbanization rates, and sprawling patterns of development dominate.

Two SSPs describe worlds in which conditions are assumed to present high challenges to adaptation. SSP3 (Regional Rivalry) foresees a world in which nationalism and security concerns lead to regionalization (rather than globalization), with weak institutions, slow technological change and economic growth, and little environmental protection. Relatively low investments in human capital lead 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. The low assumed migration rates do little to contribute to growth in these regions. Limited urban employment opportunities lead to slow urbanization, and urban settlements are poorly planned, particularly in developing countries, where inequality and fragmentation lead to a mixed pattern of urban change (e.g., pockets of wealthier, deconcentrated settlements alongside more concentrated slum-type growth). SSP4 (Inequality) has some similarities to SSP3 in terms of generally low investments in human capital, slow technological change and low income growth. However it envisions a widening gap between the majority of society and a small, well-educated, internationally connected elite that drives a portion of the economy. Broadly speaking, population growth outcomes are similar, although fertility is somewhat higher in some currently low-fertility countries and migration is moderately higher. Urbanization, however, is high in this scenario (as opposed to low in SSP3), driven by a lack of rural employment opportunities. Spatial development patterns vary across cities, with sprawl dominating in some while better planning in cities predominantly inhabited by the higher income classes leads to more concentrated development.

SSP2 (Middle of the Road) describes a world with development that occurs at rates consistent with historical patterns, and therefore has moderate levels of investment in human capital, technological change, and economic growth. Demographic outcomes are consistent with middle of the road expectations about population growth, urbanization, and spatial patterns of development. Trends vary across regions and over time, but on average fall near the center of expectations about future outcomes rather than toward the upper or lower bounds of possibilities.

Figure S1 shows global population and urbanization outcomes for the five SSPs. Country-specific projections are available online at https://tntcat.iiasa.ac.at/SspDb/. Table 1 (main text) summarizes the qualitative assumptions about population growth, urbanization, and spatial patterns of development for three country groups across the SSPs.

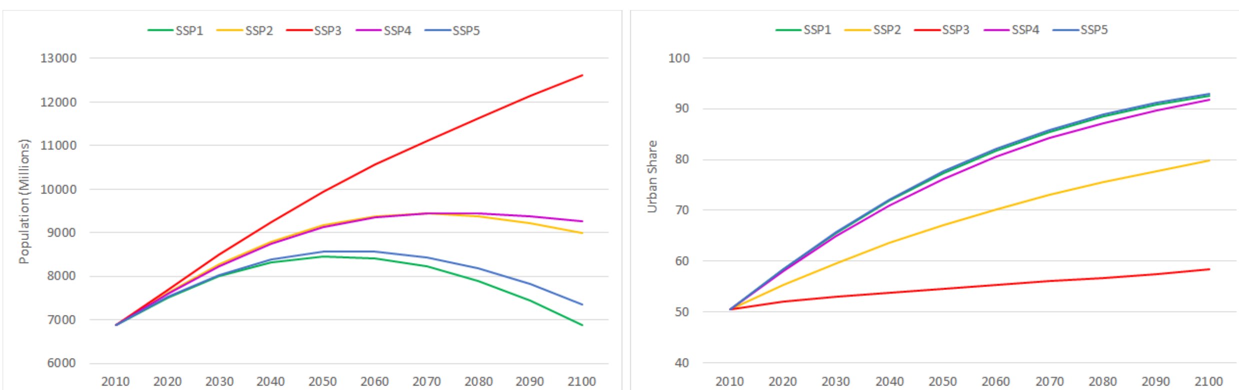

Figure 1. Global population (a) and urbanization (b) for the five SSPs.

The UN population division has also produced a series of probabilistic country-level projections to 2100 [1]. It is difficult to directly compare SSP-based projections to the UN projections, owing to the very different methodological approaches (alternative scenarios based largely on expert judgment grounded in alternative narratives, versus a probabilistic Bayesian model estimated on historical data). One point of comparison is that the middle-of-the-road SSP2 scenario yields a global population somewhat lower than the UN medium scenario. A fuller comparison is beyond the scope of our work but could inform future versions of SSP-related population projections.

S2. Countries and territories, world regions, and data sources

In this work we produce spatially explicit population projections for 232 separate countries and territories (see Table S1) for each SSP over the period 2010-2100 by downscaling projected change in the urban and rural population from the national-level to 1/8° subnational grid cells. For purposes of calibrating and parameterizing the downscaling model we classify countries/territories into 20 world regions (see Figure S2) based roughly on the United Nations Population Division geographic classification system used in the periodically published World Population and Urbanization Prospects [e.g., 2]. World regions are designed to encompass groups that exhibit similar patterns of spatial development (the calibration and parameterization process are described in more detail in section S3). Table S1 lists each of the 232 countries/territories by world region, and includes the source of national-level, SSP-specific population and urbanization projections. The bulk of the national-level population data (194 countries/territories) are from the International Institute for Applied Systems Analysis - Wittgenstein Centre for Demography and Global Human Capital (IIASA-WIC) projections [3]. The IIASA-WIC projections are based on alternative assumptions on future, fertility, mortality, migration, and educational transitions that correspond to the five SSP storylines and include all world countries/territories with a population greater than 100,000 [3]. SSP-specific projections of urbanization corresponding to the IIASA-WIC population projections were produced by the National Center for Atmospheric Research (NCAR; citation). The IIASA-WIC and NCAR projections are available online at https://tntcat.iiasa.ac.at/SspDb/.

We include an additional 38 smaller countries/territories in our projections. Population projections for most of these (35 countries/territories) are from the United Nations [2]. The UN high, medium, and low projections are adopted to represent the SSPs as a function of each income class. Table S3 indicates which UN population projection corresponds to each SSP for high, medium, and low income countries as defined by the World Bank [4]. Income class is indicated in Table S1 for all countries/territories for which the UN is the source of population data. There are no corresponding projections of urbanization for these countries/territories. Therefore, we define the population as entirely urban or rural as a function of the current urbanization rate (e.g., countries currently more than 50% urbanized are defined as urban). The exception to this rule is Taiwan, for which a single UN urbanization projections exists for the period 2010-2050 [5]. We extrapolate forward to 2100 and adopt this urbanization scenario for all SSPs. Urban/rural classification is indicated in column three of Table S1. Finally, an additional three territories (Norfolk Island, Pitcairn Island, and Svalbard) are included in our scenarios, but because no population projections exist for these territories we assume constant population over the period.

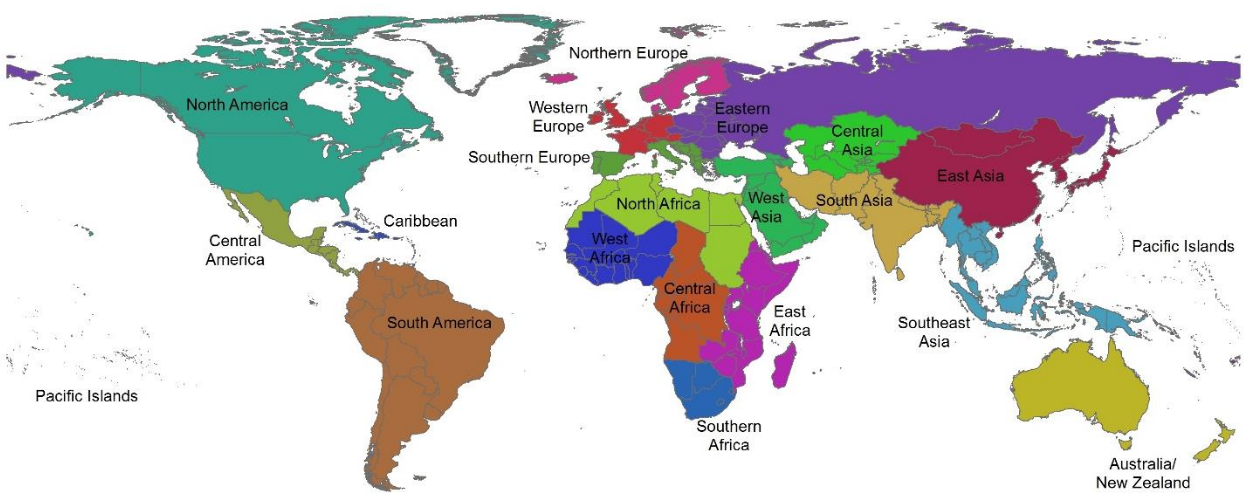

Figure S2. World regions.

Table S1. World countries and territories by region, source of population and urbanization projection, and World Bank income classification.

Region	Country/Territory	Population Projection	Urban	Income Class
Central Africa				
	Angola	IIASA-WIC	NCAR	*
	Cameroon	IIASA-WIC	NCAR	*
	Central African Republic	IIASA-WIC	NCAR	*
	Chad	IIASA-WIC	NCAR	*
	Congo	IIASA-WIC	NCAR	*
	Congo, Democratic Republic	IIASA-WIC	NCAR	*
	Equatorial Guinea	IIASA-WIC	NCAR	*
	Gabon	IIASA-WIC	NCAR	*
	Sao Tome and Principe	IIASA-WIC	NCAR	*
Eastern Africa				*
	Burundi	IIASA-WIC	NCAR	*
	Comoros	IIASA-WIC	NCAR	*
	Djibouti	IIASA-WIC	NCAR	*
	Eritrea	IIASA-WIC	NCAR	*
	Ethiopia	IIASA-WIC	NCAR	*
	Kenya	IIASA-WIC	NCAR	*
	Madagascar	IIASA-WIC	NCAR	*
	Malawi	IIASA-WIC	NCAR	*
	Mauritius	IIASA-WIC	NCAR	*
	Mayotte	IIASA-WIC	NCAR	*
	Mozambique	IIASA-WIC	NCAR	*
	Reunion	IIASA-WIC	NCAR	*
	Rwanda	IIASA-WIC	NCAR	*
	Seychelles	UN	*Urban*	Medium
	Somalia	IIASA-WIC	NCAR	*
	Uganda	IIASA-WIC	NCAR	*
	United Rep. of Tanzania	IIASA-WIC	NCAR	*
	Zambia	IIASA-WIC	NCAR	*
	Zimbabwe	IIASA-WIC	NCAR	*
Northern Africa				
	Algeria	IIASA-WIC	NCAR	*
	Egypt	IIASA-WIC	NCAR	*
	Libyan Arab Jamahiriya	IIASA-WIC	NCAR	*
	Morocco	IIASA-WIC	NCAR	*
	Sudan	IIASA-WIC	NCAR	*
	Tunisia	IIASA-WIC	NCAR	*
	Western Sahara	IIASA-WIC	NCAR	*

Region	Country/Territory	Population Projection	Urban	Income Class
Southern Africa				
	Botswana	IIASA-WIC	NCAR	*
	Lesotho	IIASA-WIC	NCAR	*
	Namibia	IIASA-WIC	NCAR	*
	South Africa	IIASA-WIC	NCAR	*
	Swaziland	IIASA-WIC	NCAR	*
Western Africa				
	Benin	IIASA-WIC	NCAR	*
	Burkina Faso	IIASA-WIC	NCAR	*
	Cape Verde	IIASA-WIC	NCAR	*
	Côte d'Ivoire	IIASA-WIC	NCAR	*
	Gambia	IIASA-WIC	NCAR	*
	Ghana	IIASA-WIC	NCAR	*
	Guinea	IIASA-WIC	NCAR	*
	Guinea-Bissau	IIASA-WIC	NCAR	*
	Liberia	IIASA-WIC	NCAR	*
	Mali	IIASA-WIC	NCAR	*
	Mauritania	IIASA-WIC	NCAR	*
	Niger	IIASA-WIC	NCAR	*
	Nigeria	IIASA-WIC	NCAR	*
	Saint Helena	UN	*Rural*	Medium
	Senegal	IIASA-WIC	NCAR	*
	Sierra Leone	IIASA-WIC	NCAR	*
	Togo	IIASA-WIC	NCAR	
Central Asia				
	Kazakhstan	IIASA-WIC	NCAR	*
	Kyrgyzstan	IIASA-WIC	NCAR	*
	Tajikistan	IIASA-WIC	NCAR	*
	Turkmenistan	IIASA-WIC	NCAR	*
	Uzbekistan	IIASA-WIC	NCAR	*
Eastern Asia				
	China	IIASA-WIC	NCAR	*
	Hong Kong	IIASA-WIC	*Urban*	*
	Japan	IIASA-WIC	NCAR	*
	Korea, Dem. People's Rep. of	IIASA-WIC	NCAR	*
	Macao	IIASA-WIC	*Urban*	*
	Mongolia	IIASA-WIC	NCAR	*
	Republic of Korea	IIASA-WIC	NCAR	*

Region Country/Territory	Population Projection	Urban	Income Class
Taiwan	UN	UN	High
Southern Asia			
Afghanistan	IIASA-WIC	NCAR	*
Bangladesh	IIASA-WIC	NCAR	*
Bhutan	IIASA-WIC	NCAR	*
India	IIASA-WIC	NCAR	*
Iran	IIASA-WIC	NCAR	*
Maldives	IIASA-WIC	NCAR	*
Nepal	IIASA-WIC	NCAR	*
Pakistan	IIASA-WIC	NCAR	*
Sri Lanka	IIASA-WIC	NCAR	*
Southeastern Asia			
Brunei Darussalam	IIASA-WIC	NCAR	*
Cambodia	IIASA-WIC	NCAR	*
Indonesia	IIASA-WIC	NCAR	*
Lao People's Democratic Republic	IIASA-WIC	NCAR	*
Malaysia	IIASA-WIC	NCAR	*
Myanmar	IIASA-WIC	NCAR	*
Papua New Guinea	IIASA-WIC	NCAR	*
Philippines	IIASA-WIC	NCAR	*
Singapore	IIASA-WIC	*Urban*	*
Thailand	IIASA-WIC	NCAR	*
Timor-Leste	IIASA-WIC	NCAR	*
Viet Nam	IIASA-WIC	NCAR	*
Western Asia			
Armenia	IIASA-WIC	NCAR	*
Azerbaijan	IIASA-WIC	NCAR	*
Bahrain	IIASA-WIC	NCAR	*
Cyprus	IIASA-WIC	NCAR	*
Georgia	IIASA-WIC	NCAR	*
Iraq	IIASA-WIC	NCAR	*
Israel	IIASA-WIC	NCAR	*
Jordan	IIASA-WIC	NCAR	*
Kuwait	IIASA-WIC	NCAR	*
Lebanon	IIASA-WIC	NCAR	*
Occupied Palestinian Territory	IIASA-WIC	NCAR	*
Oman	IIASA-WIC	NCAR	*
Qatar	IIASA-WIC	NCAR	*

Region	Country/Territory	Population Projection	Urban	Income Class
	Saudi Arabia	IIASA-WIC	NCAR	*
	Syrian Arab Republic	IIASA-WIC	NCAR	*
	Turkey	IIASA-WIC	NCAR	*
	United Arab Emirates	IIASA-WIC	NCAR	*
	Yemen	IIASA-WIC	NCAR	*
Eastern Europe				
	Belarus	IIASA-WIC	NCAR	*
	Bulgaria	IIASA-WIC	NCAR	*
	Czech Republic	IIASA-WIC	NCAR	*
	Estonia	IIASA-WIC	NCAR	*
	Hungary	IIASA-WIC	NCAR	*
	Latvia	IIASA-WIC	NCAR	*
	Lithuania	IIASA-WIC	NCAR	*
	Poland	IIASA-WIC	NCAR	*
	Republic of Moldova	IIASA-WIC	NCAR	*
	Romania	IIASA-WIC	NCAR	*
	Russian Federation	IIASA-WIC	NCAR	*
	Slovakia	IIASA-WIC	NCAR	*
	Ukraine	IIASA-WIC	NCAR	*
Northern Europe				
	Denmark	IIASA-WIC	NCAR	*
	Faeroe Islands	UN	*Rural*	High
	Finland	IIASA-WIC	NCAR	*
	Iceland	IIASA-WIC	NCAR	*
	Norway	IIASA-WIC	NCAR	*
	Svalbard	CONSTANT	*Rural*	*
	Sweden	IIASA-WIC	NCAR	*
Southern Europe				
	Albania	IIASA-WIC	NCAR	*
	Andorra	UN	*Urban*	High
	Bosnia-Herzegovina	IIASA-WIC	NCAR	*
	Croatia	IIASA-WIC	NCAR	*
	Gibraltar	UN	*Urban*	High
	Greece	IIASA-WIC	NCAR	*
	Italy	IIASA-WIC	NCAR	*
	Malta	IIASA-WIC	NCAR	*
	Montenegro	IIASA-WIC	NCAR	*
	Portugal	IIASA-WIC	NCAR	*

Region Country/Territory	Population Projection	Urban	Income Class
San Marino	UN	*Urban*	High
Serbia	IIASA-WIC	NCAR	*
Slovenia	IIASA-WIC	NCAR	*
Spain	IIASA-WIC	NCAR	*
TFYR Macedonia	IIASA-WIC	NCAR	*
Western Europe			
Austria	IIASA-WIC	NCAR	*
Belgium	IIASA-WIC	NCAR	*
Channel Islands	UN	*Rural*	High
France	IIASA-WIC	NCAR	*
Germany	IIASA-WIC	NCAR	*
Ireland	IIASA-WIC	NCAR	*
Isle of Man	UN	*Urban*	High
Liechtenstein	UN	*Rural*	High
Luxembourg	IIASA-WIC	NCAR	*
Monaco	UN	*Urban*	High
Netherlands	IIASA-WIC	NCAR	*
Switzerland	IIASA-WIC	NCAR	*
United Kingdom	IIASA-WIC	NCAR	*
Caribbean			
Anguilla	UN	*Urban*	High
Antigua and Barbuda	UN	*Rural*	High
Aruba	IIASA-WIC	NCAR	*
Bahamas	IIASA-WIC	NCAR	*
Barbados	IIASA-WIC	NCAR	*
British Virgin Islands	UN	*Rural*	High
Cayman Islands	UN	*Urban*	High
Commonwealth of Dominica	UN	*Urban*	Medium
Cuba	IIASA-WIC	NCAR	*
Dominican Republic	IIASA-WIC	NCAR	*
Grenada	IIASA-WIC	NCAR	*
Guadeloupe	IIASA-WIC	NCAR	*
Haiti	IIASA-WIC	NCAR	*
Jamaica	IIASA-WIC	NCAR	*
Martinique	IIASA-WIC	NCAR	*
Montserrat	UN	*Rural*	Medium
Netherland Antilles	UN	*Urban*	High
Puerto Rico	IIASA-WIC	NCAR	*

Region Country/Territory	Population Projection	Urban	Income Class
Saint Kitts and Nevis	UN	*Rural*	High
Saint Lucia	IIASA-WIC	NCAR	*
Saint Vincent	IIASA-WIC	NCAR	*
Trinidad and Tobago	IIASA-WIC	NCAR	*
Turks and Caicos Islands	UN	*Urban*	High
United States Virgin Islands	IIASA-WIC	NCAR	*
Central America			
Belize	IIASA-WIC	NCAR	*
Costa Rica	IIASA-WIC	NCAR	*
El Salvador	IIASA-WIC	NCAR	*
Guatemala	IIASA-WIC	NCAR	*
Honduras	IIASA-WIC	NCAR	*
Mexico	IIASA-WIC	NCAR	*
Nicaragua	IIASA-WIC	NCAR	*
Panama	IIASA-WIC	NCAR	*
South America			
Argentina	IIASA-WIC	NCAR	*
Bolivia	IIASA-WIC	NCAR	*
Brazil	IIASA-WIC	NCAR	*
Chile	IIASA-WIC	NCAR	*
Colombia	IIASA-WIC	NCAR	*
Ecuador	IIASA-WIC	NCAR	*
Falkland Islands	UN	*Urban*	High
French Guiana	IIASA-WIC	NCAR	*
Guyana	IIASA-WIC	NCAR	*
Paraguay	IIASA-WIC	NCAR	*
Peru	IIASA-WIC	NCAR	*
Suriname	IIASA-WIC	NCAR	*
Uruguay	IIASA-WIC	NCAR	*
Venezuela	IIASA-WIC	NCAR	*
North America			
Bermuda	UN	*Urban*	High
Canada	IIASA-WIC	NCAR	*
Greenland	UN	*Rural*	High
Saint Pierre and Miquelon	UN	*Urban*	High
United States of America	IIASA-WIC	NCAR	*

Region	Country/Territory	Population Projection	Urban	Income Class
Australia/New Zealand				
	Australia	IIASA-WIC	NCAR	*
	New Zealand	IIASA-WIC	NCAR	*
	Norfolk Island	CONSTANT	*Urban*	*
Pacific Islands				
	American Samoa	UN	*Urban*	Medium
	Cook Islands	UN	*Urban*	Medium
	Federated State of Micronesia	IIASA-WIC	NCAR	*
	Fiji	IIASA-WIC	NCAR	*
	French Polynesia	IIASA-WIC	NCAR	*
	Guam	IIASA-WIC	NCAR	*
	Kiribati	UN	*Rural*	Medium
	Marshall Islands	UN	*Urban*	Medium
	Nauru	UN	*Urban*	Medium
	New Caledonia	IIASA-WIC	NCAR	*
	Niue	UN	*Rural*	Medium
	Northern Mariana Islands	UN	*Urban*	High
	Palau	UN	*Urban*	Medium
	Pitcairn	CONSTANT	*Rural*	*
	Solomon Islands	IIASA-WIC	NCAR	*
	Tokelau	UN	*Rural*	Low
	Tonga	IIASA-WIC	NCAR	*
	Tuvalu	UN	*Urban*	Medium
	Vanuatu	IIASA-WIC	NCAR	*
	Wallis and Futuna	UN	*Rural*	Medium
	Western Samoa	IIASA-WIC	NCAR	*

Table S2. United Nations population projections adopted for each SSP by World Bank income class.

Income Class	Scenario				
	SSP1	**SSP2**	**SSP3**	**SSP4**	**SSP5**
High	Medium	Medium	High	Low	High
Middle	Medium	Medium	High	Low	Medium
Low	Low	Medium	Medium	High	Low

S3. Additional Methodological Detail

The spatial population downscaling model allocates projected change in national-level urban and rural population to sub-national grid cells as a function of urban and rural population potential surfaces, calculated at the beginning of each 10-year interval. Population potential is often considered as a proxy for both accessibility and attractiveness [6], and as such can be considered indicative of the various socio-economic and physical characteristics of place that attract or repel population growth. Functionally, population potential is a distance-weighted measure of the population existing within a certain bandwidth of each grid cell (see Eq. 1, main text). Those cells exhibiting the highest potential receive a proportionally larger share of projected population growth over each time step. In this section we provide additional methodological details regarding the application of the downscaling model, including (1) calibration of the model, (2) the urban and rural potential surfaces and population allocation, (3) the geospatial mask which limits population growth in areas unsuitable for human habitation, (4) the bandwidth of the population potential model, and (5) adjustments for boundary effects. Further details regarding the spatial population downscaling procedure can be found in Jones and O'Neill 2013 [7].

Model Calibration and Parameter Estimates. The population potential model used to create the potential surfaces is a parameterized negative exponential function (Eq. 1, main text), borrowed from the family of gravity-based models commonly used in transportation, urban, and economic geography. Our model includes two parameters, α and β, referred to as the "population" and "distance-decay" parameters, respectively. The β (distance-decay) parameter, in traditional geographic models, is a measure of the impact of distance on the contribution of nearby populations to potential of a given grid cell [8]. Higher values indicate a greater friction of distance and subsequently a smaller contribution. For example, if the costs associated with travel are high then the presence of nearby amenities (social, physical, or economic) contribute less to the relative attractiveness of a place and local characteristics become proportionally more important. The α (population) parameter is typically interpreted as an indicator of the potential to attract population or movements. As such, it is a proxy for the relative attractiveness of a destination, typically a function of the local characteristics which make a place attractive or unattractive [8]. Higher values of α, within the context of our model, are indicative of a greater importance of local characteristics, relative to those of nearby places, in determining relative attractiveness. In our model α and β operate as free parameters that can be estimated from historic data and/or used to impose certain patterns of spatial population change known to occur under certain development regimes (such as those implied by the SSPs). In general the distance-decay parameter controls the degree to which populations disperse or sprawl over time, while the population parameter indicates the degree to which populations will consolidate over time.

In this work we apply parameter estimates indicative of the patterns of change implied by each of the five SSPs to generate urban and rural population potential surfaces on a country-by-country basis. To better understand how model parameters produce alternative patterns of change, and subsequently to appropriately specify parameters indicative of the qualitative narratives, we calibrated the model to observed change in the urban and rural population structure over the period 1990-2000 for representative countries from each of 20 world regions (see section S2). The calibration procedure is constructed as an unconstrained minimization problem solved using the Generalized Reduced Gradient (GRG2) algorithm [9]. We fit the model such that ε_i is minimized:

$$\frac{P_{i,2000}^{obs}}{P_{T,2000}^{obs}} = \frac{P_{i,2000}^{mod}}{P_{T,2000}^{mod}} + \varepsilon_i(\alpha, \beta) \qquad \text{(Eq. S1)}$$

where P_i^{obs} is the observed population in cell i, P_T^{obs} is the total population, P_i^{mod} is the estimated population in cell i, and P_T^{mod} is the estimated total population. Because total population change is specified exogenously in the model, P_T^{obs} will equal P_T^{mod}.

The parameter estimates generated in this historical data analysis where organized to equate observed patterns of spatial change (e.g. urban sprawl) to specific parameter estimates that could then be applied where appropriate in producing future SSP-based projections. We fit the model to countries from each of the 20 world regions illustrated in Figure S2 and Table S1, choosing only countries for which the 1990/2000 GPW distributions were constructed from two separate census periods. World regions are defined to encompass countries exhibiting similar patterns of spatial development in close geographic proximity. As a starting point we used the UN Population Division geographic classification, moving countries to a more representative region when necessary. For example, the United Kingdom and Ireland were moved from Northern Europe to Western Europe, a reflection of stronger similarities in the spatial distribution of the population between these nations and the latter region. For each region/SSP we specify urban and rural model parameters (α and β, see Eq. 1 in the main text) that correspond to the development pattern described in the qualitative narratives. For the "middle-of-the-road" scenario, SSP2, we apply parameters estimated from the historic data for each world region, reflecting the assumption that future development will remain consistent with historic patterns. For each of the remaining four SSPs we deviate from these regional parameter estimates in a manner consistent with the qualitative narratives.

Urban and Rural Population Potential Surfaces and Population Allocation. Here we explain the population downscaling procedure in more detail. Figure S3 illustrates, for a fictional country consisting of 25 (5x5) cells, the allocation of urban and rural population change over one time-step for scenarios based on SSP1 and SSP3. At time (t) in our fictional country the urban population is largest in the southwest of the country, declining with movement towards the north and east. Rural population increases as we move away from the urban core before declining in the most remote regions of the country along the northern and eastern borders. It is important to note that total population is not increasing as we move away from the urban core, only the count of rural people. This is a function of the fact that as we move away from more densely populated urban areas an increasing portion of each grid cell will be classified as rural. The second row of Figure S3 illustrates urban and rural population potential surfaces for our two scenarios. The SSP1 scenario assumes slower population growth, faster urbanization, and a more concentrated pattern of development, while the SSP3 scenario assumes the opposite, faster growth, slower urbanization (i.e., greater total population growth, more of which is classified as rural), and a more sprawling pattern of change relative to SSP1. Each of the four population potential surfaces is calculated according to Eq. 1 (main text) using a unique set of model parameters reflecting the assumed pattern of spatial change in the urban and rural components of the population. Potential is considered indicative of the relative attractiveness of each grid cell to urban and rural components of the population, and as such projected future change in the urban/rural population is allocated at each time-step proportionally according to the relative distribution of population potential. From Figure S3 we find that the distribution of urban potential for the SSP3 scenario is more decentralized that that of SSP1, reflecting the more sprawling pattern of change assumed in SSP3 (relative to SSP1). The result at time (t+1) is a more dispersed urban population in the SSP3 scenario. The distribution of rural potential tends to be far more uniform than the urban distribution, reflecting an underling population distribution that itself is more uniform (the rural potential surfaces illustrated in Fig. S3 are based on a different scale than the urban distributions such that there is some contrast in the rural surfaces). Rural population is projected to decline in SSP1 and increase in SSP3 (typical of the SSP-based projections for most developing countries), leading to significant contrast in the distributions at time (t+1).

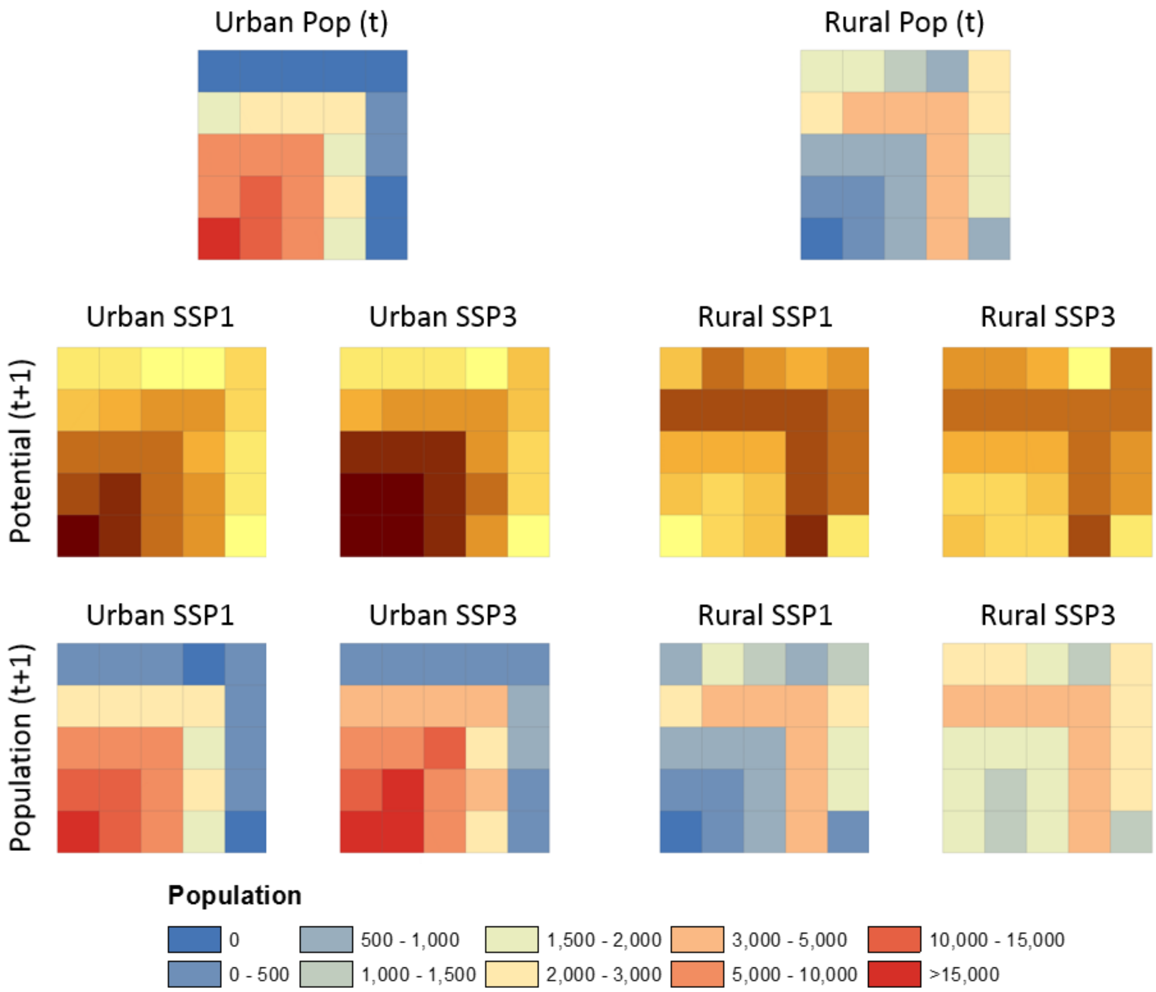

Figure S3. Scenario-based urban and rural population potential surfaces and population distributions at time (t) and (t+1) for a fictional 5x5 grid cell country.

Geospatial Mask. The spatial population downscaling model includes a geospatial mask that acts as a multiplier, proportionally scaling the population potential for each grid cell as a function of the area within each cell deemed suitable for human habitation. We construct the mask from four geospatial data layers: surface water, elevation, slope, and protected land. We overlay these data to produce a single mask from which we extract the portion of each cell suitable for habitation (l_i from Eq. 1 in the main text). The spatial distribution of l_i is illustrated in Figure S4. We use the ESRI World Water Bodies [10] dataset to mask global surface water. Elevation and slope data are from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) [11]. We use the elevation of the highest permanently populated settlement in each continent as a ceiling to exclude land from future habitation as a function of high elevation. In general, development costs increase substantially on land exhibiting a slope greater than 15%, which is also the point at which many municipalities impose development regulations [12]. Here we account for the likelihood that improved technology will reduce the costs associated with excess slope, and instead impose a threshold of 25%, an oft-cited "no-development" threshold in municipal regulations across the United States [e.g., 13]. Finally, we use the International Union for the Conservation of Nature (IUCN) World Database on Protected Areas (WDPA) to mask land as a function of mandate for protection [14]. Specifically, any area classified under IUCN categories Ia (strict nature reserve), Ib (wilderness area), II (national park), III (national monument or feature), or IV (habitat/species management area) is masked as not suitable for development/habitation.

In some cases we found existing base-year population in cells otherwise completely masked as a function of mandate for protection. There are two possible explanations. First, the algorithm used to distribute the existing population across grid-cells in the GPW base-year data does not specifically account for protected land, and as such population and protected land may overlap in the base-year. Second, in many cases new mandates for protection grandfather in existing populations (e.g. people living in newly designated national forest land in the United States). For modeling purposes we treat both of these cases identically. For example, cells that are 100% masked as a function of mandate for protection are not eligible to receive any projected future population growth. However, these cells are allowed to lose people during periods of population decline. This decision reflects our perception of real-world population change in areas with both existing population and prohibitions on new development.

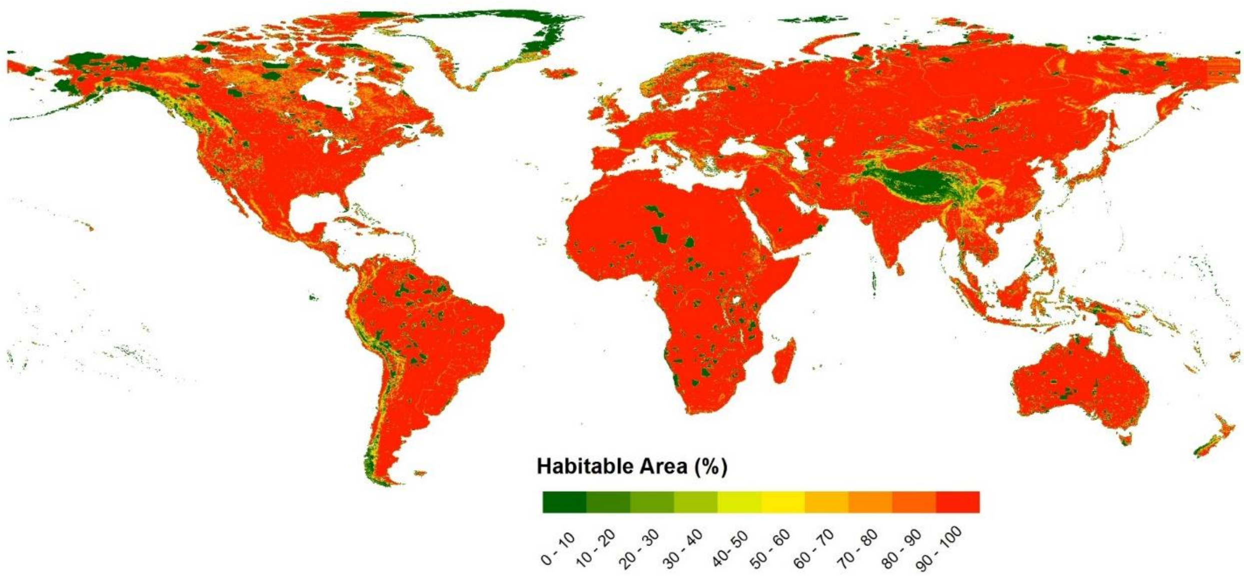

Figure S4. Habitable land by grid cell after application of the geospatial mask.

Population Potential Window. The number of cells that can contribute to the potential (attractiveness) of each cell is limited by imposing a bandwidth of 100 kilometers. Our reasoning is two-fold. First, the relative contribution of cells beyond this distance to the potential of any given cell is negligible as a result of distance-decay, thus limiting the contribution of cells outside of this distance significantly reduces computational demand without changing the underlying distribution of potential. Second, in past research on the United States this value was found to be representative of the sphere of influence of the average individual on a day-to-day basis, and is thus indicative of the maximum distance over which existing amenities contribute to the attractiveness of any given place [15].

Removing Border Effects. In previous work we identify and adjust for the influence of boundaries on the population potential model [16]. Here we apply the same methodology to adjust for border effects. The model is impacted by physical boundaries (e.g. coastlines) and closed administrative boundaries in two ways hereafter referred to as (1) the window effect and (2) the positional effect. For any cell i falling near a border the bandwidth (window) over which the calculation of potential takes place extends over the border into empty space. As a result fewer cells j contribute to the calculation of potential of cell i relative to those cells located further away from the border (the window effect). The window effect is mitigated/confounded by the positional effect, which results from the lower average distance to contributing cells j within the window of cell i, a function of the fact that the window of cell i extends into empty space. These two effects have separate but related impacts on the calculation of potential [15]. Here we summarize the derivation of the adjustment factor (a_i from Eq. 1, main text) that accounts for impact of the window and positional effects.

The window effect leads to lower population potential and consequently slower population growth for cells along coastlines and boundaries. The positional effect mitigates this effect slightly, inflating potential near boundaries because the average distance to cells within the window is smaller (i.e., the cells that are lost from the window due to the presence of the border are predominantly those that are farther away). Considered together, the window and positional effects produce a net effect in which potential begins to decline gently at the point where the window first crosses the border and falls at an increasing rate as distance to the border decreases. To account for both the window and positional effect, and thus remove the boundary effect, we apply the adjustment factor (a_i) to the potential of each cell. We eliminate the positional effect by isolating and removing from each cell the change in potential that is directly attributable to a reduced average distance to contributing cells. We then eliminate the window effect by dividing potential, for each grid cell, by the total number of contributing cells. Application of the adjustment factor essentially transforms potential from an additive measure into a distance weighted measure of the average number of people per grid cell within the window at each point in space [6].

S4. Drivers of spatial population change

Projected changes in the spatial distribution of the population for each country/SSP are primarily 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 downscaling model). To a lesser degree, patterns of population loss and the geospatial mask also impact patterns of population change, however the former does not occur in all places and the latter, because it is static across all scenarios, exhibits very similar minor effects on all SSPs. The three primary factors discussed here are the most influential, and their effects are present in every country.

Here we demonstrate the effect of each factor using Nigeria as an example. Each of the three rows in Figure S5 illustrates a comparison between two SSPs in which two of the three factors are similar, and differences in outcomes are due mainly to the remaining factor. For example, Figures S5a and S5d show the effect of aggregate population size on outcomes by comparing SSP4 and SSP5 in 2100. In these two scenarios, urbanization is the same (93%) and the style of spatial development is similar (mixed/sprawl), but aggregate population change is very different (832 and 424 million, respectively). Figure S5a shows the spatial pattern of differences, indicating that the larger population size in SSP4 is expressed as a higher population density that, while more pronounced in or near urban areas, occurs throughout the country. Figure S5d shows the corresponding distribution of grid-cells (solid lines) and population (dashed lines) across different population density categories. The larger population in SSP4 future leads, unsurprisingly, to a substantial shift in population toward higher density areas relative to SSP5. The shift in the land distribution is substantial in both SSPs, so that the most common population density from the land perspective is twice as high in both SSPs compared to the present distribution, but the shift is larger in SSP4.

Figures S5b and S5e show the effect of national-level urbanization rates by comparing outcomes from SSPs 3 and 4, in which projected total population is similar (853 and 832 million, respectively), spatial patterns are similar (mixed/mixed), but projected urbanization rates are very different (64% and 93%, respectively). The higher level of urbanization associated with SSP4 leads to a different effect on spatial distribution than higher population does, shown in Fig. S5b by the higher density in existing urban areas and lower density in rural areas, especially areas near city centers (darkest blue areas). The magnitude of the difference, however, is smaller than differences due to population size, as indicated by the relatively small differences in the distributions over density shown in Figure S5e in which SSP4 leads to slightly larger population in the most densely populated cells. With a larger fraction of the population living in high density conditions (in SSP4), there is a somewhat smaller fraction of the land area in which population density is high (and more of that is less densely populated).

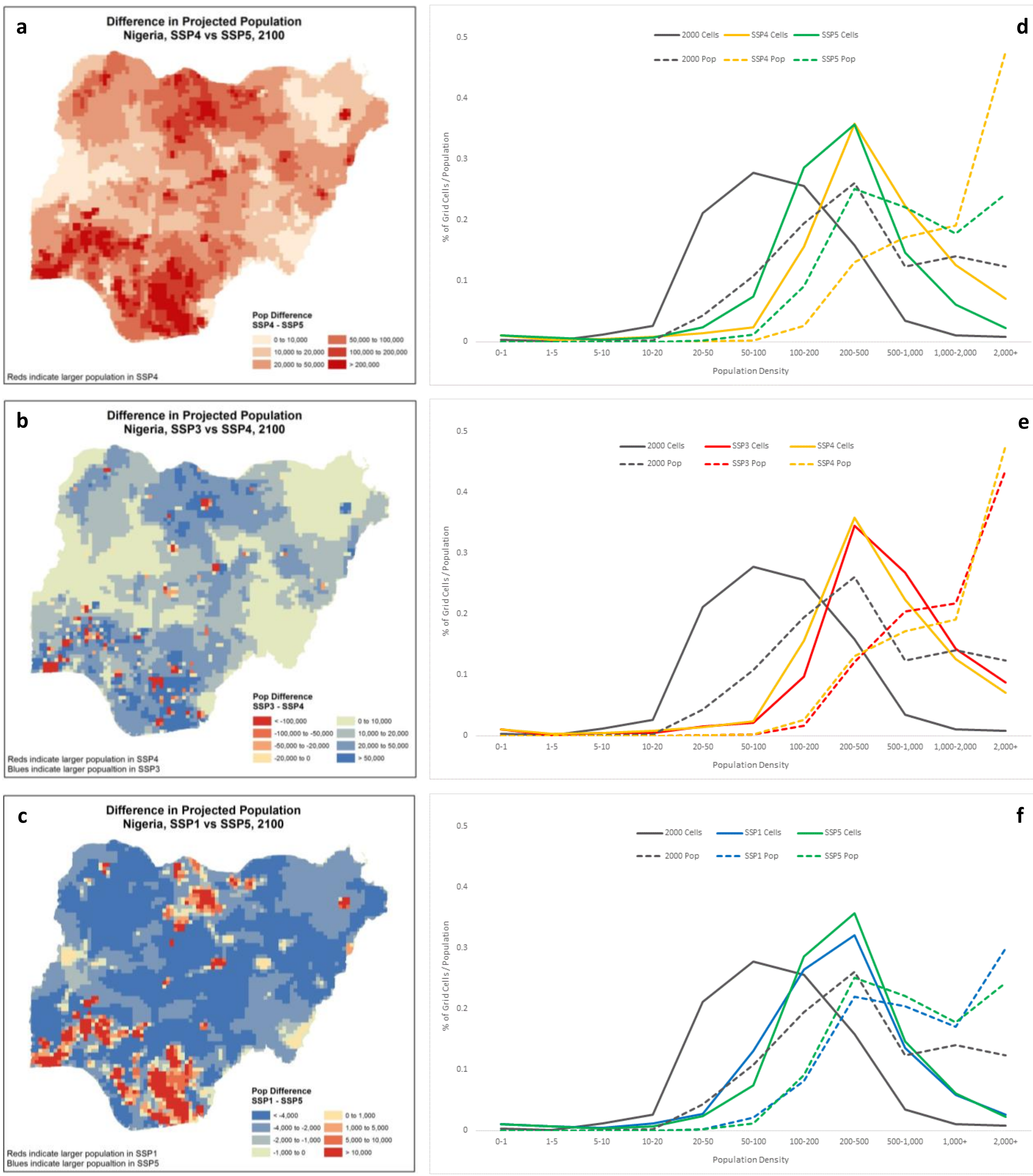

Figure S5. Difference in gridded population outcome between (a) SSP4 and SSP5, (b) SSP3 and SSP4, and (c) SSP1 and SSP5 in Nigeria (2100) and (d-f) the corresponding distribution of grid cells and population across different population density classes

The final comparison shows the effect of the style of spatial development by comparing SSPs 1 and 5 (Figures S5c and S5f), in which total population is similar (431 and 424 million, respectively), urbanization is the same (93%), but the styles of development are of the opposite extremes (concentration/sprawl). Concentrated development in SSP1 leads to larger populations in and around existing urban centers, while conversely the more sprawling SSP5 scenario leads lo larger populations further out on the urban fringe. Population density is lower in rural areas, as expected, especially in areas distant from urban areas (the darkest blue areas). Population in the most densely populated cells is higher in SSP1, which leads to a shift in the land distribution toward less densely populated areas (Fig S5f).

If we compare the average difference in population by grid-cell across all three examples we find that, in terms of relative importance in affecting spatial population change across Nigeria, aggregate national-level change is the most influential (66.1%), followed by projected urbanization (20%), and finally the more localized pattern of spatial development (9.7%). All three factors contribute to spatial change in each country/territory for which we produced projections, however the relative importance of each component varies across countries/territories as a function of the relative magnitude of projected change in national-level population and urbanization. For example, in high-growth, rapidly urbanizing countries (such as Nigeria) aggregate population change and urbanization are stronger drivers of grid-cell level change and variation across SSPs. Conversely, in highly-urbanized, slower-growth countries the importance of local patterns of spatial development more influential, as aggregate population change and urbanization rates are somewhat stagnant. In many cases, however, it is more difficult to decompose the relative contributions of each to total change as it there is typically larger variation (relative to the Nigeria example) in more than one component of change across SSP comparisons, and in many cases these forces work against one another in affecting spatial outcomes.

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