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Assessment of the potential-allocation downscaling methodology for constructing spatial population projections

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Abstract

The IIASA gridded population downscaling methodology is one of only a few existing models for constructing spatially explicit global population scenarios. Furthermore, this methodology is unique in that it does not employ proportional scaling techniques or extrapolated rates of change. Instead, the IIASA methodology applies a gravity-type spatial allocation model to distribute projected national-level change. In this technical note we present and analyze the IIASA methodology within the context of a hypothetical population situated in one-dimensional space. Our results indicate that border effects exert significant influence over spatial population outcomes. Furthermore, over a reasonable time horizon (100-150 years), we find that in most cases the IIASA methodology will have a smoothing effect on existing population distributions. This paper is the first in a series related to the construction of spatial population scenarios organized around the IIASA methodology, and the results presented within not only help to explain the IIASA scenarios, but inform feature research and refinements to the methodology.

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1. Introduction

The purpose of this technical note is two-fold: to describe an approach to constructing spatially explicit projections of future population developed at IIASA (Gruebler et al., 2007), and to assess general patterns in population outcomes produced by the model. The IIASA methodology is gravity-based approach that downscales exogenously generated national-level projections to grid cells using a population potential surface. The model replicates widely observed spatial patterns of human settlement such as urban expansion, the development of city clusters, and the growth of urban corridors. Used in the emissions scenarios developed by the Greenhouse Gas Initiative at IIASA and presented in Grübler et al., 2007, this methodology is one of only a few published approaches to constructing spatially explicit global-scale population projections.

The IIASA approach is novel in that a measure of "potential" is used as a mechanism for distributing projected future population whereas other recently released spatial projections employ proportional scaling techniques (e.g., Balk et al., 2005; Gaffin et al., 2004). Additionally, the IIASA work is unique in that three sets of scenario-dependent projections were produced (based on the SRES A2, B1, and B2 storylines), for each of which a separate country-specific urbanization scenario was developed. The resulting variation in the projected size of the urban population leads to corresponding variation in the spatial structure of the population. This variation between scenarios may be particularly useful for researchers interested in studying, for example, the relationship between emissions and the spatial structure of population. Furthermore, these scenario-dependent results provide a point of departure from which to assess grid-cell level uncertainty in spatial population projections.

Grübler et al., 2007, conclude that future research should consider methodological refinements to the gravity-based allocation process. This technical note summarizes our initial analysis of the IIASA methodology, focusing in particular on the mechanics of the potential-allocation approach. Further research and refinements to the gravity-based model are discussed in subsequent papers.

2. The IIASA downscaling methodology

The process of downscaling from the national level to grid cells consists of four basic steps, which are iterated at each time interval: (1) define grid cells within a particular country as urban or rural, (2) calculate a population potential for each grid cell, (3) allocate projected national urban population change to urban grid cells proportionally according to their respective population potentials, and (4) allocate projected national rural population change to rural grid cells proportionally according to existing population. Each of the four steps is explained in detail below[1].

Step 1. Delineate urban areas

To classify a grid cell as urban or rural the IIASA methodology employs an algorithm that relies on three data sets: the Gridded Population of the World (GPW) 2.5´ resolution population density map, the Digital Chart of the World (DCW)[2], and a geospatial luminosity index developed using satellite measurements of nighttime lights

[1] The description of the IIASA methodology draws heavily on a IIASA technical note (O'Neill et al., 2008) which describes in greater detail the methodology outlined in Grübler et al., 2007.
[2] Earth Science Information Network (ESRI), available through Penn State University

from NOAA's DMSP Operational Linescan System[3]. The GPW data are used to define the base-year spatial population distribution. Within each country, grid cells are defined as urban by overlaying the DCW and DMSP data on the gridded GPW data set, and selecting grid cells[4] using the following process: (1) select all cells from areas defined as urban by the DCW[5], (2) from this subset select the most densely populated cell, (3) if Step 2 leads to the selection of more than one cell (i.e., cells with equally dense populations) then from these cells select the one exhibiting the greatest luminosity of nighttime lights, and (4) define this cell as urban. Steps 2-4 are repeated, using the subset of cells generated in Step 1,until the total population within the urban area is equal to the UN data (in the base year) or the IIASA projections (for future years) on total urban population for the country. If, after all cells falling within DCW urban areas have been classified as urban, the total urban population is less than the national level figure then Steps 2-4 are applied to the remaining cells beginning with those immediately adjacent to cells already defined as urban, and additional grid cells are added to the urban area until the appropriate urban population is achieved.

Step 2. Calculate potential for each grid cell

At the beginning of each time interval a population potential is calculated for each grid cell. Potential is essentially a measure of the attractiveness of each cell relative to other cells in the area under consideration. As a proxy for attractiveness, and thus the

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[3] U.S. National Oceanic and Atmospheric Administration (NOAA), Defense Meteorological Satellite Program (DMSP)

[4] Base-year distribution is determined at 2.5' resolution, simulation is conducted at 7.5´, and final results are aggregated to 0.5°.

[5] The DCW contains urban agglomerations represented by polygons; grid cells that fall within a polygon meet the criteria.

various socio-economic factors that determine attractiveness, this model considers a grid cell's proximity to existing urban and rural populations. The potential for each cell is calculated as the sum of two terms: (1) the contribution of population in other nearby urban cells and (2) the contribution of population in other nearby rural cells. Potential for each cell is calculated as:

$$v_i = \sum_{j=1}^{m} \frac{P_{j,u}}{D_{ij}^2} + \sum_{k=1}^{n} \frac{P_{k,r}}{D_{ik}^2} \quad (1)$$

where v_i is potential of cell i, P is population within a grid cell, D is geographic distance between two grid cells, j is an index of the m other cells within the urban "window" around cell i, and k is an index of the n other cells within the rural "window" used in the calculation of potential. The urban window m is comprised of all urban cells that fall within a 25 cell radius, and the rural window n consists of all rural cells within a 5 cell radius[6]. Potential is calculated for all grid cells within a country, with no contributions to potential from grid cells outside national borders.

Step 3. Allocate change in population within urban areas

Within each country, the projected increase in urban population from time t to time $t+1$ is allocated according to:

[6] The urban and rural windows have radii of roughly 350 km and 70 km, respectively, at the equator and 265 km and 50 km at the mid-latitudes. The choice of radius of 5 or 25 for defining the summation areas was made to ease calculation demands; given the squared distance term in the denominator, any additional grid cells (i.e. a larger window) make a negligible contribution to the total potential of cell *i*. In addition, in rural areas it was assumed that the influence of population centers as attractors was more limited (O'Neill et al., 2008).

$$P_i^{t+1} = P_i^t + \left(P_U^{t+1} - P_U^t\right)\frac{v_i^{t+1} - v_i^t}{\sum_{j=1}^{J_U}(v_j^{t+1} - v_j^t)} \tag{2}$$

where P_U represents total urban population, and the summation in the last term occurs over all cells J_U that are defined as urban. This equation allocates growth to each urban grid cell within a country according to the proportion of the net change in total potential for all urban cells that occurs in cell *i*.

To calculate a change in potential for the base year, and thus carry out the allocation using the IIASA algorithm, a hypothetical population distribution for time *t+1* is created by increasing (or decreasing) the population in each cell by a rate equal to the national-level rate. Within urban areas, a maximum density constraint of roughly 35k-45k/km^2 is applied to prevent very large densities. In practice this only affected a few cells in the scenarios run by IIASA, as the constraint is representative of the highest population densities currently observed, such as would be found in cities like Singapore and Hong Kong. When the constraint applies, the population that would have been allocated to that cell is instead distributed over the whole country.

Step 4. Allocate change in population within rural areas

A country's projected rural population change is derived by comparing total projected national-level population change and projected urban populated change. Due to a "lack of deeper theoretical understanding of the drivers of regionally differentiated growth in rural areas" the potential-allocation approach is not applied to rural cells in the

IIASA scenarios (Grübler et al., 2007). Instead, projected rural population change is allocated across rural cells at a level proportional to the existing population.

Steps 1-4 are repeated for each time step, beginning by re-classifying urban areas after the allocation of population growth in the previous step using the method described in Step 1. If necessary, additional cells added to (or subtracted from) urban areas according to criteria such as density, however no explicit algorithm is followed (O'Neill et al., 2008).

3. A note on the population potential model

Gravity-type models in demography generally seek to simulate human behavior in the aggregate, a function for which they are widely used (Letouzé, et al., 2009). Borrowed from the physical sciences (Newton's law of gravitational potential), potential is a measure of the influence that one point in space exerts on another which, when considered an indicator of potential interaction and summed for all points, yields a relative measure of potential interaction (Rich, 1978). The potential model is most often associated with modeling existing spatial patterns and has been used in applications to simulate the distribution of human population (e.g., Deichmann and Eklundh, 1991; Sweitzer and Langas, 1995; Wang and Guldmann, 1996). Population potential is, for practical purposes, often interpreted as a relative indicator of a populations position relative to other population, and thus is considered a proxy for accessibility (Deichmann, 1996). As such, while the population potential of one point in space is meaningless by itself, relative to other points it can be considered as indicative of the ease with which human populations may be accessed. If we interpret proximity to population as a proxy for access to, for example, the consumer marketplace, employment opportunities, and urban amenities, then we can interpret population potential as a relative measure of both accessibility and attractiveness[7]. If we assume that humans are more likely to settle in places that are more accessible or attractive, then the population potential model should provide a fair approximation of the distribution of human population. Obviously this model over-simplifies a process that is somewhat more complex (locational choice), especially at the individual level and over small geographic areas. However, given that the purpose of the IIASA technique is to simulate broad-scale trends and aggregate behavior at a global scale, this choice of model seems justified.

4. Assessment

To assess the IIASA methodology we conducted simulations using a hypothetical population distributed across a one-dimensional study area[8]. We apply two notable modifications to the existing methodology. First, we allocate population change at each time step according to the fraction of total urban or rural potential occurring within each cell i, which has been shown to be equivalent to the portion of the total change in urban

[7] Population potential has been found to correlate strongly, but not perfectly, with population density. Anderson (1956) found potential useful in describing the observed variation in population density across U.S. counties. As an explanatory variable in a regression, potential is interpreted as a measure of the importance of position or a proxy for the factors affecting accessibility or attractiveness. As such, we may interpret Anderson's findings as suggesting that more densely populated counties are more accessible to larger populations or are more attractive than less densely populated counties. Neither would qualify as a surprising result.

[8] A one-dimensional study area was chosen for ease of analysis, as it constitutes the simplest array of grid cells; a set of cells organized in a straight line.

or rural potential occurring within each cell (O'Neill, 2008)[9]. Second, in our assessment of the model we apply the potential-allocation procedure described in steps 2 and 3 to the rural population as opposed to applying a proportional scaling procedure. This decision reflects our intention to consider refinements to the IIASA methodology. We classified scenarios according to three factors: the urban/rural classification, the form of the base-year distribution, and the size of the study area (see Table 1). Considering combinations of these factors we further enhanced our analysis by applying varying growth rates of the urban and/or rural population, and, in the urban/rural scenarios, varying the proportion urban in the base-year population.

Table 1. Scenario classification.

Urban/Rural Classification	**Base-Year Distribution**	**Geography**
Urban-Only	Normal	20-cell
Urban/Rural	Random	40-cell
	Uniform	80-cell
Rate of Change: -5% to 10%		
Urban portion of total population: 10% to 90%		

[9] The fraction in the second term on the right hand side of the allocation equation (fraction of the total net change in potential occurring in cell *i*) is mathematically equivalent to the fraction of current total potential in area *A* that occurs in cell *i*, i.e.:

$$\frac{v_i^{t+1} - v_i^t}{\sum_{j=1}^{m}\left(v_j^{t+1} - v_j^t\right)} = \frac{v_i^t}{\sum_{j=1}^{m} v_j^t}$$

This relationship holds for the calculation of potential based on the rural window independently, or the urban window independently, but not for the combined calculation. However it means that the creation of a hypothetical population distribution at time *t+1* is not actually necessary. It is the same as allocating based on the current distribution of potential within urban and rural areas, with those cells with the highest current potential gaining the most population (O'Neill et al., 2008).

In scenarios defined as "urban-only," all grid cells were classified as urban, and as such a window of 25 cells was universally applied to calculate potential and population change was allocated across the entire distribution. In those scenarios defined as "urban/rural," grid cells were classified as urban or rural and the IIASA methodology was applied as described above. For each geography (20, 40, or 80 cells; see Table 1) the base-year urban/rural classification was based purely on location (in each case the 10 innermost cells in the study area), and was held constant for all simulations (that is, there was no reclassification of cells from rural to urban or vice versa). A consistent base-year classification held constant over time isolated the locational effect of the urban/rural border, which allowed us to better analyze the urban/rural interface under a variety of conditions[10].

We considered three spatial distributions in the base-year: normal, random, and uniform. A normal distribution provides a baseline measure against which it is relatively simple to isolate and interpret change, but which also resembles a spatial pattern of human settlement often cited in the literature: the monocentric city. A uniform distribution is unlikely to occur in a real-world scenario. For purposes of analysis, however, the uniform distribution proved useful in isolating and describing border effects, some of which were initially overlooked in scenarios considering a normal or random distribution. Finally, we considered several random distributions which we used primarily to assess the importance of the base-year distribution in certain scenarios, but which also helped to confirm many of our conclusions. In some of these scenarios the

[10] In reality the urban/rural border is likely to shift over time. However, to improve our understanding of the mechanics of this methodology, it was advantageous to hold the border constant and isolate its impact on spatial outcomes. Further analysis discussed in subsequent papers considers a dynamic urban/rural border.

base-year distribution was not truly random, but was instead constrained such that a certain portion of the population fell into urban cells, or on one side of the distribution. These "constrained random" distributions were used as a point of comparison in which we control some factor that might affect spatial outcomes[11].

We applied the IIASA methodology to three different one-dimensional study areas consisting of 20, 40, and 80 grid cells. Many of the broad trends in the patterns produced by the model were observed consistently across all three geographies. Additionally, we found that the size of the study area itself was a factor in both spatial outcomes, and the speed with which distributions changed. The largest geography, 80-cells, was chosen because it allowed for a complete analysis of the border effects which influence spatial outcomes. Most of the results and examples discussed in this paper relate to 80-cell simulations.

The remainder of this technical note is devoted to discussion of our analysis, which is focused on the relationship between the IIASA methodology, the aforementioned scenario specifications, and the corresponding spatiotemporal outcomes. Through the course of our work we found it advantageous to first assess a single region (urban-only) model, isolate the forces driving the observed spatial outcomes, and then consider the more complicated two region (urban/rural) system. Our conclusions are organized into subsections in which we discuss both urban-only and urban/rural scenarios. In most cases understanding and interpreting the urban-only results eases the

[11] For example, to test whether the base-year distribution in an urban/rural model impacted the spatial outcome we first considered a normal base-year distribution in which 38% of the total population fell into the urban cells. We then constructed a second base-year distribution in which 38% of the total population was randomly distributed across the urban cells, and the remaining 62% randomly across the rural cells.

interpretation of the urban-rural results. The spatial implications of these results, as they apply to the construction of 100-150 year scenarios, are discussed after all of our conclusions have been presented. We finish with a brief comment on future research plans.

5. Results and Analysis

Our analysis of the IIASA methodology led to the following key conclusions, each of which will be discussed in turn:

5.1 Border effects substantially influence spatial population outcomes.

5.2 In the absence of border effects a population will move towards a uniform spatial distribution.

5.3 Over realistic time horizons, and with border effects included, initial distributions are smoothed.

5.4 The growth rate(s) will impact the speed with which population structure changes, but not the form of that change[12].

5.5 Population loss is misallocated.

5.6 The base-year distribution of potential relative to that of population is a strong predictor of long-term population change.

[12] With one very small exception; a scenario in which (1) the rural growth rate exceeds the urban growth rate, (2) rural populations exist in isolation (e.g. the rural windows don't overlap), and (3) the urban population in the intervening area (the grid cells between isolated rural cells) is not distributed normally.

5.1 Border effects substantially influence spatial population outcomes.

The future spatial distribution of a population is impacted significantly by two types of border effects: those related to the border of the entire system (e.g., national boundaries, coastlines) and those related to the location of the urban/rural border. The influence of the former is easily isolated and interpreted, while the latter is somewhat more complicated. We will first present and discuss the impact of the border of the entire spatial system (*border effects*), and then consider the impact of the urban/rural border (*urban/rural border effects*).

The IIASA methodology, applied to any spatial system, moves that system towards spatial stability[13]. A system achieves spatial stability when the relative distribution of population across grid cells no longer changes with the allocation of additional population, which is to say, the allocation of additional population becomes proportional to the distribution of the existing population. By proxy then, a system reaches stability when the distribution of population is identical to the underlying distribution of potential. In an urban/rural system spatial stability occurs within urban cells and rural cells independently. For example, urban spatial stability occurs when the distributions of population and potential, across only the urban cells, are equivalent. The entire system reaches spatial stability when both the urban and rural regions are themselves stable. The form of a distribution at spatial stability varies according to

[13] A distribution will not reach true stability as it is understood in demographic terms; instead the relative percentage of the population in each grid cell will continue to change over time by increasingly minuscule fractions. However, for practical purposes (in terms of population counts) a distribution will reach stability.

several factors (see Table 2). It is, in fact, the influence these factors exert on the impact of the borders that is responsible for the spatial distribution of a population at stability.

Table 2. Factors impacting the spatial form of stability

Factors	Urban-Only	Urban/Rural $r_u > r_r$	Urban/Rural $r_u = r_r$	Urban/Rural $r_u < r_r$
Distance Matrix	X	X	X	X
Urban/Rural Classification		X	X	X
% Urban/Rural in Base-Year			X	
Base-Year Distribution				X
Growth Rate: Urban				X
Growth Rate: Rural				X

Consider an urban-only spatial distribution which is uniform in the base-year (Figure 1A). Given the nature of the potential-allocation methodology we would expect a uniform distribution to remain uniform over time[14]. However, the distribution of potential (Figure 1A) is not uniform, and as such the distribution of population does not remain uniform (Figure 1B). In this scenario population density gradually increases in the interior and decreases nearer to the border, ultimately resulting in an arc-shaped form of spatial stability (Figure 1B). This arc-shaped pattern results from the effect of the border on the calculation of potential. Given the number of grid cells in the study area

[14] From Equation 1, if all values P_j are equal, and $v_i = \sum_{j=1}^{m} \frac{P_j}{D_{ij}^2}$ then all values v_i will be equal. If population and potential are equal across each cell *i* then the system is stable, and the distribution will not change.

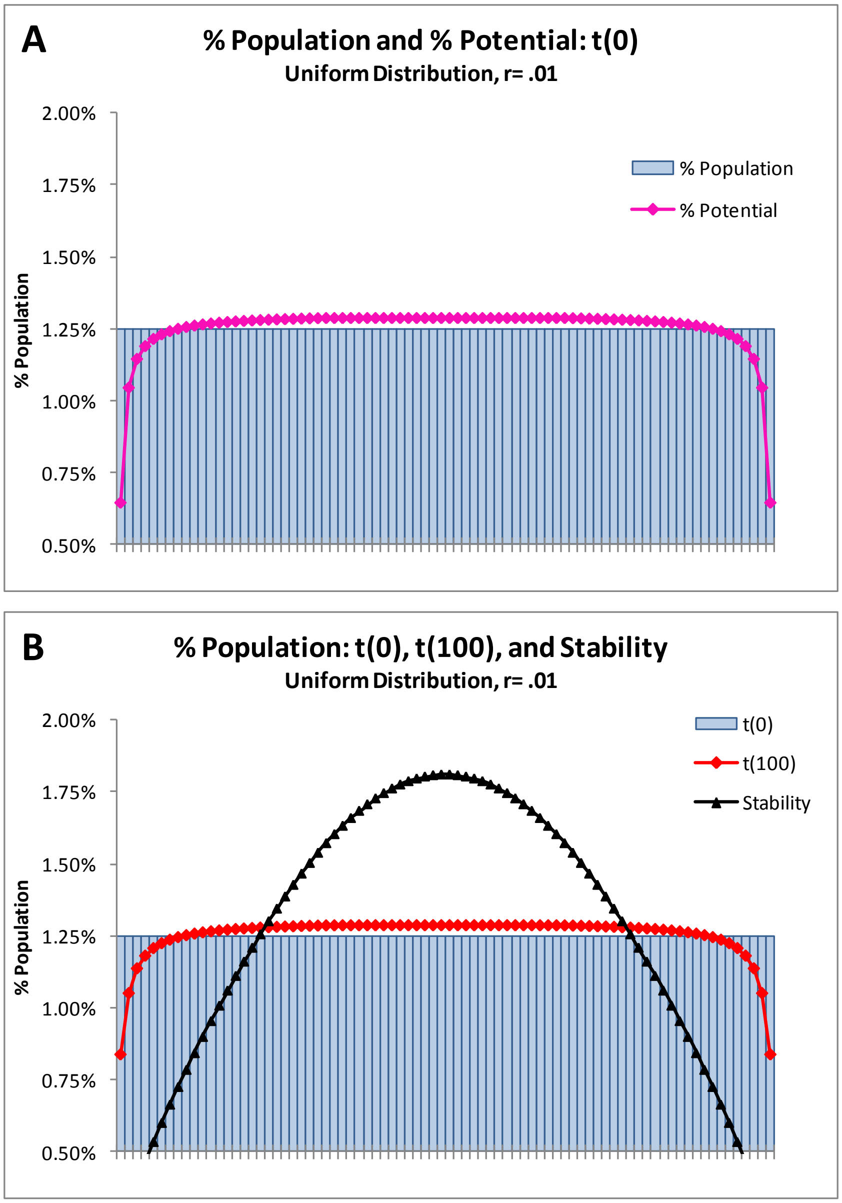

Figure 1. Distribution of population and potential in the base-year, 100-year population change, and distribution at stability: urban-only uniform scenario.

we can calculate for each cell *i* the number of other cells *j* included in the calculation of its potential, and the average distance (D_{ij}) to those cells. Because the urban window extends 25 cells in either direction from each cell *i*, those cells towards the interior of the distribution include more cells *j* in the calculation of potential (the window for these cells is less likely to extend beyond the study area) and the average distance to those cells (a measure of the penalty for distance) is lower. It is the variance in these two measures that results in a non-uniform distribution of potential, which subsequently alters the distribution of population (the border effect). We found that the border effect was present even if the study area contains a very large number of grid cells such that the calculation of potential in the interior cells is unaffected by the border. Over time, residual effects from lower potentials near the border move towards the interior cells due to the overlapping nature of the potential window.

The form of spatial stability in an urban-only system is purely a function of geography. Thus, it is the number of grid cells and the spatial orientation of those grid cells, or in simpler terms, the distance matrix, which will dictate the form of spatial stability. We refer to these factors as the *geographic factors* (which, in an urban/rural model, includes the location of the urban/rural border). As is illustrated in Figure 2, the distribution of population in the base-year does not influence the ultimate form of stability. A closed system in which there are no changes to the borders has only one form of stability which is completely independent of the base-year distribution.

Explaining the distribution of a population at spatial stability in an urban/rural scenario is a more complex exercise, as such scenarios are subject to both border effects and urban/rural border effects. To better illustrate consider an urban/rural scenario with a uniform base-year distribution and 1% annual urban and rural growth rates (Figure 3). The uniform base-year distribution, while relatively unrealistic, effectively controls for population density in the base-year which, if we also impose a uniform growth rate, allows us to easily identify the impact of the effect of both the study area and urban/rural

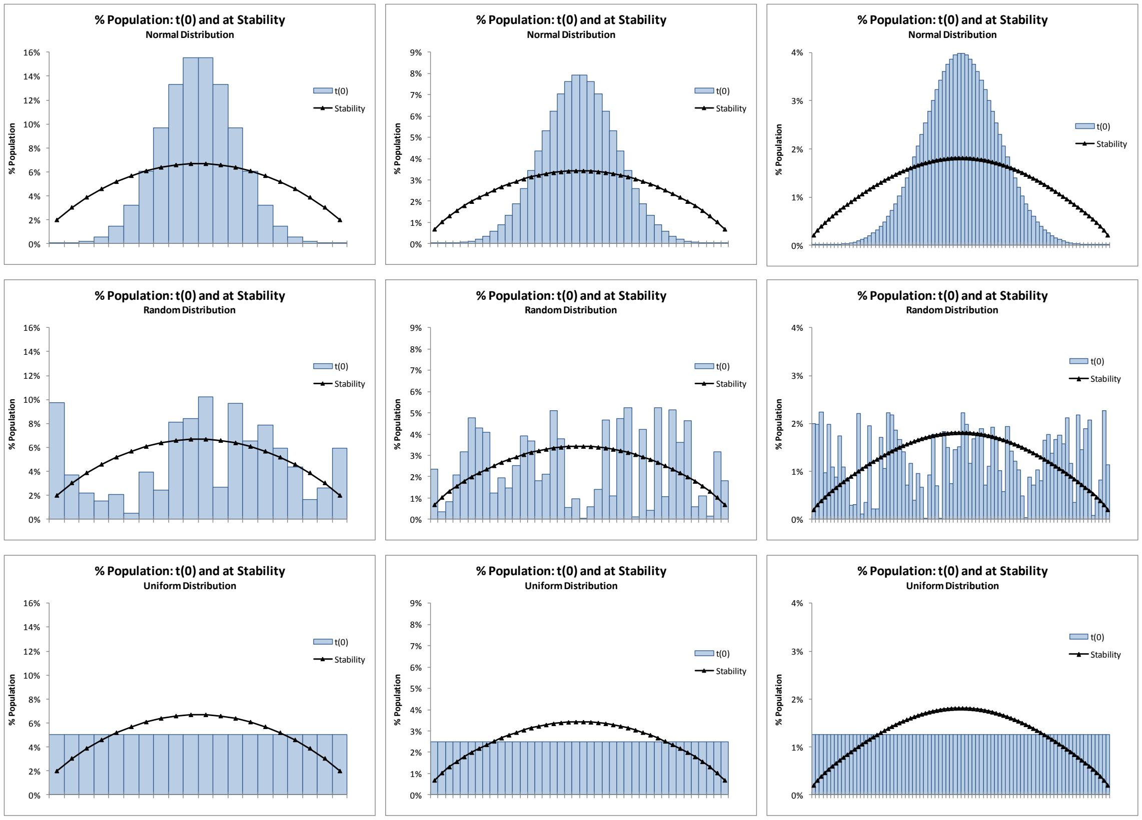

Figure 2. Distribution of population in the base-year and at stability: normal, random, and uniform scenarios; 20, 40, and 80 cells.

boundaries[15]. The most notable feature in this scenario is a double-peaked pattern evident in the distribution of potential, population after 100 years, and, most strikingly in the distribution at stability (3A and 3B). One way the location of the urban/rural boundary impacts the distribution of population is through the application of different sized urban and rural windows in the calculation of potential, which in this scenario leads to this distinctive double-peaked shape. In this particular case the cells that exhibit the

[15] Because the urban and rural growth rates are equal, and the base-year distribution is uniform, in the absence of border effects the allocation of additional population would amount to scaling-up proportional to the existing uniform pattern. If we assume that, as in the normal urban/rural scenario, the 10 innermost cells are classified as urban then the base-year urban population would be 12.5% of the total population of 1,000,000. Equivalent urban and rural growth rates of 1% would yield an additional 1,250 urban persons and 8,750 rural persons after one year, an average of 125 per cell in both the urban and rural regions. If every cell in the study area had an equivalent number of cells in their respective urban and rural potential windows, and those cells were the same average distance away, then the allocation of additional population would occur proportionally to the existing uniform population. Thus any deviation from uniformity can be interpreted as a border effect.

highest potential relative to other cells are those rural cells that fall 6-cells from the urban/rural boundary, which in the 80-cell hypothetical urban/rural study area are the cells that include the most other cells j in the calculation of potential at the smallest average distance D_{ij} .

Also noteworthy is the concave distribution evident within the urban cells. The calculation of potential in the urban cells occurs over fewer cells than in the immediately adjacent rural cells. Within the urban region the calculation of potential for the innermost cells occurs over fewer cells than those on the border, a result of the small rural window. In this case the result is lower densities in urban border cells relative to the adjacent rural cells, and within the urban region, lower densities in the most interior cells.

Figure 3C plots the distribution of population at stability for the urban-only and urban/rural uniform base-year scenarios. From this figure we can visually identify the impact of the urban/rural border, as the urban-only scenario effectively serves as a control for border effects. Border effects are evident in both scenarios, leading to lower densities in the most remote cells. However, in addition to the obvious impacts over the interior of the distribution, it is clear that the urban/rural border itself influences the effect of the regional border on the stable distribution of population.

The impact of the urban/rural border on the spatial distribution of population will vary depending on several model specifications. We classify urban/rural scenarios according to the factors that will influence the form of spatial stability in each case, which we found to be a function of the urban growth rate relative to the rural growth rate (see Table 2). As such, we consider three families of scenarios; those in which the urban

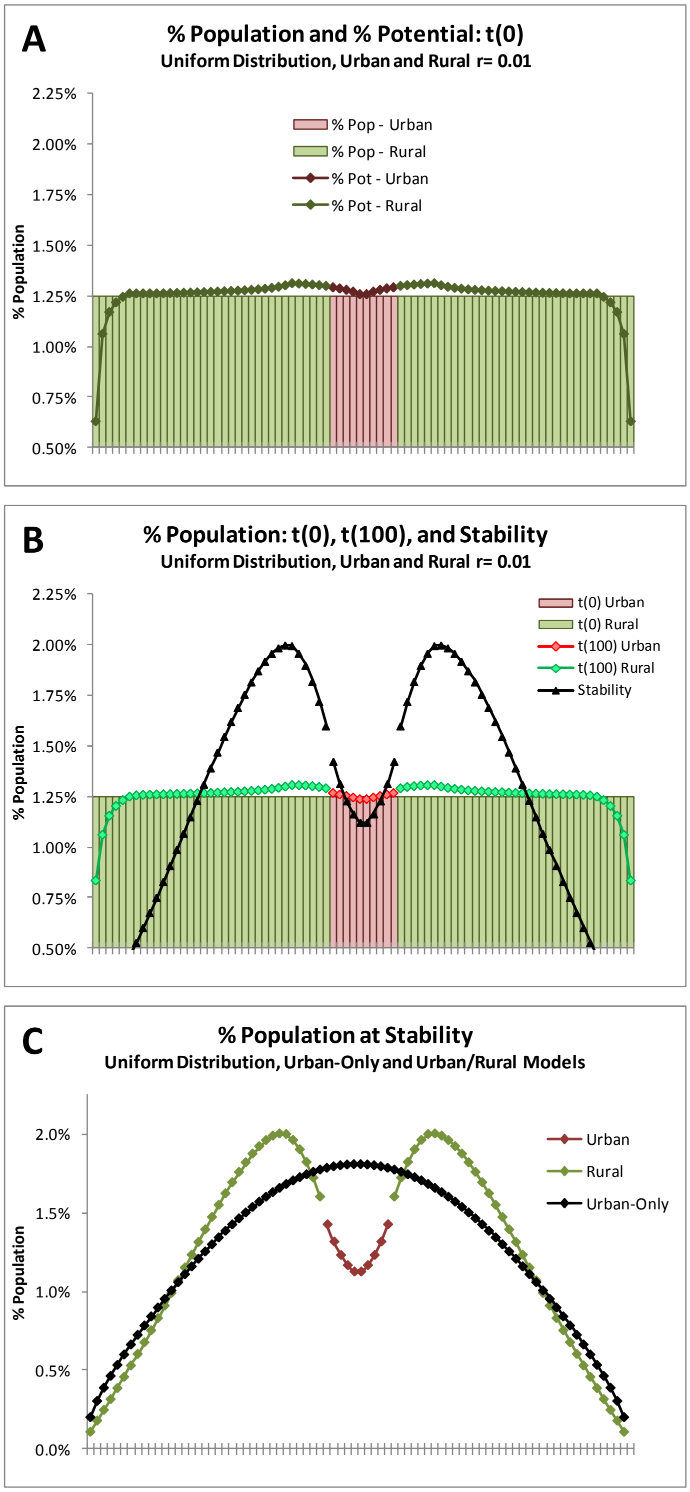

Figure 3. Distribution of population and potential in the base-year, 100-year population change, and distribution at stability: urban/rural uniform scenario.

growth rate exceeds the rural growth rate, those in which urban and rural growth is equal, and those in which the rural growth rate exceeds the urban growth rate. For scenarios in which the urban growth rate exceeds the rural growth rate the distribution at spatial stability is a function of only the distance matrix and the location of the urban/rural border. , as they relate to the size and shape of the study area and the location of the urban/rural border. When the urban and rural growth rates are equal, it is the distance matrix, location of the urban/rural border, *and* the portion of the total population that is urban or rural in the base-year that will determine the form of stability. If the rural growth rate exceeds the urban growth rate (a rare case in the "real-world") then, in addition to geography and the urban/rural portion of the base-year population, the spatial structure of the base-year population as well as the actual urban and rural growth rates determine stability. The patterns produced by each of these three families of scenarios are explored in more detail below within the context of the scenarios listed in Tables 3 and 4.

Table 3. Urban/rural scenarios.

Scenario	Base-Year Distribution	% Urban Base-Year	Proportional Split*			
			RL	RR	UL	UR
Normal	Normal	0.382	0.50	0.50	0.50	0.50
Random	Random	0.159	0.474	0.526	0.443	0.557
Random High Urban	Random	0.9	0.531	0.469	0.54	0.46
Random Equal	Random	0.382	0.50	0.50	0.443	0.557
Random Unequal	Random	0.382	0.292	0.708	0.492	0.508
Uniform	Uniform	0.125	0.50	0.50	0.50	0.50

* The portion of the urban or rural population falling on either side of the distribution.
RL - Rural Left, RR - Rural Right, UL - Urban Left, UR - Urban Right

Table 4. Families of scenarios

$r_u > r_r$ $r_u = 1.5\%,\ \ r_r = 0.5\%$	$r_u = r_r$ $r_u = 1\%,\ \ r_r = 1\%$	$r_u < r_r$ $r_u = 0.5\%,\ \ r_r = 1.5\%$
Normal Random Random High Urban Uniform	Normal Random Random High Urban Random Equal Random Unequal Uniform	Normal Random Random Equal Random Unequal

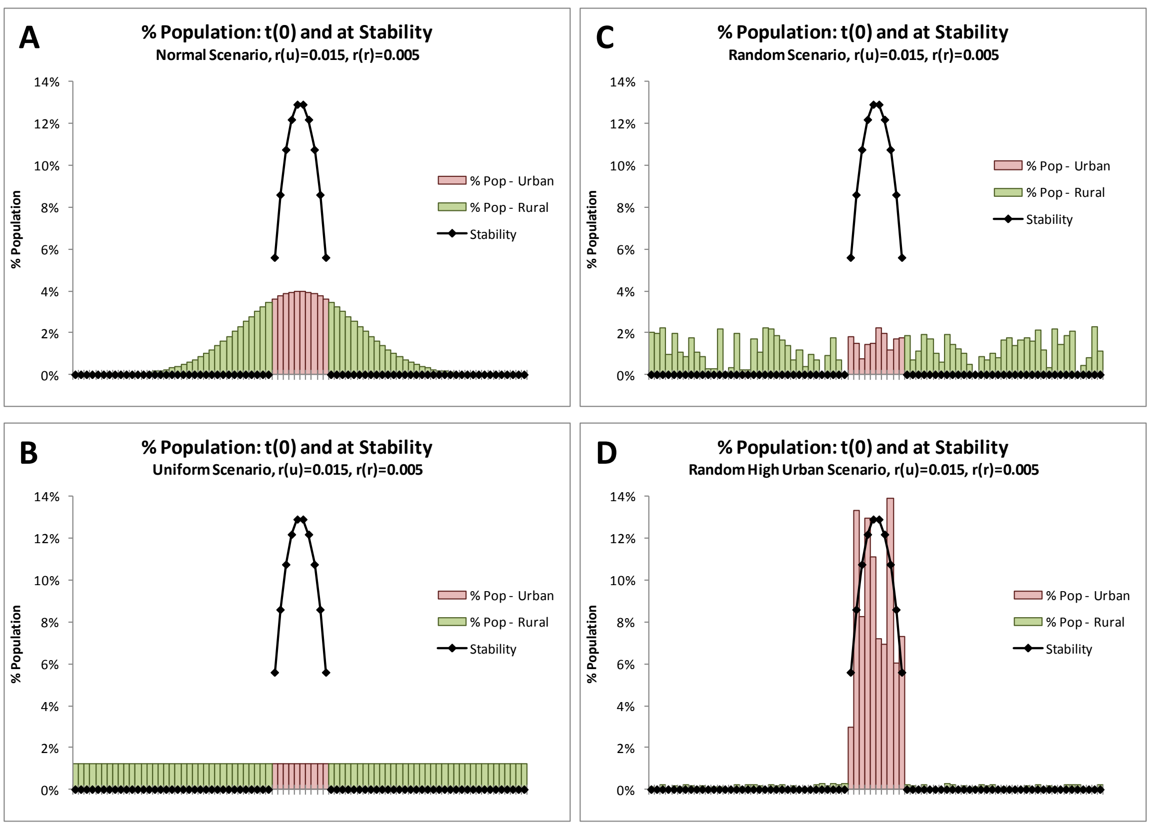

Figure 4. Distribution of population in the base-year and at stability: normal, random, random high urban, and uniform scenarios; urban growth exceeding rural growth.

Our classification scheme is better illustrated in Figures 4-7. Using the 80-cell urban/rural study area, we begin with the normal random, random high-urban, and uniform base-year distributions. Assuming annual urban and rural growth rates of 1.5%

and 0.5%, respectively, we apply the IIASA methodology to each distribution until spatial stability is achieved. Results are plotted in Figure 4. In all cases the form of spatial stability is identical. Essentially, as the urban population grows relative to the rural population the contribution of the rural population to the potential of the urban cells becomes insignificant, at which point the urban/rural border impacts the distribution of the urban population in the same way that the study area border impacts the entire distribution. The entire system reaches stability when the urban and rural regions reach stability independently, a point at which urban cells contain roughly 99% of the population. The smaller rural population is heavily skewed towards the urban border (75% within 5 cells of the border). We tested alternative combinations of growth rates (urban > rural) and found that any urban/rural system in which the urban growth rate exceeds the rural growth will move towards this same form of spatial stability. The magnitude of the discrepancy will only affect the time necessary for the system to reach stability, not the form of stability itself. Only a change in the geographic factors will cause the population distribution at spatial stability to change.

If we consider the same four scenarios, but apply an annual urban and rural growth rate of 1%, the outcome is somewhat different (Figure 5), as each results in a different form of spatial stability. The normal and random high-urban scenarios exhibit densely populated urban cells accompanied by a rapid decline in rural density with distance from the urban/rural border. In contrast, the random and uniform scenarios exhibit the double-peaked pattern, discussed earlier, in which the highest densities occur in the rural region several cells removed from the urban/rural border. The form of spatial stability, when geographic factors are held constant and urban and rural growth rates are

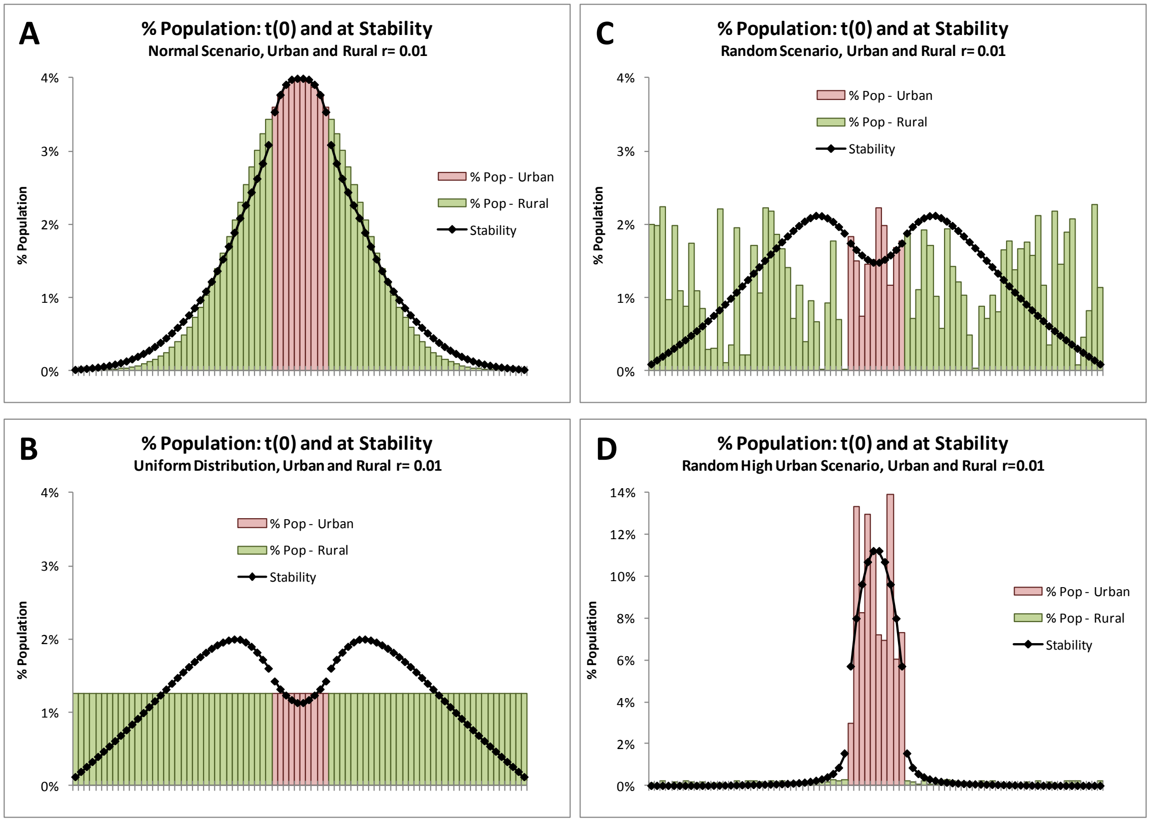

Figure 5. Distribution of population in the base-year and at stability: normal, random, random high urban, and uniform scenarios; equal urban and rural growth rates.

equal, is a function of the portion of the population classified as urban or rural in the base-year. A larger urban population will lead to a more concentrated distribution at stability, while the reverse will lead to larger concentrations in the centrally located rural cells[16]. The form of the distribution in the base-year, however, does not affect the form of spatial stability. In Figure 6 we consider the normal, normal equal, and normal unequal scenarios, all of which have the same base-year urban/rural proportion. As a result, the population distribution at spatial stability is also the same in all three scenarios.

The final family of scenarios to consider includes those in which the rural growth rate exceeds the urban growth rate. In reality rural growth rates are highly unlikely to

[16] The urban portion of the base-year populations in the four scenarios in Figure 11 are: random high-urban (90%), normal (38.2%), random (15.9%), and uniform (12.5%).

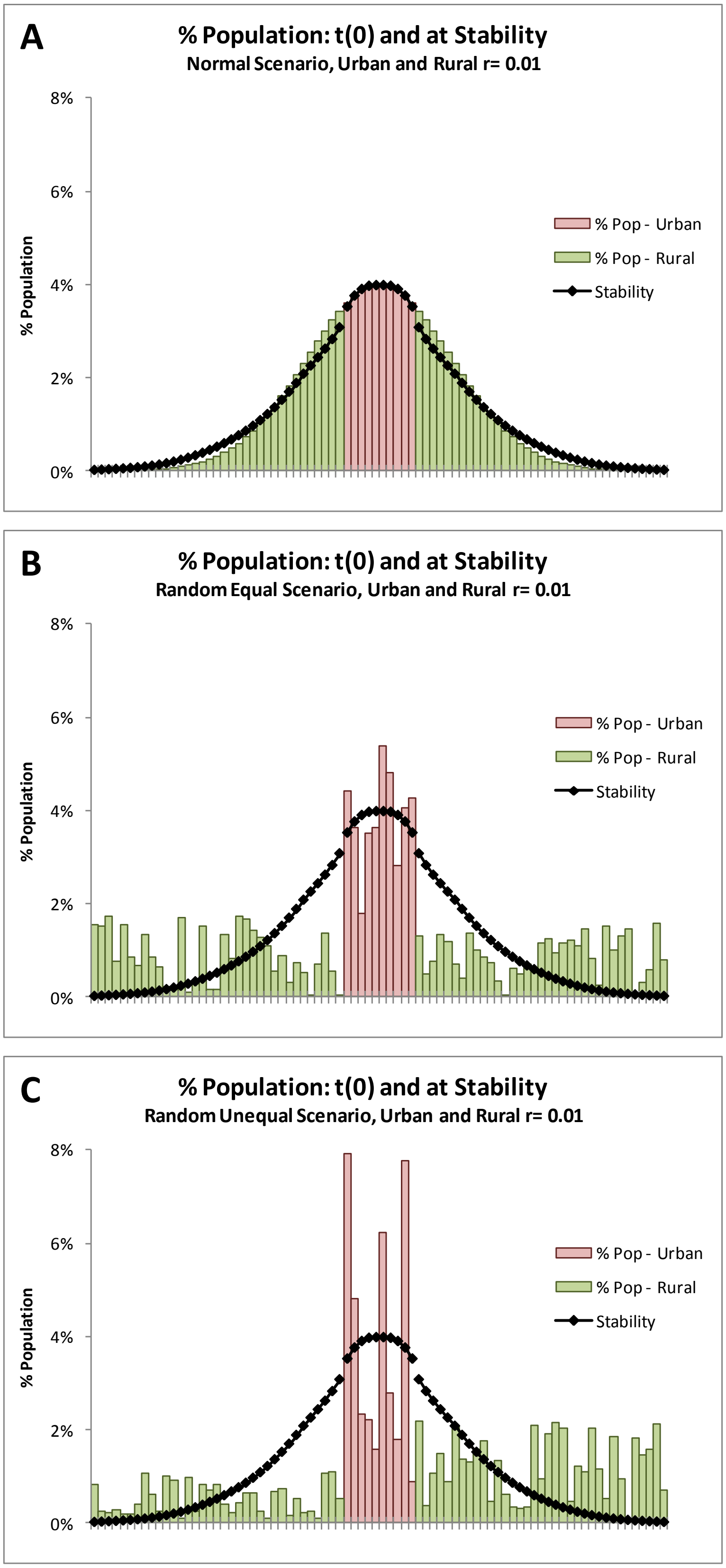

Figure 6. Distribution of population in the base-year and at stability: normal, random equal, and random unequal scenarios; equal urban and rural growth rates.

exceed those in urban areas for any extended period of time, both because the dominant trend throughout the world is urban growth at the expense of rural regions, and any rural area that experienced significant growth would soon be reclassified as urban. However, for purposes of understanding the dynamics of the model, we will discuss these scenarios here. Figure 7 plots results for the normal, random, random-equal, and random-unequal scenarios, applying annual urban and rural growth rates of 0.5% and 1.5%, respectively. In each case the distribution of the population at spatial stability is double-peaked. At stability, rural cells contain roughly 99% of the total population, and the urban population is heavily skewed towards the urban border. Again these patterns are extremely unlikely to occur in any real-world scenario. However, some useful information can be extracted from the results in Figure 7. Unlike scenarios in which the urban growth rate either equals or exceeds the rural rate, we found the form of spatial stability in these scenarios to be sensitive to the spatial structure of base-year population and, to a lesser extent, the growth rates themselves. Consider the double-sided distribution evident in the four scenarios depicted in Figure 7. In each case, over time, the urban population became insignificantly small in relation to the rural population, and thus made no significant contribution to the potential of any rural cells. As such, the urban/rural border became effectively the same as the border of the study area. Because the rural window is not large enough to span the divide between the two groups of rural cells (on either side of the urban cells), the structure of the population within each of the two rural regions evolved independently towards spatial stability, eventually reaching the arc-shaped distribution which results from the effects of the study area border.

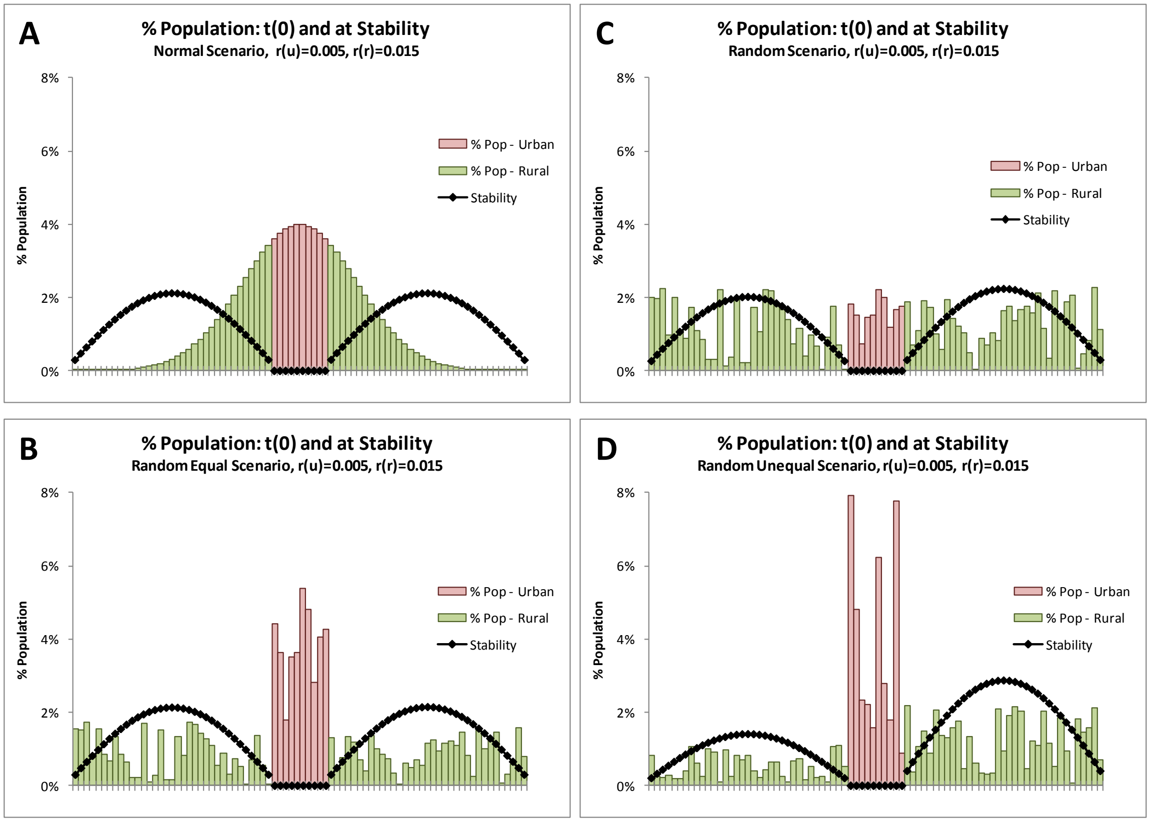

Figure 7. Distribution of population in the base-year and at stability: normal, random, random high urban, and uniform scenarios; rural growth exceeding urban growth.

If, in any scenario, a rural region evolves in isolation from any other rural region (e.g. the rural windows don't overlap), the structure of the base-year distribution then becomes a factor in the form of spatial stability. For example, in our scenarios, the portion of the population each of the two rural regions at stability is largely a function of the portion each contained in the base-year. Contrast the form of spatial stability resulting from the normal (7A) and random-unequal (7D) scenarios. The normal scenario, in which the distribution is symmetric, yields a result in which each rural region contains 50% of the total population at stability. The random-unequal scenario, in which roughly 71% of the rural population was on the right side of the distribution in the base year, yields a result in which the rural population is split 67% to 33% in favor of the right side (see Table 5).

Table 5. Proportional split in rural population

Scenario	Base Year		Stability	
	RL	RR	RL	RR
Normal	0.50	0.50	0.50	0.50
Random	0.474	0.526	0.474	0.526
Random High Urban	0.531	0.469	0.509	0.491
Random Equal	0.50	0.50	0.498	0.502
Random Unequal	0.292	0.708	0.327	0.673
Uniform	0.50	0.50	0.50	0.50

In addition to the form of the base-year distribution, we found that the relative size of the urban and rural growth rates had a slight effect on spatial outcomes, an effect which itself was largely governed by the spatial form of the base-year distribution. Table 5 lists the portion of the rural population on the left and right side of each the distributions in the base-year and at stability. Consider the normal and uniform scenarios as baselines in which, due to their symmetrical nature, the proportions will not change. Of the remaining three scenarios only the random-equal begins with an equally distributed rural population. We find, however, that at stability a slightly larger portion of the rural population is on the right side of the distribution. This slight shift results from the initial orientation of the urban population, which is skewed towards the right (see Table 5). In the early years of the simulation the urban population is large enough, relative to the rural population, to influence the allocation of additional population through the calculation of potential. The skewed urban distribution leads to slightly higher potentials in the rural cells on the right side, and thus the slight change in proportion. The influence of the urban population diminishes over time, as the rural population grows in relation to the urban population. The speed with which this influence dissipates will impact the size of the proportional shift. It is through this mechanism that the relative size of the urban/rural growth rates impacts the form of stability. The proportional shift in the rural population in the random-equal scenario is larger when the discrepancy between the urban and rural growth rates is also larger.

Similarly, note the slight shift in the proportional distribution of the rural population in the random unequal scenario. In this scenario the urban population is very slightly skewed away from the direction of the change (Table 5). Thus it is not the distribution of the urban population causing change, but instead it is the presence of the urban population causing a smoothing effect in the early years of the simulation. The same smoothing effect is evident in the random high-urban scenario. Because the urban window is large, the urban population contributes to the potential of most of the rural cells on both sides of the distribution. Thus, when the urban population constitutes a relatively large portion of the total population, as it does in the early time steps, the distribution of potential across the rural cells is far less skewed than the distribution of the existing population. The result is a proportional shift, the size of which, once again, will depend on the relative growth rates.

Finally, from the random scenario, note in the base-year the slightly larger rural population on the right side of the distribution, and the similarly skewed urban population. In spite of the right-leaning urban population, a slight proportional shift to the left occurs at stability. This result suggests that the smoothing effect of the urban population is stronger than the directional pull which results from skewness. Additionally, note that the proportional shift is smaller than in either of the other scenarios. While the smoothing and pull effects in this scenario are working opposite directions, which will lead to a smaller observed shift, further testing indicates that it is the relative size of the base-year urban population (16% in the random scenario, 38% in the other scenarios) which led to the smaller shift. Quite simply, a smaller population will exert less influence on the overall pattern.

These results, although derived from unrealistic scenarios, are not superfluous. A sustained period of rural growth at the expense of urban growth is unlikely, if not impossible. However, there is historical precedent for such a trend over shorter periods of time. Through a nuanced understanding of the forces driving this methodology it becomes easier to explain and/or predict spatial population outcomes.

5.2 In the absence of border effects a population will move towards a uniform spatial distribution.

Any spatial system, regardless of the base-year distribution, area of the region, or growth rate, will move towards a uniform population distribution over time *if* border effects are removed. Population growth at each time step is allocated to grid cells proportionally according to potential. The calculation of potential for each cell i is essentially a measure of the population density in other nearby cells (weighted by distance), but does not include any measure of population density in cell i itself. As such, those cells most likely to have large potentials are those located near densely populated cells, but they need not be densely populated themselves. The result is a smoothing effect, which moves the distribution of population towards uniform.

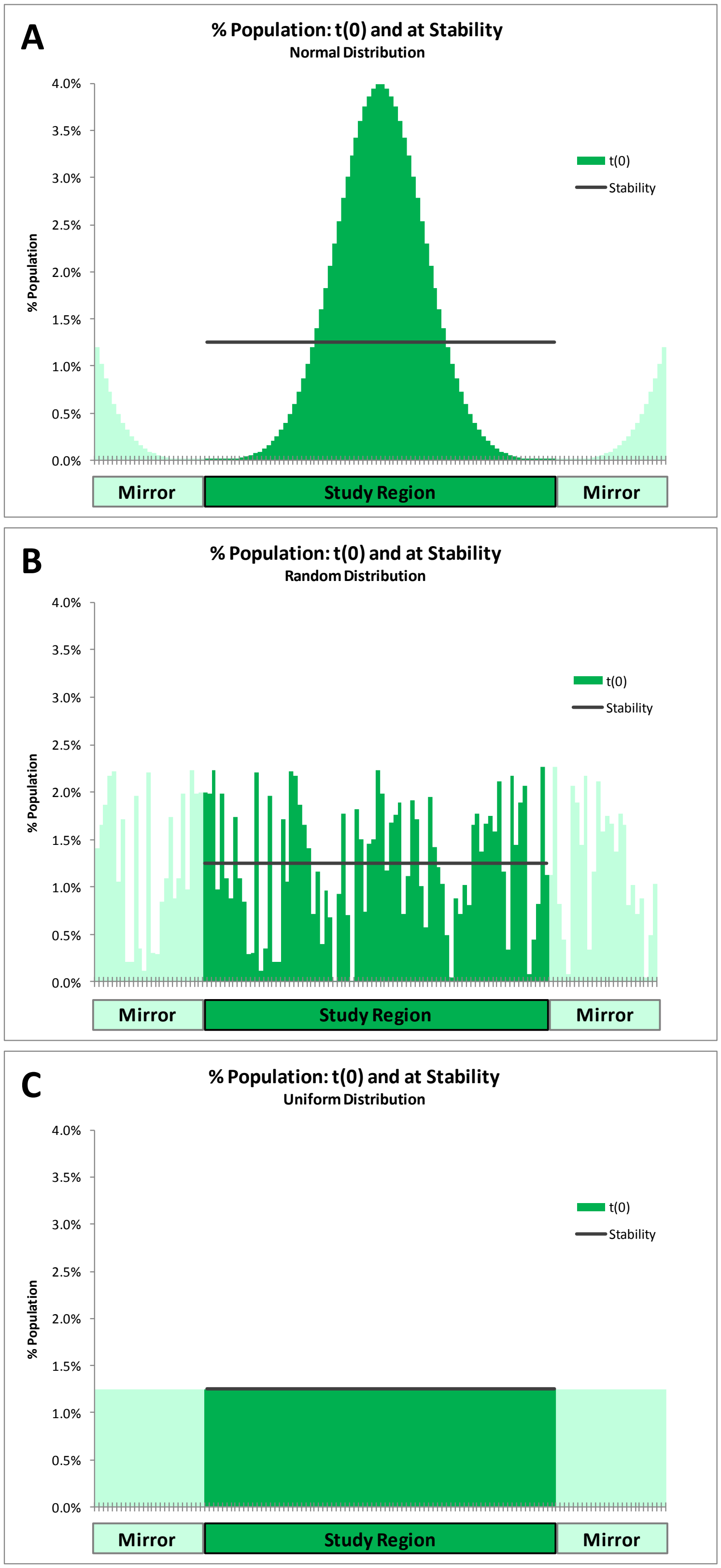

Figure 8. Distribution of population (including mirrored cells) in the base-year and at stability: normal, random, and uniform urban-only scenarios.

Consider first a set of urban-only scenarios (Figure 8) which are only subject to border effects. As noted in the previous section, the border effects the calculation of potential by truncating the windows of those cells nearest to the border. To control for this effect we simply “mirror” the last 25-cells on either side of the distribution out beyond the border. These mirrored cells are only used in the calculation of potential of other cell (that is, we do not calculate potential for or allocate any additional population to these cells). This simple procedure ensures that each cell *i* will include the same number of cells *j*, at the same average distance (D_{ij}), in the calculation of potential. As is illustrated in Figure 8, any system will evolve towards a stable, uniform distribution regardless of the form of the base-year distribution.

If the region under consideration consists of both urban and rural cells then the trend towards uniformity exists *within* the urban area and *within* the rural area, but not necessarily across the entire region. Because changes in urban and rural population are allocated separately, each area effectively operates as an independent system in a manner similar to the urban-only system discussed in the previous paragraph. However, because the calculation of potential includes both an urban and rural contribution, the populations do exert some influence on one another. To control for this influence we can limit the calculation of potential to “like-cells” only. For example, potential for an urban cell *i* is calculated considering only other urban cells *j*. If we also control for border effects using the mirroring technique (within both the urban and rural regions independently[17] we find

[17] In this case the urban/rural border must be considered the equivalent of the regional border, and urban/rural cells must be mirrored such that the windows of all cells within both the urban and rural regions (independent of one another) are of equal size.

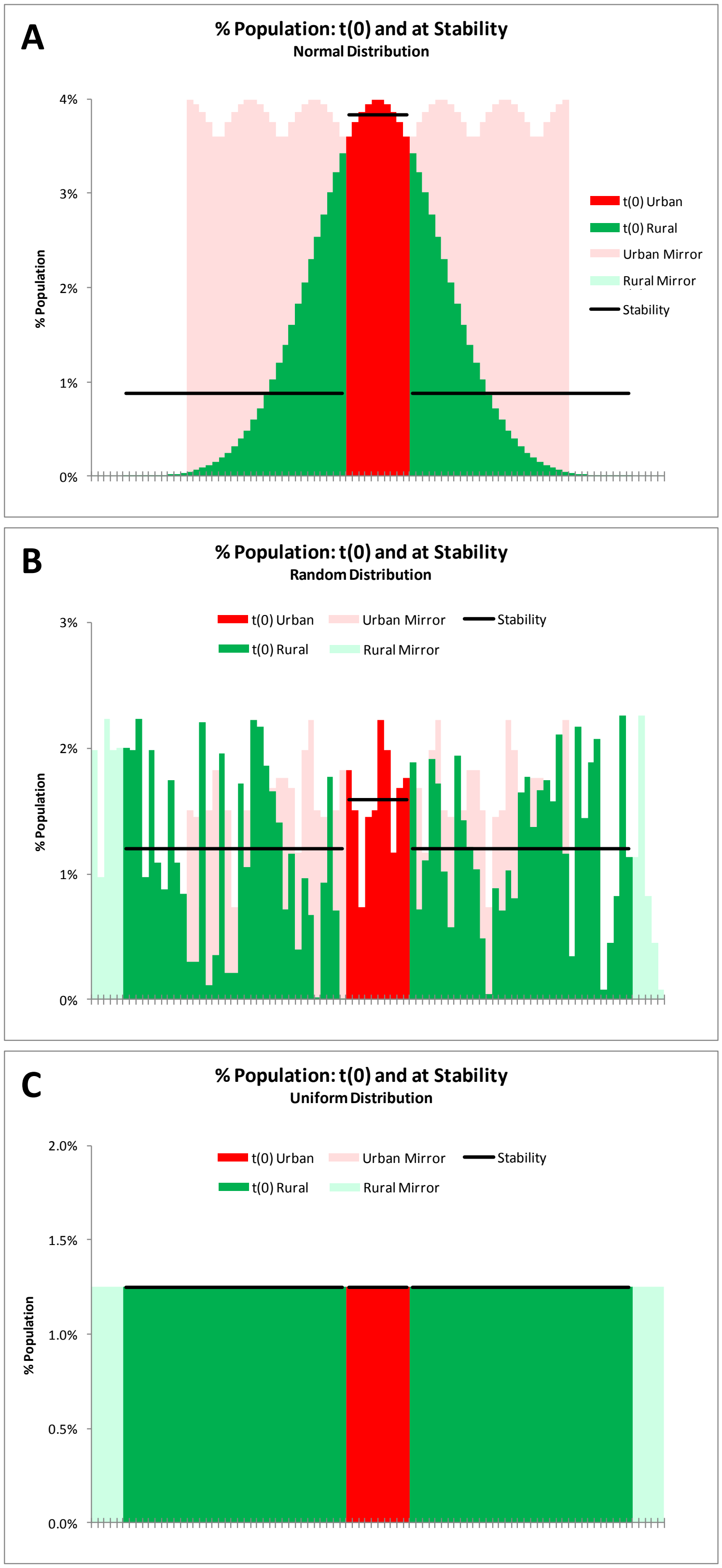

Figure 9. Distribution of population (including mirrored cells) in the base-year and at stability: normal, random , and uniform urban/rural scenarios.

that both the urban and rural populations will evolve towards a uniform stable distributions independent of one another (Figure 9).

We suggest using the mirroring technique, or another similar method, to eliminate border effects. There is no reason to believe that population is repelled by any type of border, be it natural or political. However, we do not suggest controlling for urban/rural border effects in the manner described above. These simulations were run for illustrative purposes. Urban and rural populations do exert influence over one another, and we can expect certain spatial patterns to occur along the urban/rural border. It is unclear the extent to which the IIASA methodology is capable of replicating these patterns, and as such we intend to address issues related to the urban/rural border in future work.

5.3 Over realistic time horizons, and with border effects included, initial distributions are smoothed.

In our analysis we considered three forms of base-year distributions: normal, uniform, and random. As is previously noted, the normal and random distributions are more indicative of real-world spatial population distributions. Over more realistic time horizons (100-150 years) and, in urban/rural scenarios, when considering more common growth rates (i.e., an urban rate greater than or equal to the rural rate), the IIASA methodology results in a smoothing of the initial distribution.

Figure 10 includes plots of 100-year change in the distribution of population, as well as potential in the base-year, for normal and random base-year urban-only scenarios assuming 1% annual growth. Note that in both cases the distribution of potential in the base-year is flatter than the distribution of population. Also of note are several cells from the random distribution containing very small portions of the total base-year population yet very large portions of potential, and vice-versa. These cells experience a significant gain/loss of population relative to other cells over the 100-year period. The distribution of potential in the base year, which determines the allocation of additional population, can thus be considered a leading indicator of population change over the long term. Additionally, note the similarities between the distribution of potential in the base-year and population after 100-years, the former pulls the latter towards its distribution over time.

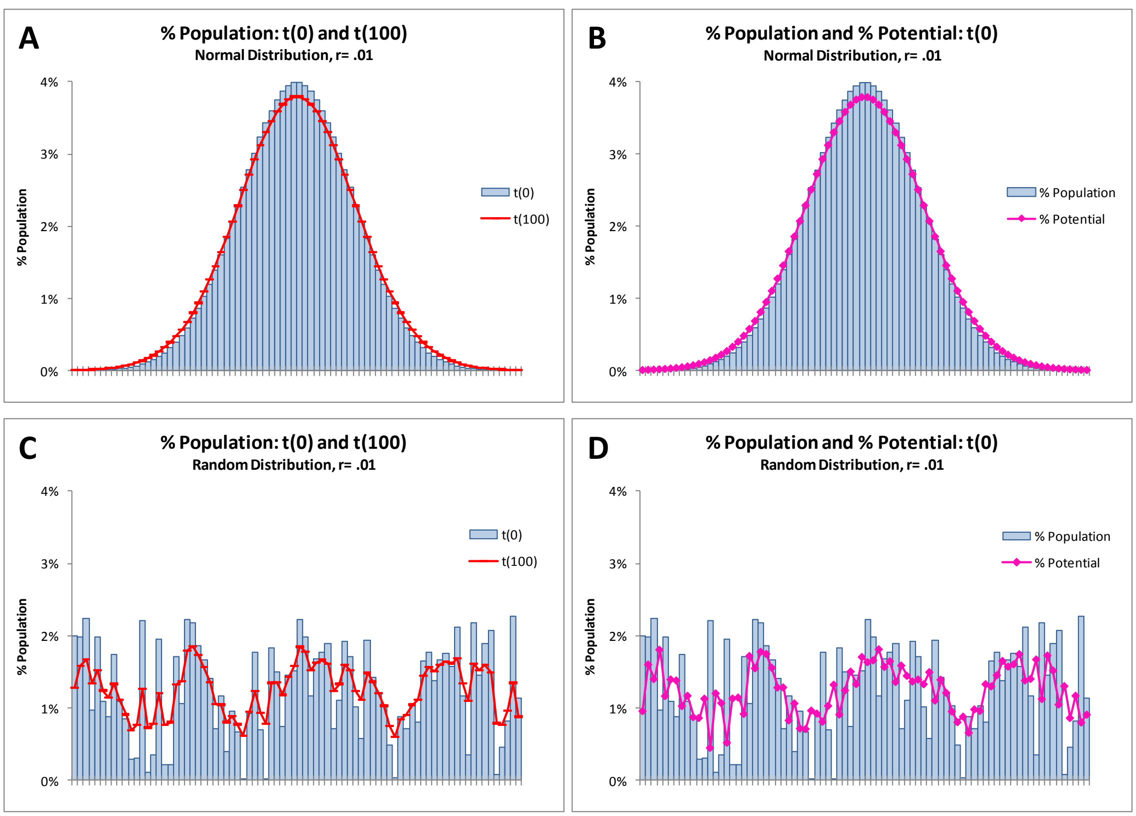

Figure 10. Distribution of population and potential in the base-year, and 100-year population change: urban-only, normal and random scenarios.

Results from normal and random base-year urban/rural scenarios are presented in Figure 11. In the random scenario movement towards uniformity over time is evident, both within the urban and rural regions independently, and across the entire study area. That same trend is more difficult to identify in the normal scenario. If we look closer at the interior cells (Figure 12A) it appears that the distribution of population after 100-years is actually moving away from the distribution of potential, particularly in the urban cells and contrary to findings from the urban-only simulations. However, if we consider the urban and rural cells independent of one another (Figures 12B and 12C) the patterns previously identified in the urban-only models are evident. In both the rural and urban regions there is clear, albeit slight, movement towards uniformity, and the distribution of population moves towards the initial distribution of potential over time.

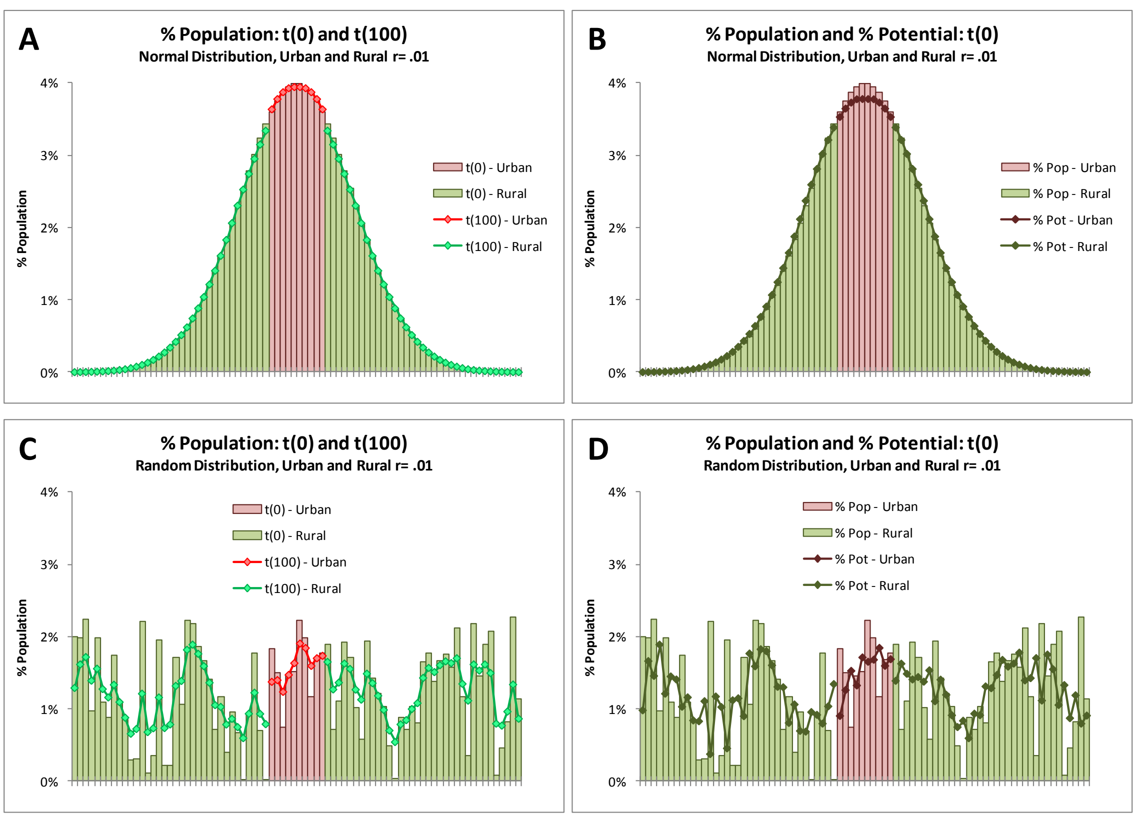

Figure 11. Distribution of population and potential in the base-year, and 100-year population change: urban/rural, normal and random scenarios.

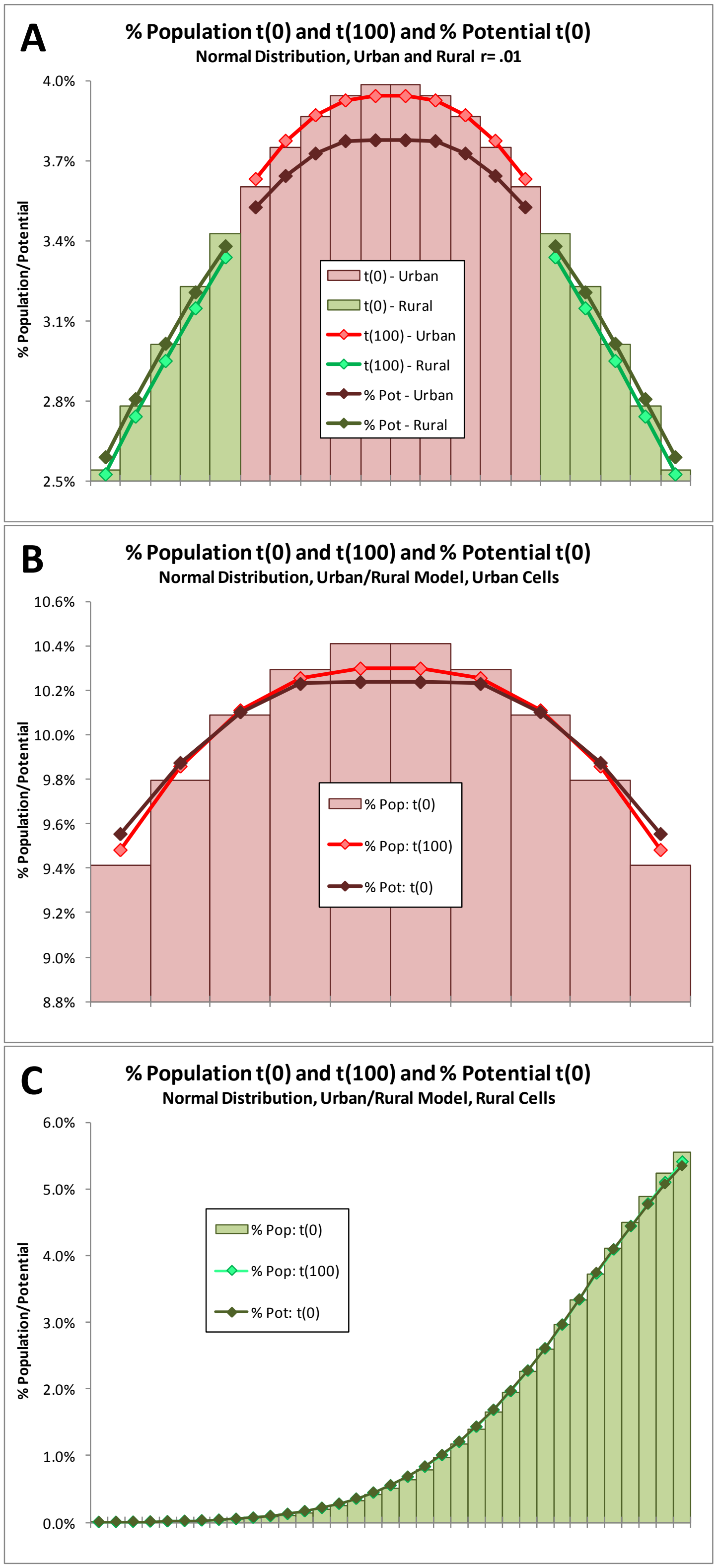

Figure 12. Distribution of population and potential in the base-year, and 100-year population change: urban/rural, normal distribution.

5.4 The growth rate(s) will impact the speed with which population structure changes, but not the form of that change.

With the exception of the very specific example discussed in the previous section, the growth rate has no bearing of the spatial structure of a distribution at stability. Instead, the growth rate is a key determinant in the time necessary for a distribution to reach stability. As is illustrated in Figure 13, the number of cells, base-year distribution, and urban/rural classification also factor into the time to stability, which can be modeled as a negative exponential function of the growth rate. More important than the form of the function, it is apparent that under any realistic growth regime the time period necessary to reach spatial stability is extremely long. Furthermore, because the IIASA methodology includes a density ceiling, it is very likely in most scenarios that many grid cells will reach the population cap before the system reaches stability[18].

From our analysis we can make a few statements regarding the speed with which a population moves towards spatial stability. In general, a population will take longer to reach spatial stability if the geographic area under consideration is larger (e.g., more grid cells, see Figure 13C), the growth rate is slower, and there is a large degree of spatial heterogeneity in the base-year distribution (13A). In this case, spatial heterogeneity refers to the degree to which the population density in one cell is *dissimilar* to that in nearby cells. Typically, humans tend to cluster spatially, and as such there is a large degree of spatial homogeneity in population density. The normal and uniform scenarios reflect this pattern. Random scenarios exhibit more heterogeneity. The effect that the

[18] The exceptions would be very small geographic areas that are very lightly populated and where the growth rate is low.

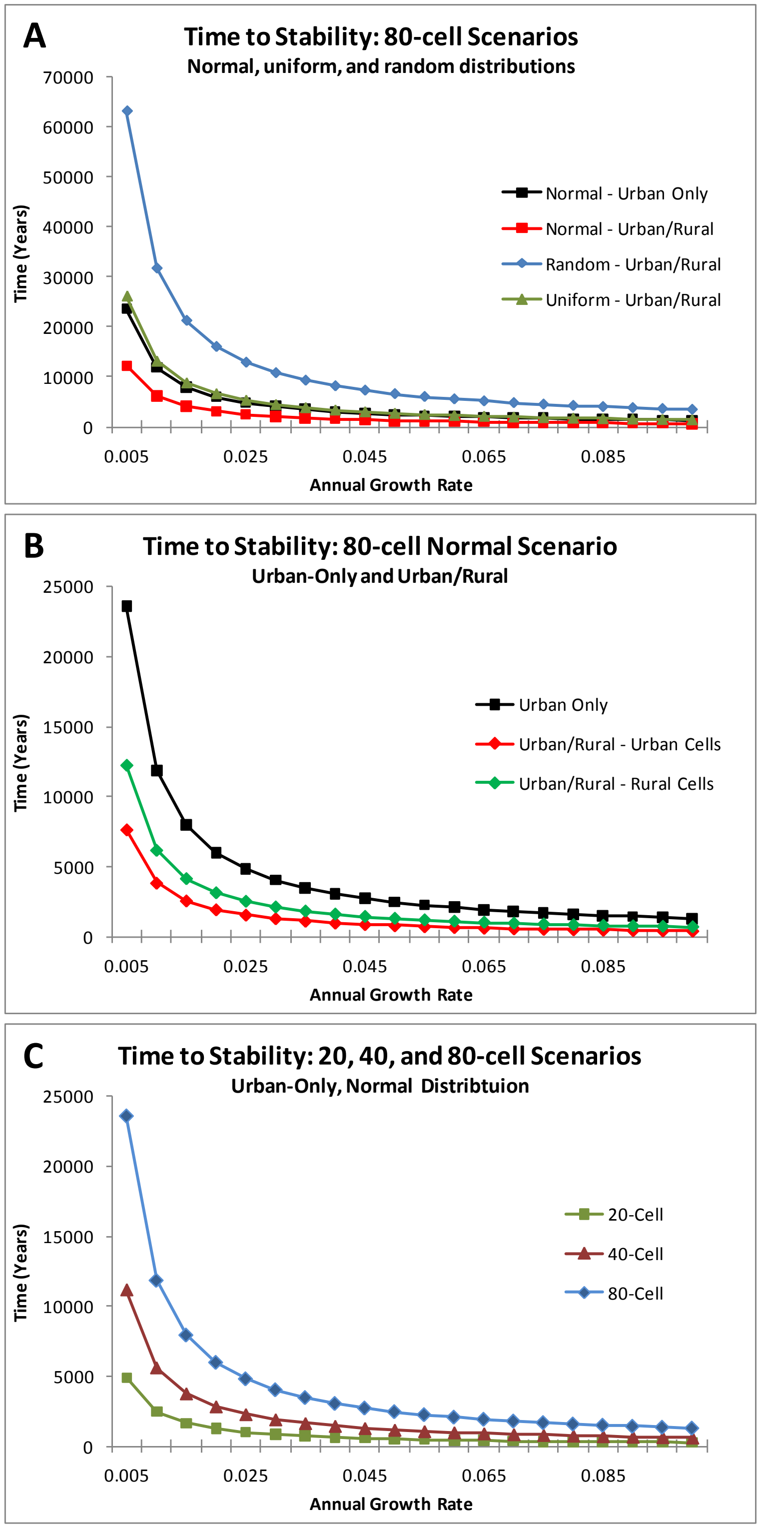

Figure 13. Time to stability at varying growth rates.

size of the study area has the time necessary to reach stability depends on the type of scenario. For example, two 80-cell normal scenarios, one of which is an urban-only model and the other an urban/rural model, exhibit very different times to stability. The urban/rural, in fact, reaches stability quicker. Because the urban and rural regions effective move towards stability independently, the 80-cell urban/rural scenario is nearly the equivalent of considering a separate 70-cell rural system and 10-cell urban system. Because the urban and rural geographies, independent of one another, are smaller than the urban-only geography, the urban/rural system will reach stability first (Figure 13B).

These trends are evident in urban-only scenarios and within the urban and rural populations in urban/rural scenarios. As is noted several times previously, in the urban/rural model each population reaches stability independently. It is worth noting, however, that the population that is driving growth will reach stability first. Thus, if the urban growth rate is larger, the urban population will reach stability first (see Figure 13B). If both populations are growing at the same rate, the urban population is still more influential due to the larger urban window, and thus will again reach stability first.

5.5 Population loss is misallocated.

To this point our results have considered systems experiencing growth. Population decline, however, is a commonly observed phenomenon in both rural and urban areas. Because the model distributes any population change proportionally to potential, the potential-allocation approach misallocates population loss[19]. If we consider

[19] The IIASA methodology was designed specifically to allocate urban change, which through much of the world is positive. Notable exceptions include areas of urban stagnation and industrial decline, which can

population potential as a proxy for relative position and thus accessibility and/or attractiveness, then a higher potential in cell A relative to cell B should be interpreted as cell A being a more attractive place to live. It stands to reason, then, that when population change is positive a larger portion of the change should be allocated to cell A. However, in periods of population decline it is logical to assume that those places deemed less attractive should suffer a larger portion of the total population loss (using the previous example, cell B should experience more loss relative to cell A). The potential-allocation model, however, allocates *change* as proportional to potential, thus leading to relatively more population loss in those cells deemed more attractive. This pattern is best illustrated when considering a uniform distribution (see Figure 14). Population potential is highest in the interior cells, thus those cells absorb a larger relative portion of the population decline, leading to a distribution skewed towards the borders in both the urban-only and urban/rural scenarios.

The IIASA methodology was an attempt to move away from the proportional allocation of population change, and thus to more accurately model spatial population dynamics. Much of the world, particularly the fastest growing regions of Asia and Africa, is experiencing rapid urbanization. The IIASA methodology will, in the short-term, allocate proportionally more population growth to areas that are already urban, a pattern commonly found in the observed data. However, it is clear that to expand the applicability of this methodology it must be refined to address population loss, both urban

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be found in the Midwestern United States and in parts of Western Europe, and those countries experiencing (or forecast to experience) population decline, as is the case in many Eastern and Southern European countries as well as Japan. Rural population loss is a very common phenomenon in both developed and developing countries. The IIASA methodology was not designed to address rural loss, however, it is our hope to expand the IIASA approach to more accurately model rural change, so we consider the ramifications of the potential-allocation approach here.

and rural. Within the framework of the existing methodology we suggest a relatively simple solution; during periods of population decline allocate population change proportionally according to the inverse of potential. This solution, which corrects a fundamental flaw in the logic of the model, is suggested as a stop-gap measure against misallocating population loss until further research and testing can be conducted.

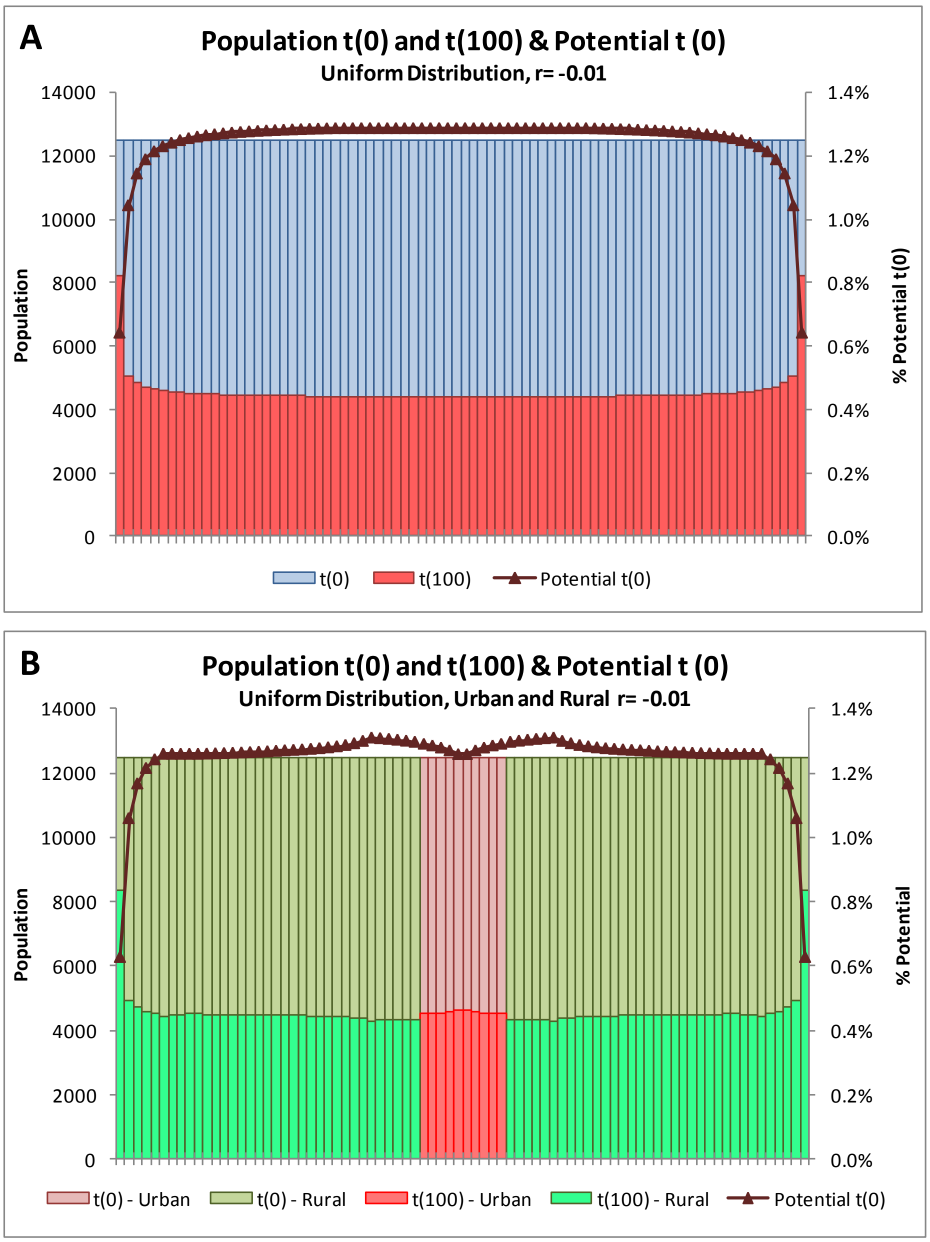

Figure 14. Allocation of population loss: 100-year urban-only and urban/rural scenarios.

5.6 The base-year distribution of potential relative to that of population is a strong predictor of long-term population change.

The allocation of projected future population change occurs proportionally according to potential at each time step. As such, the distribution of potential at time *t* will alter the distribution of population at time *t+1* such that it more closely resembles the distribution of potential. The cell specific difference between the relative portion of potential and population at time *t* correlates perfectly with the change in the relative portion of the population in each cell from time t to *t+1*, considering the total population in an urban-only scenario (Figure 15A), and the urban and rural populations independently in an urban/rural scenario (Figure 15B and 15C). This correlation is perfect for every single period time-step out to spatial stability, at which point all values go to zero. The mathematical relationship (slope of the line) between relative population change and the difference in the relative distributions of base-year potential and population is a function of the growth rate. A higher growth rate yields a steeper slope. Thus, in an urban/rural scenario in which the urban growth rate exceeds the rural rate (Figure 15C) the urban slope will be steeper than the rural slope, and perfect correlation will exists within the urban and rural cells independent of one another.

The relationship between potential and population is dynamic. The initial distribution of potential is a function of the base-year population distribution. At each time step the distribution of potential alters the distribution of population through the allocation of additional population which, in turn, alters the subsequent distribution of potential. Thus, the distributions move together as the cycle continues over time. As a result, the correlation between the base-year difference between the distributions of potential and population, and the change in the distribution of population from the base-year to time $t + x$, where $x > 1$, will be less than perfect, and will weaken as x increases. However, our research indicates that the shift in the distribution of potential, and subsequently population, are generally very small at each time step. As such, the relationship remains robust over the period of time with which most long-term population projections are concerned (≈ 100 years). Figure 16 illustrates the correlation between base-year difference in population and potential and the 100-year change in the distribution of population for the urban-only and urban/rural scenarios. Note the very high correlation coefficients.

As a result of this strong correlation, it is possible to identify grid cells that will gain or lose population relative to the other cells in the study area simply by considering the base-year distribution of population and potential. It may also be possible to, although somewhat more difficult, to generate a projected spatial population map using only these distributions and the assumed rate of change. This would require, however, some knowledge of the speed with which the population distribution will change relative to the growth rate, as well as the geographic characteristics of the study area. Isolating these relationships would require actually applying the IIASA model and using the results to derive the necessary functions. It may be useful, in the future, to consider some form of classification system based upon geography and growth rates from which one may select a redistribution function to project the future spatial population structure. The advantage of such a system would be significantly reduced computational demands in relation to the IIASA methodology.

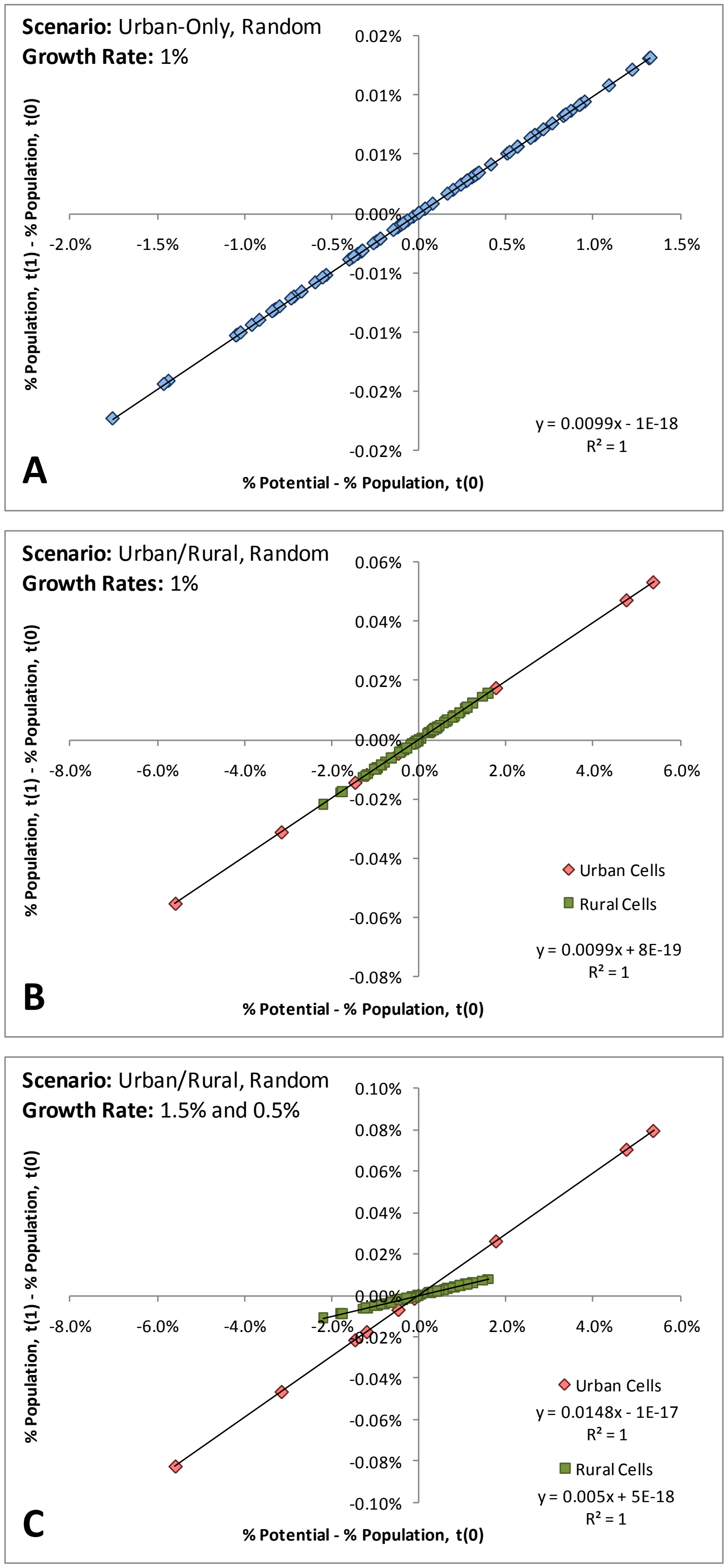

Figure 15. Difference between base-year potential and population against one-year population change; urban-only and urban/rural random scenarios.

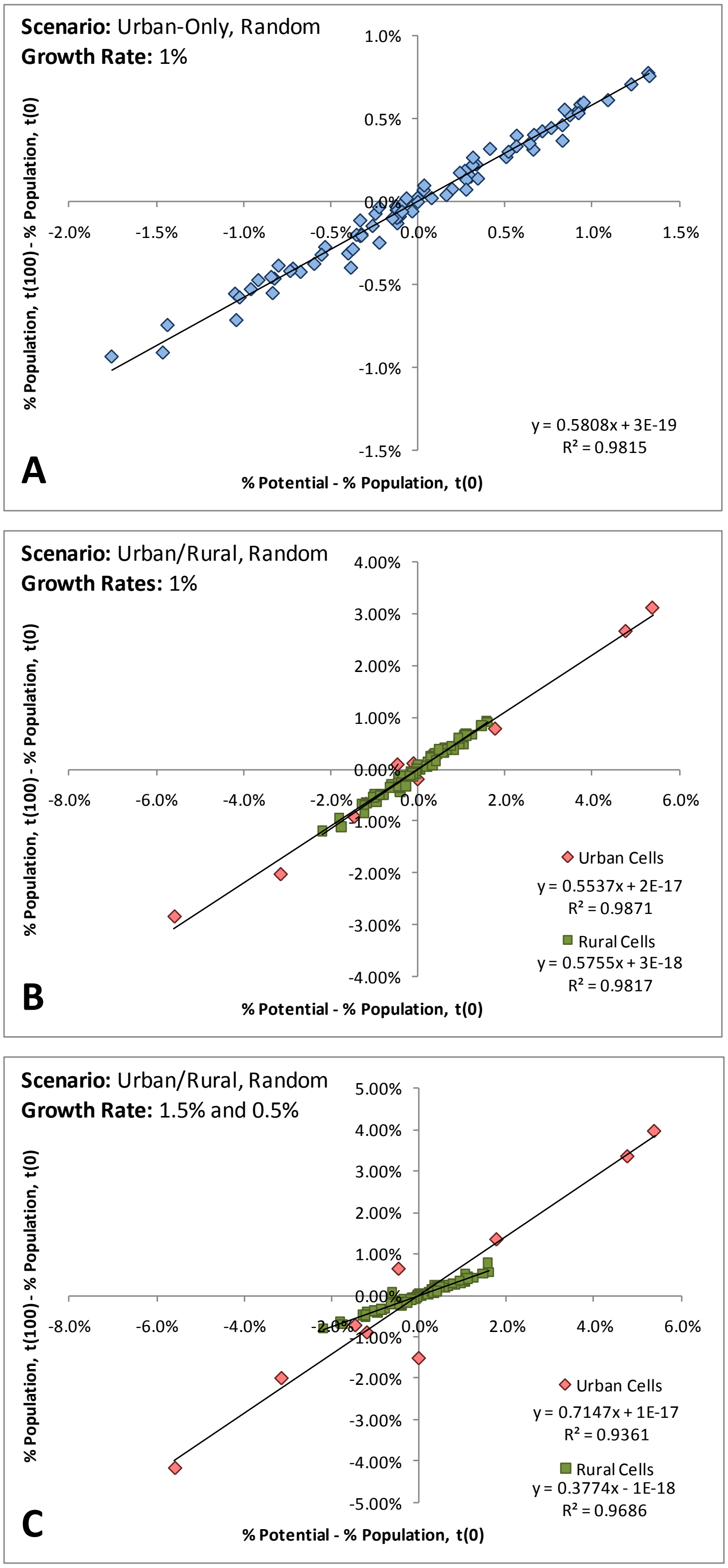

Figure 16. Difference between base-year potential and population against 100-year population change; urban-only and urban/rural random scenarios.

6. Spatial implications of our conclusions

The functioning of the IIASA methodology has important implications in a modeling environment. We can use the above analysis to anticipate likely patterns in spatial population outcomes produced by the model given certain characteristics of the region in question. Through our analysis we came to five key conclusions concerning the IIASA methodology. Four of those conclusions have implications regarding spatial outcomes produced by the model over a typical long-term time horizon (100-150 years). We briefly discuss each in turn below.

6.1 Border effects substantially influence spatial population outcomes.

Border effects prevent the IIASA methodology from moving any population to uniformity. Conversely we can say that it is because of border effects that the model results in spatial outcomes (at stability) that have any shape other than uniform. We can classify border effects into two groups, those related to the border of the study area and those resulting from the location of the urban/rural border. The former produce easily identifiable patterns which can be anticipated in any scenario, while the latter are generally more complex and scenario dependent.

In any scenario, the relative magnitude of the projected population change will be lower in cells that are closer to the border of the study area. The impact of the border diminishes with distance. However, due to the overlapping nature of the potential windows, the border of the study area affects the entire distribution, leading to an over-allocation of population in the interior of the study area, and an under-allocation in the exterior. This affect will occur regardless of the base-year distribution and the urban/rural classification scheme. Over a 100-150 year period the effect may be relatively difficult to tease out, particularly if the base-year population distribution lacks an identifiable/quantifiable pattern.

The urban/rural border affects the projected distribution of population through two mechanisms; the allocation rule and the calculation of potential. Due to the allocation methodology (i.e., the separate allocation of urban and rural change within their respective regions) spatial outcomes are often extremely sensitive to the location of the urban/rural border. Projected urban growth throughout much of the world significantly exceeds the corresponding rural change. In such cases, the allocation of urban population change within only urban cells leads to a distinct drop in density along the urban/rural border. Even in cases where potential is similar in cells on either side of the border (as it often is), because significantly larger growth is allocated across urban cells (of which there are likely to be fewer) a gap develops quickly. Furthermore, because rural growth is often very modest, even in cases where the rural cells on the border have very high potential relative to other rural cells, the allocation of very low growth may make it impossible for a rural cell on the border to achieve the density necessary to be reclassified.

Because the calculation of potential considers urban and rural windows of different sizes, the location of the urban/rural border has a significant effect on the distribution of potential within both urban and rural regions. The spatial pattern resulting from the urban/rural border effect varies, and is highly dependent on the geography of the study area and the existing distribution of population. The spatial effects that can be linked to the size of the potential windows are all related to the number of cells *j* contributing to the potential of each cell *i*. For example, the urban window influences the distribution of rural potential insomuch as the potential of a rural cell that falls outside a 25 cell radius of the urban border does not receive any urban contribution. If the urban population in question is large enough this could lead to a gap in density over time. Similarly, because the rural window has a much smaller 5 cell radius, within an urban area only those cells within a 5 cell radius of the urban border receive a rural contribution to potential. Under the right circumstances urban cells near the rural border may have higher potentials, and thus may grow more quickly than the interior urban cells.

The range of spatial outcomes resulting from urban/rural border effects is too wide to consider in detail here. The scenarios cited above are presented as examples of the two distinct mechanisms through which the urban/rural border impacts the distribution of projected population; the allocation rule and the potential windows. Both the form of urban/rural border effects, and the degree to which those effects influence spatial outcomes, are closely related to the geography of the study area, the relative urban and rural growth rates, and the base-year distribution of population.

6.2 In the absence of border effects a population will move towards a uniform spatial distribution.

The tendency of the model to move any distribution towards uniformity will, in most cases, produce a spatial projection in which population spreads outward from densely populated urban centers. Relative to the most densely populated urban cells, adjacent cells of lower base-year density will experience more growth. The effect is a sprawling pattern of growth. Despite general movement towards uniformity, significant time is necessary for the model to actually produce a uniform pattern (if we control for border effects), unless the geographic area in question is very small and/or the growth rate is very high. Over a period of 100-150 years the visible effects of the trend towards uniformity, if the urban population is expected to grow, will be urban growth in the form of sprawl and to a lesser extent increased densities in the urban core. Additionally, the development of urban corridors may become evident. The latter occurs as those areas located between urban centers grow in relation to other lower density areas, a result of higher potential due to proximity. If, as is often observed, the urban growth rate is significantly higher than the rural rate of change, then the model may produce a significant drop in density along the urban/rural border. We characterize this pattern as a border effect, and discuss it further in the next section.

6.3 The growth rate(s) will impact the speed with which population structure changes, but not the form of that change.

The impact of the growth rate on projected spatial population outcomes is relatively simple to interpret. We found that the assumed rate of change, urban or rural, has no effect on the spatial patterns produced by the model. Instead, growth rates only affect the speed with which those changes occur. A faster rate of change shortens the time period necessary for the model to produce a spatially stable population distribution. The form of that distribution, however, is a function of other characteristics of the model. Thus, if considering a time horizon of 100-150 years and the assumed growth rates are varied, scenarios in which the growth rate is higher (if urban/rural growth rates are equal) will produce an outcome that is further along the path to stability. If the urban growth rate is assumed to be larger than the rural rate, then it is the magnitude of the difference between the rates that governs speed to stability, with the largest difference leading to the fastest change.

6.4 Population loss is misallocated.

In the absence of any change to the methodology, population loss is allocated proportionally according to potential in the same manner as population gain. Therefore, if the total projected population (urban or rural) is expected to decline, the largest portions of that decline are allocated to the cells with the highest potentials, which as discussed previously is counter to the concept of population potential. If the expected decline is urban, then in most scenarios where the urban population is established (i.e., a large portion of the total population), and the study area is characterized by urban nodes, proportionally more population loss will occur in the urban core. In many cases this pattern is not unrealistic. For example, many older industrial cities in the Midwestern United States have experienced significant urban population loss over the past 50 years. In many cases this decline is far more pronounced in the old industrial core, while populations on the younger urban fringe have remained more stable. However, it does mean the methodology will not produce a pattern indicative of urban revitalization or gentrification unless the total urban population increases. In the far more unlikely scenario of urban population decline in a region where the urban population does not constitute a large portion of the total population and dense urban nodes are the exception, proportionally more urban population loss is likely to occur on the urban fringe.

The misallocation of population loss within the context of population potential may be more problematic in rural areas. Again, IIASA did not apply the potential-allocation methodology to rural populations, but it is our intention to expand the methodology to include rural areas in lieu of the proportional allocation of rural change. During periods of rural decline, very common throughout the world, population loss is disproportionally allocated to those rural cells with the highest potential. In the highly-urbanized developed world these cells almost always fall on the urban/rural border. Thus rural population loss would be concentrated in those areas nearest to urban centers. In many cases this is the equivalent of suburban population loss, an unlikely occurrence given historical trends. In the developing world, where urban populations are not as large, the pattern of potential may be slightly different, more closely resembling the double-peaked distribution noted earlier. In such a scenario rural population loss would be most pronounced in an area slightly removed from the urban/rural border, but in general closer to the urban center than the most remote rural areas. Such a pattern would be very difficult to justify.

We offer a simple solution to the misallocation problem, considering the inverse of potential is projected population change is negative. Through this solution rural population loss would, in most cases, be allocated in a manner more indicative of historical trends, and consistent with the concept of potential. Urban population loss poses a more difficult problem. The existing potential-allocation methodology will produce a pattern that, in some cases, is justifiable, and yet is also the result of a process that is intuitively counter to the concept of potential. At this time, further consideration of this problem is necessary.

7. Future analysis

This technical note reviews our initial analysis of the IIASA downscaling methodology, and includes a few minor refinements. We plan to follow up with two additional reports, the first of which will assess the performance of the model in a test against historical census data considering the state of Iowa. Second, we introduce a gravity model in place of the potential model in the calculation of population potential. Additionally, we then parameterize the gravity model which may widen the range of potential spatial outcomes produced by the model. In addition to these immediate plans, we have identified several methodological questions we intend to address related to the urban/rural classification and allocation techniques, the justification for the urban and rural windows and the spatial scale of the application. Additionally, we hope our future work will open up the possibility of exploring a calibrated gravity model capable of reproducing commonly observed patterns in spatial settlement, and introducing some level of stochasticity into the model.

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