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Preliminary Steps towards Integrating Climate and Land Use: The Development of Land-Use Scenarios Consistent with Climate Change Emissions Storylines

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ABSTRACT

Climate and land use change are major components of global environmental change with feedbacks between these components. The consequences of these interactions also show that land use may exacerbate or alleviate climate change effects. Based on these results it is important to use land use scenarios that are consistent with the specific assumptions underlying the climate change scenarios. The Integrated Climate and Land Use Scenarios (ICLUS) project developed outputs that are based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) social, economic, and demographic storylines and downscaled these to the United States. ICLUS outputs are derived from a demographic model and a spatial allocation model that distributes the population as housing across the landscape for the four main SRES storylines and a base case. The model is run for the conterminous United States and output is available for each scenario by decade to 2100. In addition to maps of housing density across the conterminous United States, this project also generated maps of impervious surface cover based on the housing density projections. This report describes the modeling methodology for the ICLUS project, some initial analyses using the ICLUS outputs, and recommendations for further research.

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LIST OF ABBREVIATIONS AND ACRONYMS

A1	The A1 storyline in the *Special Report on Emissions Scenarios*
A2	The A2 storyline in the *Special Report on Emissions Scenarios*
B1	The B1 storyline in the *Special Report on Emissions Scenarios*
B2	The B2 storyline in the *Special Report on Emissions Scenarios*
GCM	General Circulation Model
GCRP	Global Change Research Program
HD	Housing Density
HUC	Hydrologic Unit Code
ICLUS	Integrated Climate and Land Use Scenarios
IPCC	Intergovernmental Panel on Climate Change
MIGPUMA	Migration Public-Use Microdata Areas
MRLC	Multi-Resolution Land Characteristics
NLCD	National Land Cover Database
PUI	Percent Urban Imperviousness
PUMA	Public-Use Microdata Areas
PUMS	Public-Use Microdata Samples
SERGoM	Spatially Explicit Regional Growth Model
SRES	Special Report on Emissions Scenarios

PREFACE

This report was prepared jointly by ICF International, Colorado State University, and the Global Change Research Program in the National Center for Environmental Assessment (NCEA) of the Office of Research and Development at the U.S. Environmental Protection Agency (U.S. EPA). The report describes the methodology used to develop and modify the models that constitute the EPA Integrated Climate and Land Use Scenarios (ICLUS). The scenarios and maps resulting from this effort are intended to be used as benchmarks of possible land use futures that are consistent with socioeconomic storylines used in the climate change science community. The two-way feedbacks that exist between climate and land use are not yet fully understood and have consequences for air quality, human health, water quality, and ecosystems. In this report we describe the first steps towards characterizing and assessing the effects of these feedbacks and interactions by developing housing density and impervious surface cover scenarios. These outputs facilitate future integrated assessments of climate and land-use changes that make consistent assumptions about socioeconomic and emissions futures. EPA's intention is to use the results of this first phase of modeling to inform and facilitate investigation of a broader set of impacts scenarios and potential vulnerabilities in areas such as water quality, air quality, human health, and ecosystems. More specifically, this research will enable more sophisticated model runs that will evaluate the effects of projected climate changes on demographic and land use patterns and the results of these changes on endpoints of concern.

AUTHORS AND REVIEWERS

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EXECUTIVE SUMMARY

Climate and land use change are major components of global environmental change. Assessments of impacts associated with these changes often show interactions and two-way feedbacks between climate and land use. The consequences of these interactions also show that land use could exacerbate or alleviate climate-change effects. Based on these results it is important to use land-use scenarios that are consistent with the specific assumptions underlying recognized international climate-change scenarios.

The EPA Integrated Climate and Land Use Scenarios (ICLUS) project developed outputs that are based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) social, economic, and demographic storylines. We downscaled these storylines to the United States and modified U.S. Census Bureau population and migration projections to be consistent with these storylines. ICLUS outputs are derived from a demographic model and a spatial allocation model that distributes the population projections generated by the demographic model into housing units across the landscape. The demographic model is at the county scale and the spatial allocation model is at the 1 ha pixel scale. Each scenario is run for the conterminous U.S. to 2100.

The results of this first phase of this project are designed to provide a foundation for evaluation of a broader set of impacts scenarios and potential vulnerabilities in areas such as water quality, air quality, human health, and ecosystems. More specifically, these scenarios will underlie more sophisticated model runs that will evaluate the effects of projected climate changes (e.g., sea level rise) on demographic and land use patterns and the results of these changes on endpoints of concern. The products generated in this first phase are consistent with socio-economic storylines used by the climate change modeling community, but it does not explicitly integrate climate change variables into the models.

The EPA-ICLUS project uses the SRES storylines because these storylines are used as direct inputs into general circulation models used by the climate change science community. This link facilitates integrated assessments of climate and land use, because the broad underlying assumptions are the same. The SRES describe storylines along two major axes, economic vs. environmentally-driven development (A-B) and global vs. regional development (1-2), which make up the four combinations of storylines, A1, A2, B1, and B2. We adapted these storylines for the United States by changing fertility, domestic and international migration, household size, and travel times from the urban core.

The demographic model is composed of five components, fertility, mortality, domestic in-migration, domestic out-migration, and net international migration, which are calculated using a cohort-component model and a gravity model. The population is divided into cohorts that are age-, gender-, and race/ethnicity-specific. Changes due to these five components of change are estimated over time as each cohort is tracked separately. The gravity model is used to track domestic in- and out-migration by county. Components of the gravity model include certain county amenities and functional distance that connects counties based on population locations and transportation infrastructure. The resulting county-based population projections are the inputs to the spatial allocation model.

The spatial allocation model distributes the population into housing units across the country at a 1 ha pixel scale. The model used in this project is the Spatially Explicit Regional Growth Model (SERGoM). SERGoM uses five main base datasets: housing units and population based on the 2000 census, undevelopable lands, road and groundwater well density, commercial/industrial land use from the National Land Cover Database, and county population projections from the demographic model described above. Household size and travel times are adjusted to reflect the assumptions of the different SRES storylines. These modifications result in different spatial allocations among the scenarios such that the B storylines show more compact growth focused around urban areas and the A storylines show less compact growth overall and more housing in suburban and exurban densities.

The scenarios result in a range of projected increases in urban and suburban area across the United States. The smallest increase is 56% for the B1 scenario and the largest increase is 156% for A2. These increases in housing can be translated to changes in impervious surface cover, which can be used to examine impacts on water quality, for example. Our results show that there could be a doubling to nearly a tripling of watersheds (8-digit HUCs) that are likely to be stressed from impervious surface coverage of at least of 5%. These changes will vary regionally across the country.

This report describes the modeling methodology for the EPA-ICLUS project and some initial analyses using the outputs. There are many additional modifications that are possible to explore additional land use futures and there are many options for further research. Model modifications can be made to further explore policy and planning alternatives such as Smart Growth development patterns. The demographic and spatial outputs can be used in numerous analyses examining potential future impacts on air quality, water quality, traffic and associated emissions, and regional growth rates.

1 INTRODUCTION

Climate change and land use change are global drivers of environmental change. Impact assessments frequently show that interactions between climate and land use changes can create serious challenges for aquatic ecosystems, water quality, and air quality. In many cases, it is impossible to determine the impact of climate change without consideration of land use and land cover dynamics. While land use can exacerbate climate impacts, land use planning, policy, and management can also create important adaptation opportunities to increase the resilience of sensitive socioeconomic or ecological systems.

Integrated assessments of both climate and land use changes currently are limited by fragmented information on potential future land use. In many cases individual municipal areas have conducted extensive analyses, but it is impossible to place results in regional or national contexts. Moreover, the studies are often based on inconsistent or poorly documented socioeconomic storylines. The motivation for the EPA-ICLUS project was derived from the recognition of the complex relationships between land use change and climate change impacts and the absence of an internally consistent set of land use scenarios that could be used to assess climate change effects.

The EPA-ICLUS project developed scenarios for two important aspects of land use, housing density and impervious surface cover, for the entire conterminous United States for each decade through 2100. These scenarios are based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) social, economic, and demographic storylines (Nakićenović 2000). These scenarios are rendered using a combination of models representing demography, including domestic and international migration, and spatial allocation of housing (Figure 1-1). The resulting scenarios (1) enable us, our partners, and our clients to conduct assessments of both climate and land use change effects across the United States; (2) provide consistent benchmarks for local and regional land use change studies; and (3) identify areas where climate-land use interactions may exacerbate impacts or create adaptation opportunities.

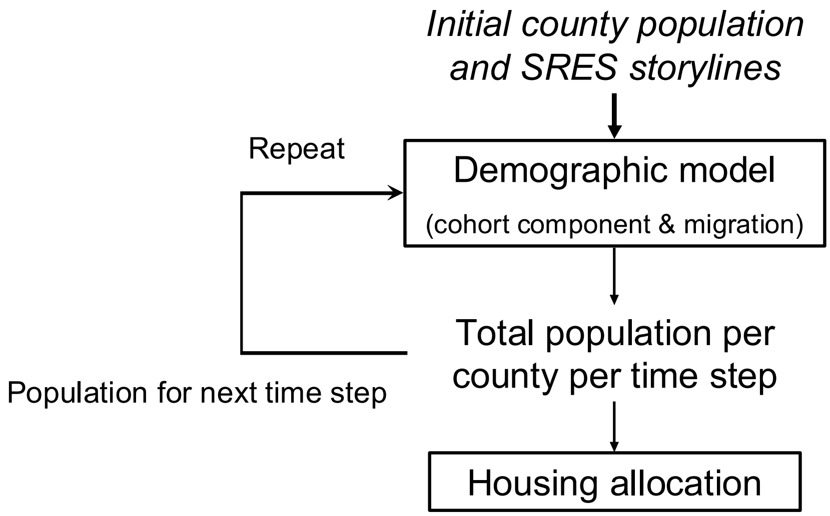


Figure 1-1: Model and information flow within the EPA-ICLUS project

The U.S. Environmental Protection Agency's Global Change Research Program (GCRP) in the National Center for Environmental Assessment of the Office of Research and Development began investigating the availability of state and county-level population projections in 2004. Initial efforts evaluated the availability, sources, and extent of state and county-level population projections with an emphasis on identifying projections for the time period from 2050 through 2100. These efforts yielded numerous datasets, but very few sources projected populations to 2050 and beyond. Demographic projections for these later years are particularly relevant when considering the impacts of climate change on ecosystems, water infrastructure, transportation infrastructure, and land protection efforts. Population and land use projections based on economic factors such as regional income and employment growth can shift dramatically over time. Projections based on fundamental demographic drivers such as fertility and mortality are somewhat more stable, particularly over longer time frames. Therefore, the ICLUS project uses demographic projections as the basis for modeling changes in housing density.

The modeling framework (Figure 1-1) presented in this report uses demography to drive the number and migration of people, while a spatial allocation model governs the distribution of people on the landscape in housing units. The demographic model has two parts, a cohort-component model and a gravity model. The spatial allocation is conducted using an established Geographic Information System (GIS)-based model, SERGoM (Theobald 2001, 2003, 2005). The study was designed to provide county-level demography and housing density for the conterminous United States with housing density allocations for each 1 ha pixel for each decade through 2100.

2 SRES DOWNSCALING TO THE UNITED STATES

The socio-economic storylines in the SRES are derived from anticipated demographic, economic, technological, and land-use changes data for the 21st century, and are highly aggregated into four world regions (Nakićenović et al. 2000). The SRES describe linkages between physical changes in climate and socio-economic factors, because they link development pathways with greenhouse gas (GHG) emissions levels used as inputs to general circulation models (GCMs) (Rounsevell et al. 2006). There have been other scenario-development exercises to assess future impacts on a range of endpoints, including the Millennium Ecosystem Assessment (MEA, 2005), which also describes economic and environmental conditions in the future. The benefit of using the SRES storylines is their direct link to GCMs. This enables us to link our land-use projections to emissions and future climate scenarios for integrated assessments of the effects of land use change and climate change in a consistent way.

Modeling and projecting human activity into the future is a challenge for many reasons. Any attempt to project demographic and economic changes over time must contend with large degrees of uncertainty. Furthermore, taking discontinuous events into consideration—ones that would have a profound effect on any anticipated trajectory—is even more difficult. Nevertheless, a forward-looking approach to environmental and economic problems encourages us to look into the future to attempt to better understand the challenges that lie ahead, and to better prepare our society to confront those challenges.

By taking a scenario approach to such modeling efforts, we acknowledge this inherent uncertainty and consider a variety of possible trajectories. This approach results in a range of outputs. No single output may be the "right" one, but together they paint a picture of a likely range of possible futures. The primary challenge to the scenario approach lies in developing a reasonable range of scenarios that can be used in multiple modeling efforts.

The emissions scenarios in the SRES cover a wide range of possible paths for the primary social, economic, and technological drivers of future emissions. These scenarios have since become the standard input of socio-economic information for GCMs and other land-use change modeling efforts (e.g., Solecki & Olivieri, 2004; Reginster & Rounsevelle, 2006; Rounsevelle et al. 2006) providing a reasonable set of scenarios to bound the potential futures with respect to climate change. By using the SRES storylines as the basis for the scenarios investigated by this project, the results may be put into the context of widely available and peer-reviewed climate-change model output (e.g., IPCC, 2001; IPCC, 2007).

2.1 OVERVIEW OF THE SRES STORYLINES

The development of SRES consisted of three main steps, beginning with qualitative "storylines" that describe broad economic, environmental, technological, and social development patterns that could unfold over the 21st century (Nakićenović et al. 2000). Next, particular quantitative paths for the fundamental driving forces of emissions, including population and gross domestic product (GDP), were selected for each storyline. Finally, six different modeling teams produced quantitative interpretations of the storylines, using the quantitative paths for driving forces as inputs, resulting in 40 different scenarios for energy use, land use, and associated GHG emissions over the next 100 years (Nakićenović et al. 2000). The SRES describe storylines along two major axes, economic vs. environmentally-driven development (A-B) and global vs. regional development (1-2), which make up the four combinations of storylines, A1, A2, B1, and B2 (Figure 2-1). There are between 6 and 18 emissions scenarios within each of the four SRES storylines. Table 2-1 provides a summary of the qualitative fertility, mortality, and migration assumptions made by the SRES authors for each storyline for the industrialized country regions and the developing country regions; these qualitative assumptions served as the framework for the more quantitative inputs for the scenarios.

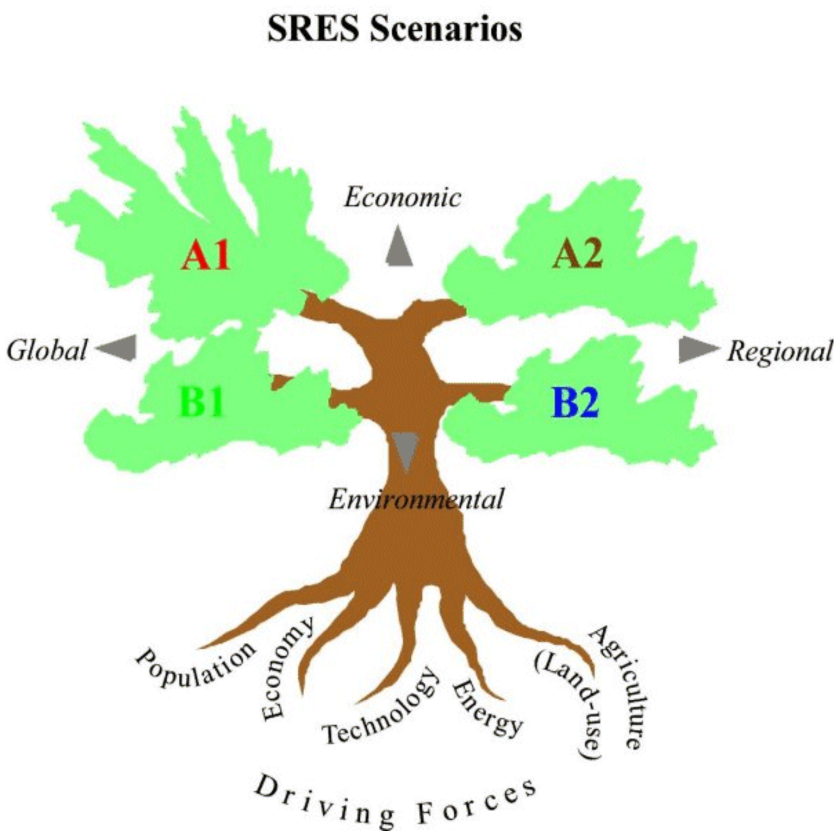


Figure 2-1: Illustration of the SRES scenario families along two dimensions that indicate the relative orientation of the storylines along the axes of global or regional development and economic or environmental concerns (reprinted from Nakićenović et al. 2000).

Table 2-1: Qualitative Demographic Assumptions in global SRES Storylines

Storyline	Fertility	Mortality	Migration	Projection Source
A1/B1	IND: medium DEV: low	IND: low DEV: low	IND: medium DEV: medium	IIASA, 1996
A2	IND: high DEV: high	IND: high DEV: high	IND: medium DEV: medium	IIASA, 1996
B2	IND: medium DEV: medium	IND: medium DEV: medium	IND: medium DEV: medium	UN, 1998

IND = "Industrialized country regions"; "DEV" = Developing country regions". The "high", "medium", and "low" descriptions are interpreted as relative to the overall outlook within each region (i.e., high fertility in the IND region means the high end of the plausible range for that region, but may in fact be lower than low fertility paths for the DEV region, which occupy the low end of the plausible range for the DEV region).

Based on descriptions in the SRES report (primarily in sections 4.3 and 4.4 of the SRES report), a summary of the reasoning for these assumptions is provided below:

- In the A1 storyline, rapid economic development, associated with improved education and reduced income disparities, is assumed to drive a relatively rapid fertility decline in the high fertility regions. Global population is expected to rise until peaking in the middle of the century, after which fertility is generally below replacement level. Fertility in industrialized regions is assumed to follow a medium path at least in part so that, relative to the developing regions, the scenario is consistent with the assumption that social and economic convergence will lead to demographic convergence as well. For mortality, it is assumed that the conditions leading to low fertility are also consistent with relatively low mortality, so mortality is assumed to be low in all regions. No explicit discussion of migration is provided, although the projection eventually adopted assumes medium migration levels.

- In the A2 storyline, the regional orientation and slower rate of economic growth, limited flow of people and ideas across regions, and orientation toward family and community values was judged to be consistent with a relatively high fertility in all world regions. Mortality was assumed to be high as well, based on the assumption that conditions leading to high fertility would also lead to relatively high mortality in all regions. Although the storyline describes a limited flow of people across regions, the storyline authors assumed medium migration flows, as in all other storylines.
- The B1 storyline shares the same population projection as the A1 storyline, although for somewhat different reasons. Rapid social development, particularly for women, and an emphasis on education drives a relatively rapid decline in fertility in developing country regions (as opposed to the A1 storyline, in which economic development is seen as the main driver). Reasoning for fertility in industrialized countries, and for mortality and migration assumptions, are the same as in A1.
- In the B2 storyline, economic development is moderate, particularly in the developing country regions. However education and welfare programs are pursued widely and local inequity is reduced through strong community support networks. The mix of moderate economic development and strong but heterogeneous social development results in an assumption of medium fertility and mortality paths. Migration is again assumed to be medium, with no explicit discussion of this choice.

Demographic assumptions in SRES are intended to be consistent with storylines and with other driving force assumptions. Consistent relationships among these factors mean that the demographic assumptions occur in the context of other socio-economic trends in a way that is not at odds with established theory, the weight of historical experience, or current thinking in the literature on determinants of demographic trends. For example, a key factor differentiating population assumptions across SRES scenarios is the assumed speed of the transition from high to low fertility in regions with relatively high current fertility. The transition occurs faster in the A1 and B1 scenarios, and slowest in the A2 scenario. These choices are based on the rationale that there are a range of conditions that contribute to fertility transitions, including economic development, education, labor force opportunities for women, and the spread of ideas about modern lifestyles (Lee, 2003). These factors are present, and stronger, in the A1 and B1 storylines (in different combinations) and absent, or weaker, in the A2 storyline. Thus, in this case, there is a clear notion of consistency in which storyline elements can be said to favor preferentially a particular demographic outcome.

However, consistency does not mean that the assumed demographic trends are the only possible outcomes, or in some cases even the most likely outcomes, conditional on a particular storyline. In some cases, storylines serve only as weak constraints on demographic futures, and a wide range of demographic assumptions might all be consistent with the broader development trends. For example, the demographic transition reasoning just described applies only to countries with relatively high fertility (e.g., substantially above replacement level of about 2 births per woman). These conditions occur for only about half the current population of the world, and for only the first half (or even less) of the 21st century, according to projections (Lee, 2003). Once the transition to low fertility is complete, there is little theoretical basis for linking subsequent fertility changes or cross-country differences to particular socio-economic trends; a wide range of outcomes is possible (O'Neill, 2005). Yet SRES scenarios link the pace of economic growth with fertility outcomes (i.e., demographic transition-type reasoning) for all regions of the world, and for the entire century. It is certainly possible that rapid economic growth will be associated with relatively low fertility (and slow growth with high fertility) in post-transition societies, and it is not inconsistent in the sense of contradicting established theory (though this is at least partly because there is no single established theory to contradict). Completely opposite associations (e.g., low fertility with slow economic growth) are equally plausible (and equally consistent) for post-transition societies.

Thus in considering the implications of SRES storylines for demographic outcomes at the national and sub-national level, it must be kept in mind that it is possible that a wide range of different assumptions could be judged to be consistent with SRES. Indeed other studies have developed alternative demographic assumptions for SRES storylines, with different quantitative outcomes (Hilderink, 2004), or have quantified a range of plausible outcomes associated with scenario storylines (O'Neill 2004, 2005, 2005b).

2.2 INTERPRETING AND DOWNSCALING THE SRES STORYLINES

The SRES storylines do not provide a clear blueprint for downscaling to the local or even the national level. In incorporating the SRES storylines into county-level projections for the United States, an effort was made to be consistent in qualitative terms with the global SRES storylines. Given the wide range of potential interpretations, this consistency was understood to imply that the qualitative trends do not contradict established theory, historical precedent, or current thinking. It was also a goal to model a wide a range of assumptions, while remaining consistent with the SRES and U.S. demographic patterns. Rationales connected to SRES storylines are discussed briefly for each scenario. For each of the storylines adapted to the United States, the fertility assumptions are exactly consistent with the global assumptions, while domestic and international migration patterns leave more room for interpretation and are more specifically adapted to the United States. The low U.S. Census scenario for mortality was chosen for all storylines used in the modeling (see 6Appendix B for more information).

2.2.1 A1 Storyline Adapted for the United States

A1 represents a world of fast economic development, low population growth, and high global integration. In this storyline fertility is assumed to decline and remain low in a manner similar to recent and current experience in many European countries (Sardon, 2004). A plausible rationale would be that the rapid economic growth in this scenario leads to continuing high participation of women in the workforce, but it becomes increasingly difficult to combine work with childbearing due to inflexibilities in labor markets. At the same time, social changes in family structures lead to increasing individuation, a rise in divorce rates, a further shift toward cohabitation rather than marriage, later marriages and delayed childbearing, all of which contribute to low fertility. Substantial aging resulting from the combination of low birth rates and continued low death rates raises the demand for immigration. Meanwhile, economic growth throughout the world and an increasingly unified global economy encourage the free movement of people across borders. Domestic migration is anticipated to be relatively high as well, as economic development encourages a flexible and mobile workforce.

2.2.2 B1 Storyline Adapted for the United States

This storyline represents a globally-integrated world similar to A1, but with greater emphasis on environmentally sustainable economic growth. Like A1, fertility is assumed to be low due to higher incomes and economic development. International migration is expected be high due to widespread economic development and freer global flows. Domestic migration however is lower due to a combination of factors. First, an increased focus on sustainability leads to a reduction of subsidies for development in previously rural counties with significant natural amenities. Second, the information oriented economy increases demand for specialized labor pools and increases the number of high paying jobs in traditional large urban centers.

2.2.3 A2 Storyline Adapted for the United States

The A2 storyline represents a world of continued economic development, yet with a more regional focus and slower economic convergence between regions. Fertility is assumed to be higher than in A1 and B1 due to slower economic growth, and with it, a slower decline in fertility rates. International migration is assumed to be low because a regionally-oriented world would result in more restricted movements across borders. Domestic migration is high because, like in A1, the continued focus on economic development is likely to encourage movement within the United States.

2.2.4 B2 Storyline Adapted for the United States

The B2 represents a regionally-oriented world of moderate population growth and local solutions to environmental and economic problems. Fertility rate is assumed to be medium, while international and domestic migration are low due to the local emphasis, focus on sustainability, and increasing number of jobs in urban centers. International migration is low due to the regional orientation, as with A2. Domestic migration is low due to the more environmental orientation, as with B1.

The SRES storylines adapted to the United States were integrated into our modeling framework. We modified both the demographic and spatial allocation models for each of the four scenarios.

3 DEMOGRAPHIC PROJECTIONS

3.1 OVERVIEW

The ICLUS demographic model utilizes a cohort-component methodology. The cohort-component methodology is a common technique for projecting population on the basis of five independent variables or components of population change: fertility, mortality, domestic in- and out-migration, and net international migration. The population is divided into cohorts that are age-, gender-, and race/ethnicity-specific. Changes due to these five components of change are estimated over time as each cohort is tracked separately, hence the term “cohort-component” (Siegel and Swanson, 2004).

The methodology is flexible in that different assumptions can be applied to each component of population change. For example, fertility—or the number of births—is estimated by multiplying cohort-specific fertility rates (births per woman) times the population of each cohort of women. Different rates can be applied to women of different ages and ethnicities. Furthermore, these rates can change over time or between different scenarios. In all cases, the fundamental method stays the same while changes in the rates can be used to simulate different SRES scenarios.

The population of a county in any year t as estimated by the model is determined using the following equation:

Equation 3-1: Cohort-component model

$P_t = P_{t-1} + B - D + NDM + NIM$

Where:

P_t = Population in year t

P_{t-1} = Population in the previous year

B = Births in year t

D = Deaths in year t

NDM = Net Domestic Migration in year t

NIM = Net International Migration in year t

Beginning with an initial set of populations, annual components of change are applied in the following process, which are repeated annually until the desired end year is reached.

1) Add births by cohort
2) Deduct deaths by cohort
3) Add net international migration
4) Add net domestic migration by combining domestic in-migration and out-migration (Estimated every fifth year, as discussed below.)
5) Age population one year and repeat for the next year

This methodology is illustrated in Figure 3-1 below. The cycle begins with an initial Year 2005 population and is repeated until reaching Year 2100.

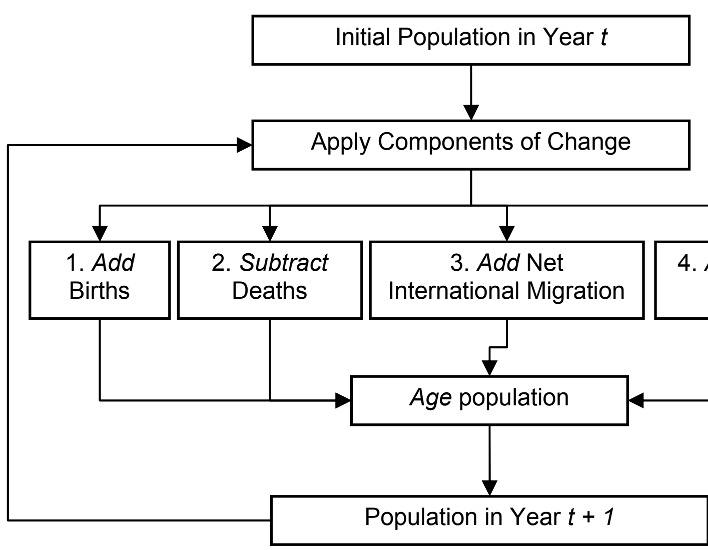


Figure 3-1: Demographic model flow

Table 3-1 provides a qualitative description of how we modified the global storylines to the U.S. As a general observation, note that the proposed fertility and mortality assumptions follow the SRES assumptions, with the exception that the A1 scenario assumes low fertility (rather than medium as in SRES). In addition, the international migration assumptions assume high and low immigration in scenarios B1 and A2, respectively (rather than medium as in SRES). These choices are made in order to explore a fuller range of demographic trends for the United States than in SRES, since the SRES storylines contained only a limited range of projections for the North America region (O'Neill, 2005). It should also be noted that these assumptions are not designed to cover the widest possible range of population size outcomes; e.g., the combinations resulting in the highest and lowest population sizes are not explored here. In all cases the mortality rate was kept constant across all scenarios. This was partly due to data availability—the Census Bureau did not release alternate scenarios for mortality rates. Experiments with adjusting these mortality rates (shown in Figure B-4 in 6Appendix B) demonstrated relatively little change in total national population due to variations in the mortality rate.

Table 3-1: Summary of Qualitative Adjustments to the Demographic Projections

Scenario	Demographic Model		
	Fertility	*Domestic migration*	*Net international migration*
A1	Low	High	High
B1	Low	Low	High
A2	High	High	Medium
B2	Medium	Low	Medium
Baseline	Medium	Medium	Medium

In the following sections, the methods and data used for the initial population and each component are discussed in greater detail.

3.2 INITIAL POPULATION

In order to use the rates for components of change provided by the U.S. Census Bureau (U.S. Census Bureau, 2000) (discussed below), it was necessary to begin with an initial Year 2005 population dataset that was disaggregated using the same cohorts. These cohorts in the rates data are divided into two genders (male and female), 100 age groups (0-99 in one year increments), and five racial/ethnic—or "bridged race"—groups (Hispanic, non-Hispanic White, non-Hispanic Black, non-Hispanic American Indian or Alaskan Native, and non-Hispanic Asian or Pacific Islander).[1] This represents 1000 distinct population cohorts (2 genders x 100 ages x 5 bridged race groups).

County populations using bridged race and one-year age cohorts were most readily accessible using the Bridged-Race Vintage 2006 dataset for July 1, 2005 provided by the National Center for Health Statistics (NCHS, 2007). After downloading and parsing the data, two manipulations

[1] In general, the U.S. Census Bureau considers the primary racial categories to be American Indian/Alaskan Native, Asian/Pacific Islander, Black, and White. "Hispanic origin" is considered an ethnic category. The race and ethnicity categories used by the Census have changed over time. In the 2000 Census, participants were allowed to identify with two or more racial groups for the first time. This project utilized the "bridged race" categories listed above as a way of making data collected with one set of categories consistent with data collected using another set of categories.

were required. First, the dataset provided eight bridged race categories—the non-Hispanic populations of the four race groups and the Hispanic populations of the four race groups. The Hispanic populations were summed and combined into a single bridged race group. This group, along with the four non-Hispanic race groups, comprised the five bridged race groups used throughout the model.

Second, the census dataset provided one-year age groups from ages 0-84 and combined all others in the 85+ age group. In order to extend the age distribution through 99 years, the 85+ population data was disaggregated into ages 85-99. We used the national age 85-99 populations by race and gender from the 2000 Census to allocate the 85+ age group from the NCHS data. We assumed an identical race- and gender-specific age distribution in each county for the Year 2005 base population. Although this step likely led to some distortions, the effects are not long-lasting in the model as the initial 85-99 age groups "age out" of the model by 2015.

3.3 FERTILITY AND MORTALITY

Fertility and mortality followed a simple methodology. For fertility, the number of children born equals the number of women in a given cohort times the average number of children born annually to every 1000 women in that cohort divided by 1000. Because virtually all births occur to women between the ages of 10 and 49, only those cohorts are considered in this model. These births are summed by race and used to create a new age zero cohort. To allocate births between males and females, we calculated a historic ratio of 1046 males born for every 1000 females born and assumed that this ratio holds steady (Matthews and Hamilton, 2005).

Similarly, mortality is estimated by multiplying the number of people in a given cohort times the cohort-specific mortality rates. The resulting number of deaths is then subtracted from the cohort. Unlike fertility, all cohorts are subject to mortality. Therefore, mortality rates are applied to each cohort. Although an increasing number of Americans is living to the age of 100 or more, the model assumes 100% mortality after age 99 for the sake of computational efficiency. Even with continued rates of survivorship past this age, the 100+ age group will remain a miniscule portion of the population.

For fertility and mortality rates, the U.S. Census Bureau's "Component Assumptions of the Resident Population by Age, Sex, Race, and Hispanic Origin" were used (U.S. Census Bureau, 2000). These are the same data used in Census projections. These components of change are associated with the 1990 National Projections and are used in both the 1990 State Projections (Campbell, 1996) and the 2000 National Projections (Hollman et al., 2000). While it would be preferable to use more recent data, at this time components of change based on the 2000 Census have not yet been released. While the rates are national averages, county differences that arise in fertility and mortality are a reflection of each county's unique age, sex, and racial composition.

For both fertility and mortality, the so-called Middle Series of component information was used as the baseline. Fertility rates are provided in a single file; mortality rates for each component are provided in three different tables, for the years 1999-2010, 2015-2055, and 2060-2100. Projected fertility rates are provided for each year to 2100, but beginning with 2010, mortality rates are provided in five year increments only. We assumed that 2010 mortality rates held steady from 2010-2014, 2015 mortality rates held steady from 2015-2019, and so on.

The Census Bureau also provides a low and high scenario for fertility. Alternative scenarios for mortality were not available. While the middle series was used in this "base case," the low and high series were used when developing projections specific to the SRES storylines. The low data set was used for the A1 and B1 scenarios, the medium set was used for the B2 scenario, and the high set was used for the A2 scenarios.

3.4 NET INTERNATIONAL MIGRATION

The projections for net international migration utilized a simple method based on the U.S. Census Bureau's international migration projections for the entire country. These files contain the projected net international migration for each gender, age, and race cohort for the years 2000-2100. Like the fertility and morality rates, these data are provided by the Census (U.S. Census Bureau, 2000).

Since the tables "Foreign-born Net Migration to the United States" contain only national level data, it was necessary to allocate the national migrants to the counties. Using 2000 Census data (U.S. Census Bureau, 2007, Summary File 3, Table P22), we determined each county's share of the total population of recent immigrants (i.e. those who entered within the last five years). These county shares were then used to allocate each cohort of immigrants among the nation's counties. The estimated number of immigrants in each cohort was then added to the existing county population of each cohort. This method assumes a constant distribution of recent immigrants based on Year 2000 immigration patterns. While we anticipate that many of the current "gateway counties" will continue to draw a large share of new immigrants, it is likely that new settlement patterns will develop in the future.

The Census Bureau provides a low, medium, and high series for net international immigration. In the base case, the middle series was used. The medium and high series were used when developing SRES storyline-specific projections. The high series was used for the A1 and B1 storylines, while the medium series was used for the A2 and B2 storylines. The low set was not used because the values projected under the U.S. Census Bureau's low set were so far below current levels of immigration (Figure 3-2, Census Bureau, 2008) that they were considered to be unrealistic for these purposes.

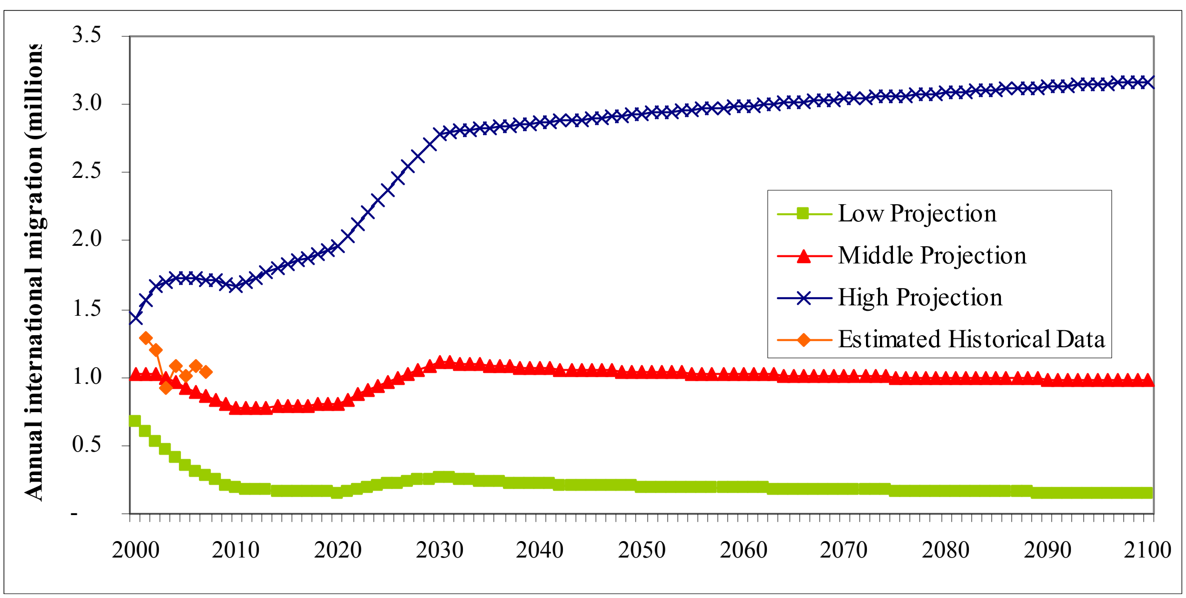


Figure 3-2: Projected Net International Migrations under U.S. Census Bureau Scenarios

3.5 DOMESTIC MIGRATION AND GRAVITY MODELING

Domestic migration is the most complex component of change included in this population model. In contrast to straightforward processes like fertility and mortality, which may be predicted in aggregate with reasonable confidence, domestic migration is much more difficult to predict. People move within the United States with relative frequency—according to the 2000 Census, approximately 44 percent of Americans lived at a different address in 2000 as they did in 1995 (Perry and Schachter, 2003) These migrations occur for a wide variety of personal and economic reasons that are difficult to predict. Unlike international immigration, which can be thought of as a single external source of immigrants, domestic migration works two ways—migrants must choose to leave one place and resettle in another place.

To estimate domestic migration, this project utilized a "gravity model" approach. Gravity models are a common type of spatial interaction model in which a dependent variable (in this case, migration flow between a pair of counties) is estimated as a function of a series of independent variables (Rodrigue et al. 2006). Common independent variables include population and distance (Haynes and Fotheringham, 1984); natural amenities, such as climate variables and bodies of water, have also been shown to affect migration patterns, particularly in rural areas (McGranahan, 1999). Among these, temperate summers and warm winters have the strongest correlation with population growth (R^2=0.38 and R^2=0.27, respectively), a finding that holds true even when correcting for macro-trends such as the general movement from the Northeast and Midwest to the South and West (McGranahan, 1999). Other work has also shown that amenity-rich mountain and coastal areas are highly successful at attracting migrants, particularly those who are affluent and/or retired (Manson and Groop, 2000). While a wide variety of independent variables were tested, the final gravity model used in this effort included the following independent variables: population of the origin and destination counties, selected climate variables of the origin and destination counties, water surface area of the origin and destination counties, ratio of 2000 county population to 1980 population of the destination county, and the distance between counties.

The final model form and model coefficients were estimated by analyzing 1995 to 2000 migration data reported in Public Use Microdata Samples (PUMS) (Census Bureau, 2003). Using county-to-county migration data as the dependent variable and the various county attributes as dependent variables, we ran a series of stepwise regression analyses to select the most statistically significant set of dependent variables and estimate the model coefficients. Below, we discuss how each data source for the regression analyses was developed, the resulting model form, and the way this model was implemented in the overall demographic model.

3.5.1 1995-2000 Migration Data

The 2000 Census Public-Use Microdata Samples (PUMS) data provides detailed records of individual domestic migrations and characteristics of these migrants between 1995 and 2000 (Census Bureau, 2003). However, the raw data does not readily provide county-to-county migration counts. Because the migrations are organized by the destination state, in-migrants to any given state can be analyzed using that state's PUMS file, but analysis of out-migration requires analyzing data from all 50 states, the District of Columbia, and Puerto Rico. This project used a national migrant file created by the New York State Data Center from the individual state and area files.[2]

[2] The website for the New York State Data Center is http://www.empire.state.ny.us/nysdc/default.asp.

The second challenge with the PUMS data is that it is organized by Public-Use Microdata Areas (PUMAs). Counties and PUMAs overlap in a non-systematic way. Large urban counties consist of multiple PUMAs, while small rural counties are often combined into a single PUMA. To further complicate the issue, the spatial area that PUMS uses to capture migration origins (where respondents lived in 1995), the so-called Migration PUMA (MIGPUMA), is not the same spatial area as the one used to capture where they lived in 2000 (the PUMA). The MIGPUMA is a larger area, and there can be one or more PUMAs contained within the MIGPUMA.

Because we required a database that contains migration, attraction factors, production factors, and distance information for pairs of areas, introducing the MIGPUMA into our spatial framework would have required re-calculating all of the other variables at the MIGPUMA level, and aggregating the migration data (destinations) to the MIGPUMA level, losing considerable local detail. Instead, we elected to proportionately assign MIGPUMA origins to its constituent PUMAs, on an average basis.

Furthermore, retaining a county-based framework is practical because the amenity data is available only for counties and counties are a more popularly understood and conceptualized units than PUMAs. For the sake of consistency and simplicity, we then proportionately assigned PUMA origins and destinations into counties based on the proportion of each PUMA's population belonging to one or more counties. In the case of large metropolitan counties, several PUMAs were typically aggregated to a single county, while in suburban and rural areas, PUMAs were often split among two or more counties. As a result of the transition from MIGPUMA to PUMA to county, the current migration data set provides county-to-county flows.

These county-to-county flow data were then aggregated into various age groups. Since migration behavior is hypothesized to vary for different age groups, different gravity models were calibrated for different age cohorts. In initial runs, the population was divided into ten-year cohorts, from 0-9 to 90 and up, and a different gravity model was estimated for each. We observed some broad differences in behavior between the older (over 50) age groups and the younger age groups, presumably due to differences in migration patterns due to retirement. However, the differences between the ten individual models were not found to be significant enough to warrant ten different age groups. As a result, the dataset was recoded into just two age groups: 0-49 and 50+.

3.5.2 County Attribute Data

After recoding the migration data set from the original geographies to counties, we then added the county data that would be included as independent variables in the analysis. These variables include county environmental amenities, population, and 1980-2000 population growth, which serves as a proxy for economic growth.

The source for the amenity information used in the regression was found in a database compiled by the USDA (McGranahan, 1999), which utilizes data originally collected from the Center for National Health Statistics, U.S. Department of Health and Human Services. The amenity index includes a range of climatic and amenity factors that are thought to influence migration. The data used from this set include:

- Mean temperature for January, 1941-70;
- Mean hours of sunlight for January, 1941-70;
- Mean temperature for July, 1941-70;

- Mean relative humidity for July, 1941-70; and
- Percent water area.

County population data were drawn from the U.S. Census Bureau's *City and County Data Book*, 2000 edition. The population over age 50—used in analyses of the 50-99 age group—was determined from data downloaded from the 2000 U.S. Census (Summary File 1, Table P12). The 2000 county population data, combined with 1980 and 1990 county populations provided by the Census Bureau (U.S. Census Bureau, 1992), were used to calculate the growth rate of counties between 1980 and 2000. This term was added after initial model runs resulted in declining populations in medium-sized counties that exhibited strong growth in the 1980s and 1990s.

3.5.3 Distance Matrix

A full county-to-county distance matrix was the final data input used in developing the gravity model. Typical methods of migration movement between geographic locations (e.g., city to city or county to county) assume that interaction can be estimated as straight-line county centroid-to-centroid distance (Conley and Topa, 2002). Two main deficiencies are that: (1) often the geographic centroid of a county poorly represents the population-weighted centroid of a county; and (2) humans do not move around on the ground optimally using a straight-line strategy, rather we are constrained to transportation infrastructure which in turn has evolved in response to major topographic and water features.

Because of these deficiencies, we developed a "functional" estimate of county-to-county interaction. The main assumptions incorporated into the county-to-county functional distance calculations are that the amount of interaction, and more specifically migration, between counties are better approximated by examining: (a) where in a county population is located, and (b) how much ground- (and water-) based transportation infrastructure is in place.

The geographic centroids of each of 25,150 U.S. Census Bureau-defined places (within coterminous United States) were found and assigned to the county in which they were located. The population (2000 Census) was then used to weight each point, and the population-weighted centroid for each county was determined. For roughly a half-dozen counties, the population-weighted centroid was calculated to be outside the boundaries of its respective county. For these, the centroid was manually moved back into its respective county. We also generated a centroid for a couple of counties in Nevada that did not have places in them (visually in the center).

We generated a cost-weight surface using major roads such that the weights were assigned the assumed average speed limit assigned by road type. Cost distance was then computed using the population-weighted centroids as the "seeds", computing minutes travel time T along the roads. For each adjacent (first-order neighbor) county-county pair i,j we adjusted the travel time to account for k multiple roads (multiple connections between population centroids) to compute an interaction weight W. The equation used to calculate the interaction weight W is presented in Equation 3-2 below.

Equation 3-2: Cost-Weight Surface for County Pairs

$$W_{ij} = 1/\left(\sum_{k}(1/T_k)\right)$$

Where:

W_{ij} = Interaction weight for the county-county pair *i, j*

T_k = Travel time for *k* multiple roads

We then generated a network and used a network-based least-cost path algorithm to compute effective distances along paths of pair-wise segments using the FunConn tools (Theobald et al., 2006). We developed a distance matrix of pairwise functional distances (W_{ij}) computed in minutes travel time. We exported this matrix from the GIS database in a list of from-county, to-county, weight format (over 9 million records for 3109 counties times 3108 destination counties) to the gravity model data table. We also manually added linkages between counties that are served with regular ferry service as delineated in the U.S. Transportation Atlas 2006 (e.g., across Lake Michigan and Nantucket Island).

3.5.4 Model Specification

After collecting the above data, it was reorganized into a single data table. Each record in the data table contained the number of migrations from one county to another, the attributes of the origin county, the attributes of the destination county, and the functional distance between them. In keeping with the traditional functional form of gravity models, which states migration is proportionate to attraction and production variables, and inversely proportional to distance, the functional form of the model used was as follows:[3]

Equation 3-3: Gravity Model

$$F_{ij} = \alpha \times P_i^{(\beta 1 + \beta 2 \times Pi)} \times Jt_i^{\beta 3} \times Js_i^{\beta 4} \times St_i^{\beta 5} \times Sh_i^{\beta 6} \times W_i^{\beta 7} \times P_j^{(\beta 8 + \beta 9 \times Pj)} \times Jt_j^{\beta 10} \times Js_j^{\beta 11} \times St_j^{\beta 12} \times Sh_j^{\beta 13} \times W_j^{\beta 14} \times G_j^{\beta 15} \times d_{ij}^{\beta 16}$$

Where:

F_{ij} = the migration of the population from county *i* to county *j* from 1995 to 2000

P = the population of a county in 2000. For the 0-49 age group, total population was used. For over-50 age group only the over-50 population was used.

Jt = the mean January temperature for a county

Js = the mean January hours of sunlight for a county

St = the mean July temperature for a county (S = Summer)

Sh = the mean July humidity for a county (S = Summer)

W = the percent water area for a county

G = county growth rate, expressed as the ratio of 2000 population to 1980 population

d_{ij} = the functional distance between *i* and *j*

α, $\beta 1$, ... $\beta 16$ = parameters estimated by the regression model.

In order to estimate this equation using multiple regression, a logarithm of both sides is taken, which yields the following linear equation.

[3] The parameters estimated by the regression model (provided below) are positive for those variables that are directly proportional to migration (e.g., population) and negative for those variables that are inversely proportional to migration (e.g., distance).

Equation 3-4: Logarithmic Transformation of the Gravity Model Equation

$$\begin{aligned}\mathrm{Log}(F_{ij}) = {} & \log(\alpha) + \beta1\times\log(P_i) + \beta2\times P_i\times\log(P_i) + \beta3\times\log(Jt_i) + \beta4\times\log(Js_i) + \beta5\times\log(St_i) + \\ & \beta6\times\log(Sh_i) + \beta7\times\log(W_i) + \beta8\times\log(P_j) + \beta9\times P_j\times\log(P_j) + \beta10\times\log(Jt_j) + \beta11\times\log(Js_j) + \\ & \beta12\times\log(St_j) + \beta13\times\log(Sh_j) + \beta14\times\log(W_j) + \beta15\times\log(G_j) + \beta16\times\log(d_{ij})\end{aligned}$$

We also ran a variety of regionally-specific experimental runs to consider if different effects were observed on a regional basis. The four Census-defined regions are the Northeast, South, Midwest, and West. Although some differences were observed between the different regions, the marginal improvement in model fit offered by regionally-specific models was outweighed by the complexity of developing a separate model for each pair-wise combination of regions.

In the equations above, population is treated differently from other variables. Initial model runs used the form:

$$\log(\text{migration}) = a + b \times \log(\text{population}) + \text{other terms}$$

so that migration is proportional to $(\text{population})^b$. Under this model, log(migration) always increases with log(population) at the same rate (assuming $b > 0$), all else being equal. When running the model over many decades, this caused the model to predict that most of the population of many small counties would migrate to nearby large counties. However, such a scenario is unrealistic as large counties grow increasingly crowded and the differential between land prices in the urban core and on the sub- and ex-urban edges grows. We then modified the model so that the slope b is not constant but varies slowly with the size of the population. The new model used $b = c + d \times \text{population}$, providing the following form:

$$\log(\text{migration}) = a + c \times \log(\text{population}) + d \times \text{population} \times \log(\text{population}) + \text{other terms}$$

With this revised equation, migration is proportional to $(\text{population})^{(c + d \times \text{population})}$. As expected, the fitted c coefficient was positive while the d coefficient was small and negative, so that for small populations, the new model looks like the old model, but for large populations, log(migration) increases with log(population) at a slower rate. This model resulted in projections more consistent with expectations: with more modest growth the largest populations did not grow in extreme proportions, while the suburban and exurban counties (particularly those in between two relatively close cities) grew the fastest.

3.5.5 Stepwise Regression Results

Table 3-2 below provides a summary of the stepwise regression results, including the model R^2 and the individual parameters. The R^2 indicates the overall goodness-of-fit of the regression models, or what percentage of the variance of the logarithm of the flow is explained by the independent variables. The estimates for each parameter in the models are also provided. The regression modeling was performed using a stepwise approach, such that at each step a term was added if the significance level was < 0.05 and terms were removed if the significance level was >= 0.05. For these models, all the regression parameters except for one regression parameter in the 50+ model were statistically significant at each step ($p < 0.0001$), i.e., the improvement in goodness-of-fit was statistically significant. The relative explanatory power of each variable is provided in Table 3-3 below. These results show that population and distance represent the majority of the model's explanatory power. While certain amenity variables may be more important in rural counties, when considered with much larger urban and suburban counties, the additional contribution of these variables is smaller, though still significant.

We also ran a correlation on each of the independent variables to determine the prevalence of collinearity among these variables. In nearly all cases, all pairs of variables were found to be statistically collinear at the $p<0.0001$ level, although many of the estimated squared correlations (R^2) were small. With such an extremely large sample size (n=2,397,007, or the number of migration records in PUMS), it is relatively easy for even very low R^2 values to be statistically significant. In this case, having a very significant p-value simply suggests that the data are inconsistent with a true correlation of zero, but they could be consistent with some very small, but non-zero, correlation.

Table 3-2: Gravity Model Results

	Age Group*	
Variable	**0-49**	**50+^**
Adj. R^2	0.665	0.6591
Intercept ($\log(\alpha)$)	5.74014	3.14215
Production Population	0.7756	0.78429
$(\text{Production Population})^{\text{Production Population}}$	-9.12E-09	-5.63E-08
Production January Temp.	0.07301	N/A
Production January Sun	0.04666	-0.15858
Production July Temp.	-1.28061	-0.85029
Production July Humidity	-0.4482	-0.22306
Production Water Surface	0.01199	-0.00422
Attraction Population	0.85084	0.84382
$(\text{Attraction Population})^{\text{Attraction Population}}$	-1.58E-08	-8.83E-08
Attraction January Temp.	0.01362	0.09291
Attraction January Sun	0.06784	0.09263
Attraction July Temp.	-0.78317	-0.78248
Attraction July Humidity	-0.38647	-0.28732
Attraction Water Surface	0.0192	0.01334
Attraction 1980-2000 Growth Rate	0.30131	0.54938
Distance	-0.98919	-0.83684

All parameters were significant at the $p<0.0001$ level, with the exception of Production January Temp. in the 50+ model, which was not significant.
* The variable result values correspond to the β-values in Equations 3-3 and 3-4.
^ Population over age 50 was used in place of total population in the Age 50+ model.

Table 3-3: Ranking of the contribution of independent variables to explanatory power of the models

Rank	Ages 0-49	Partial R-Square for Each Variable	Cumulative Model R-Square	Ages 50+*	Partial R-Square for Each Variable	Cumulative Model R-Square
1	Attraction Population	0.3150	0.3150	Attraction Population	0.3315	0.3315
2	Production Population	0.2130	0.5280	Production Population	0.1976	0.5291
3	Distance	0.1231	0.6511	Distance	0.1143	0.6433
4	Production July Humidity	0.0052	0.6563	Attraction 1980-2000 Growth Rate	0.0062	0.6496
5	Attraction July Humidity	0.0030	0.6593	(Attraction Population)$^{\text{Attraction Population}}$	0.0023	0.6518
6	(Attraction Population)$^{\text{Attraction Population}}$	0.0023	0.6615	Attraction July Humidity	0.0025	0.6543
7	Production July Temp.	0.0010	0.6625	(Production Population)$^{\text{Production Population}}$	0.0020	0.6563
8	Attraction 1980-2000 Growth Rate	0.0010	0.6636	Production July Temp.	0.0016	0.6579
9	Production Population ^ Production Population	0.0007	0.6643	Production July Humidity	0.0007	0.6586
10	Attraction July Temp.	0.0004	0.6647	Production January Sun	0.0002	0.6588
11	Attraction Water Surface	0.0001	0.6648	Attraction July Temp.	0.0001	0.6589
12	Production January Temp.	0.0001	0.6649	Attraction January Temp.	0.0001	0.6590
13	Production Water Surface	0.0001	0.6650	Attraction Water Surface	0.0001	0.6591
14	Attraction January Sun	0.0000	0.6650	Attraction January Sun	0.0001	0.6591
15	Production January Sun	0.0000	0.6650	Production Water Surface	0.0000	0.6591
16	Attraction January Temp.	0.0000	0.6650			

* Population over age 50 was used in place of total population in the Age 50+ model.

3.5.6 Model Flow

Having estimated the gravity model parameters, the gravity model was incorporated into the overall demographic model to estimate domestic migration. Because the underlying migration data used in this analysis measured migration over a five-year period, the migration was estimated at five year intervals.

Using a pair of nested loops, the model cycles through each pair of counties, estimating the migration from each county to every other county. Using the same amenity and distance data discussed in Section 3.5.1 - 3.5.3 and the current estimated county populations as calculated by the model, it enters the terms into the gravity model equation provided above for each of sets of model parameters for each of the two age groups.

Because the gravity model does not consider race, gender, or age beyond the two broad age groups, every estimation of migration from county A to county B must be applied to the individual age, gender, and race groups. The model assumes that all groups within one migration model are equally likely to move, so it allocates the total migrants from one county to another based on the relative populations of each group in the origin county. In reality, it is likely that migration patterns vary by factors such as age, race, and immigrant status. However, the initial data set used here did not provide the level of specificity needed to add greater detail to the gravity model analysis.

Once migrants from one county to another are estimated by age, race, and gender, these migrations are then subtracted from the origin county and added to the destination county. This process is then repeated for every pair of counties. One major exception is that for counties that fall in the least populated quintile of counties (approximately 620 counties), with a maximum population in 2000 of 9,350, the gravity model is not applied, and no domestic migration is assumed for those counties. The counties were included in the regression modeling, and analyses indicated that the smallest counties are less likely to conform to the modeled behavior. This higher error rate, combined with the powerful attraction of large counties, caused many small counties to decline precipitously. Although excluding them from the model likely leads to some distortions in these counties, collectively they account for roughly 1% of the national population. Therefore it is unlikely that their exclusion has much effect on the remainder of U.S. counties.

3.5.7 Gravity Model and U.S.-Adapted SRES Scenarios

The gravity model provides many potential levers for adjusting migration patterns to account for various future scenarios. To model the high and low migration patterns needed for the SRES storylines adapted to the United States, total migrations were scaled in order to estimate greater flows of people. In the A1 and A2 storylines, where domestic migration is assumed to be higher than in the base case, all migrations were increased by 50 percent. In the B1 and B2 storylines, where domestic migration is assumed to be lower than in the base case, all migrations were reduced by 50 percent. Appendix B includes a discussion on testing other migration assumptions.

3.6 MODEL RESULTS

The demographic model was run for a base case (all parameters set to "medium") and for the four SRES-compatible scenarios. A variety of sensitivity tests with a wider array of model inputs were also carried out. These tests and the results are discussed in greater detail in Appendix A. Model runs calculated population on an annual basis for 2005-2100, with county totals reported for five-year intervals. These outputs were then used as inputs to the spatial allocation model (Section 4). While the detailed model output is too large to present here, a summary discussion of the demographic model results follows.

Figure 3-3 shows the total population for the conterminous U.S. for the years 2005-2100, as modeled in the base case and four SRES-compatible scenarios. A2, with high fertility and high net international migration represents the highest population scenario. The base case and scenario B2 are the middle scenarios, with medium fertility and medium international migration. The difference between these two scenarios lies in the domestic migration, where the base case assumes middle-of-the-road migration flows, while B2 assumes low domestic migration flows. As a result of this distinction, the county populations in urban and suburban areas generally grow faster than in rural areas in the base case, but the experiences of individual counties vary. A1 and B1, with low fertility and high international migration are the lowest of the population scenarios. The primary difference between these scenarios occurs at the domestic migration level, with an assumption of high domestic migration under A1 and low domestic migration under B1. The effect of different migration assumptions becomes evident in the spatial model when the population is allocated into housing units across the landscape. A more extensive discussion of the regional differences in population growth is included in Section 5.1.

In general, the need for additional development is directly proportional to population growth. As shown in Table 5-3 below, the growth in the extent of urban and suburban areas is greatest in the scenario with the highest project population growth (A2). The growth in urban and suburban areas in the other scenarios is analogous to their population growth: B2 and the Base Case are in the middle, while A1 and B1 are the lowest. With impervious surface, the results are somewhat different (Table 5-5), indicating that the allocation and housing parameters adjusted in SERGoM such as household size and commute travel time are a greater driver of changes in impervious surface than population alone. In this case the A1 and A2 scenarios have the highest growth in impervious surface, while the B1 and B2 scenarios have the lowest. This suggests that decisions about which lands are utilized are as important as actual population growth in driving land use impacts. The impacts of the population scenarios on land use and the methodologies used to model this are explored in the following chapters in greater detail.

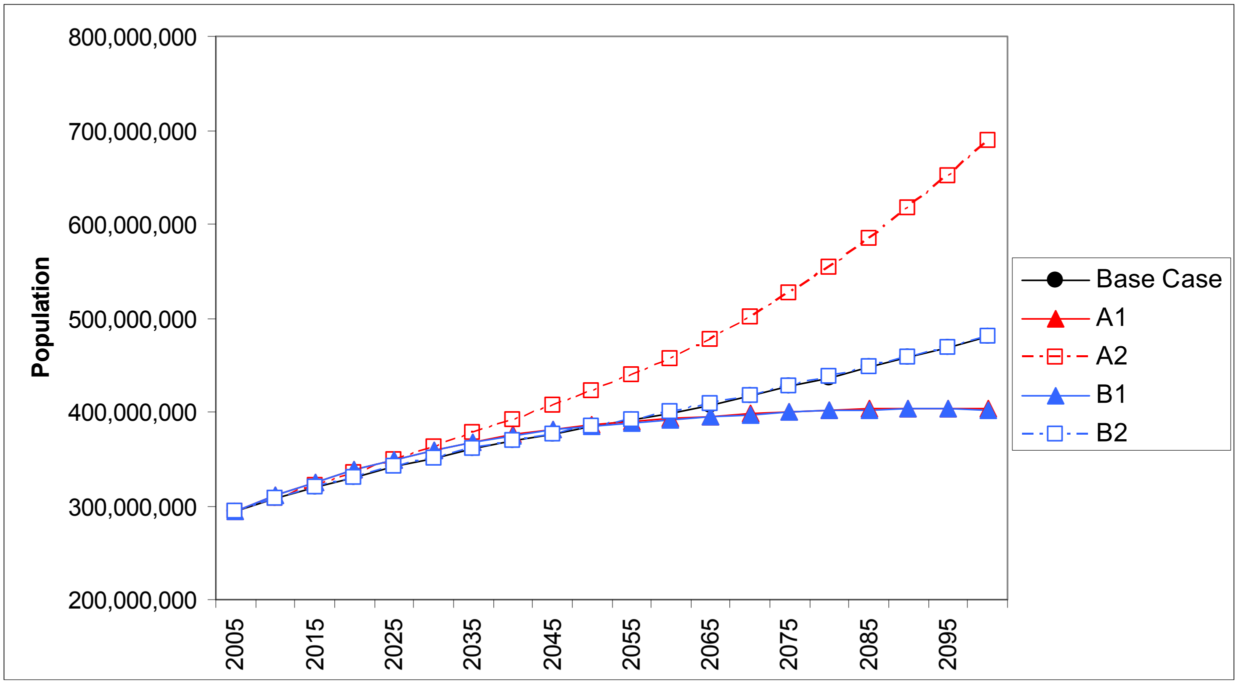


Figure 3-3: Total Population under Five ICLUS Scenarios. Scenario B2 and the Base Case have the same population trajectories, as do scenarios A1 and B1.

3.7 COMPARISON OF DEMOGRAPHIC MODEL WITH EXISTING PROJECTIONS

In order to substantiate the results of the demographic model, we compared the projected county populations for five states with population projections developed by the states themselves. The five states used were California, Colorado, Florida, Minnesota, and New Jersey. All state projections were for the year 2030, except for New Jersey, which was for the year 2025. These states were selected based on data availability and regional diversity.

Differences between the state-developed projections and the ICLUS projections were anticipated. The ICLUS projections were developed using a single national model, while the individual state methodologies, while not analyzed, were likely developed using state-specific methods and information not available on the national scale.

The results of these comparisons are shown in Figure 3-4 through Figure 3-8. For each of the five states, the graphs depict the difference between the ICLUS projections and the state projections expressed as a percentage of the state projection on the Y-axis and the log of the county population on the X-axis. Each data point represents one county. While the results are mixed, the position of each trend line below the X-axis indicates that ICLUS estimates were lower than state estimates, on average. This is likely due to a combination of several factors:

- Higher estimated fertility, domestic in-migration, or international in-migration in the state estimates than in the ICLUS estimates;
- Differences in the state methodology that likely do not fully estimate migration patterns in other states; and
- Local knowledge about specific areas targeted for new development that was not included in the ICLUS demographic model.

A second important observation is the slight positive slope in each trend line. This indicates that the ICLUS model is likely to underestimate the population of smaller counties more than larger counties. This result was anticipated because of the large power of population in the gravity model—in original runs, large counties grew enormous and small counties were reduced to nothing over several decades. As a result, the lowest quintile of counties were excluded from the gravity model and a limiting term was added that helped slow growth in the largest counties. The downside of this is that the ICLUS model is not able to predict population growth due to migration in small rural counties with high natural amenities. McGranahan (1999) discusses the role of natural amenities in driving rural population growth, and while the ICLUS model included natural amenities so as to model this trend, the stronger predictive power of population overwhelmed the impact of natural amenities.

In terms of overall population though, the trend line indicates that the larger the county, the more likely it was to be closer to the X-axis. This indicates that the percentage difference between state projections and ICLUS projections is smaller for large counties, where a majority of the population lives. With the exception of Florida, where the difference between the total state population projection and ICLUS was 11 percent, all of the other state projections discussed here differed from ICLUS by less than 7 percent. Given the heterogeneity of data and methods inherent in the state-specific projections as compared to the national approach applied at the county level for ICLUS, we were satisfied with the performance of the ICLUS demographic model.

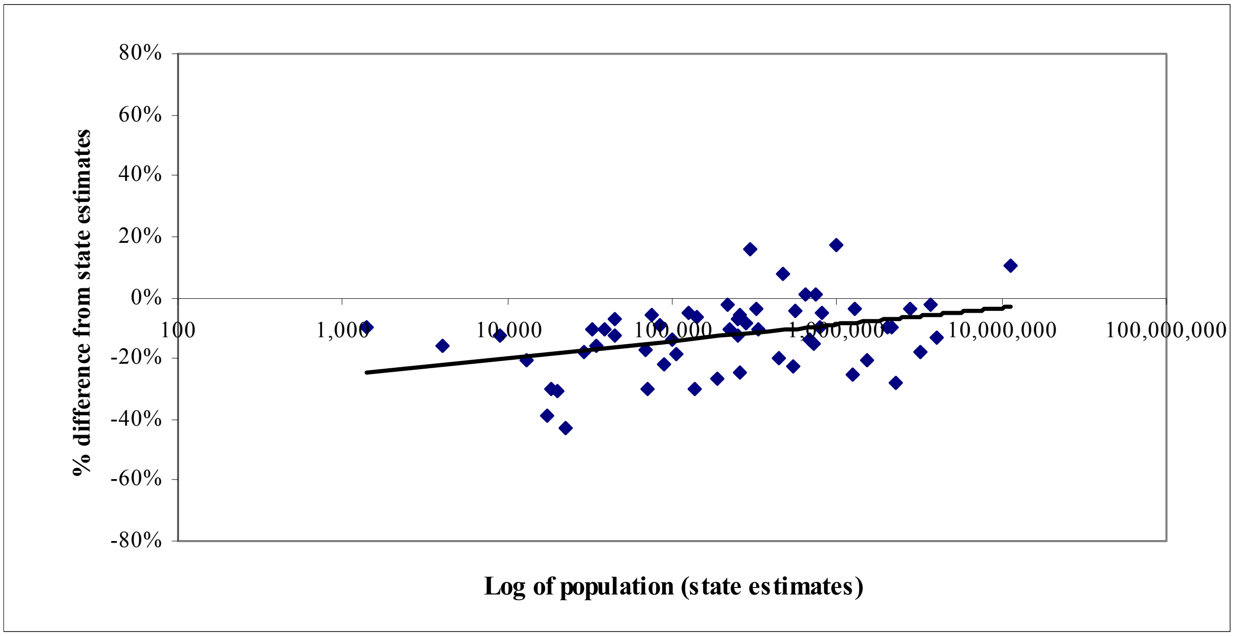


Figure 3-4: Comparison of California and ICLUS (base case) 2030 Projections

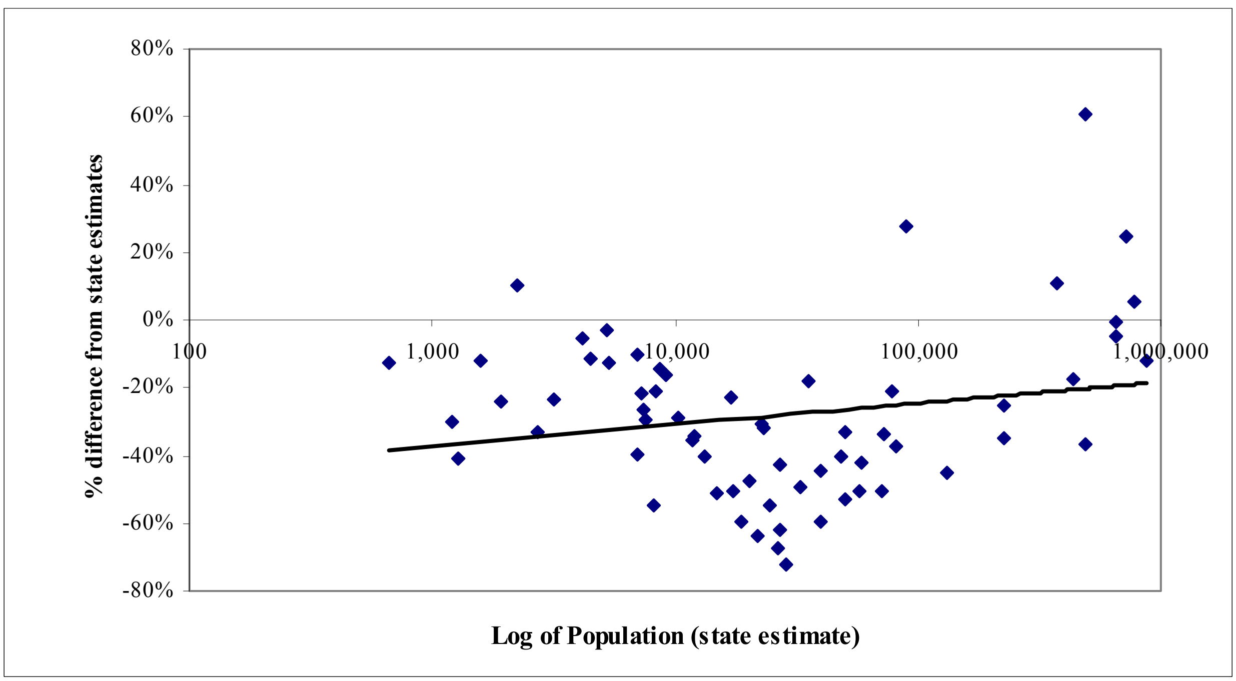


Figure 3-5: Comparison of Colorado and ICLUS (base case) 2030 Projections

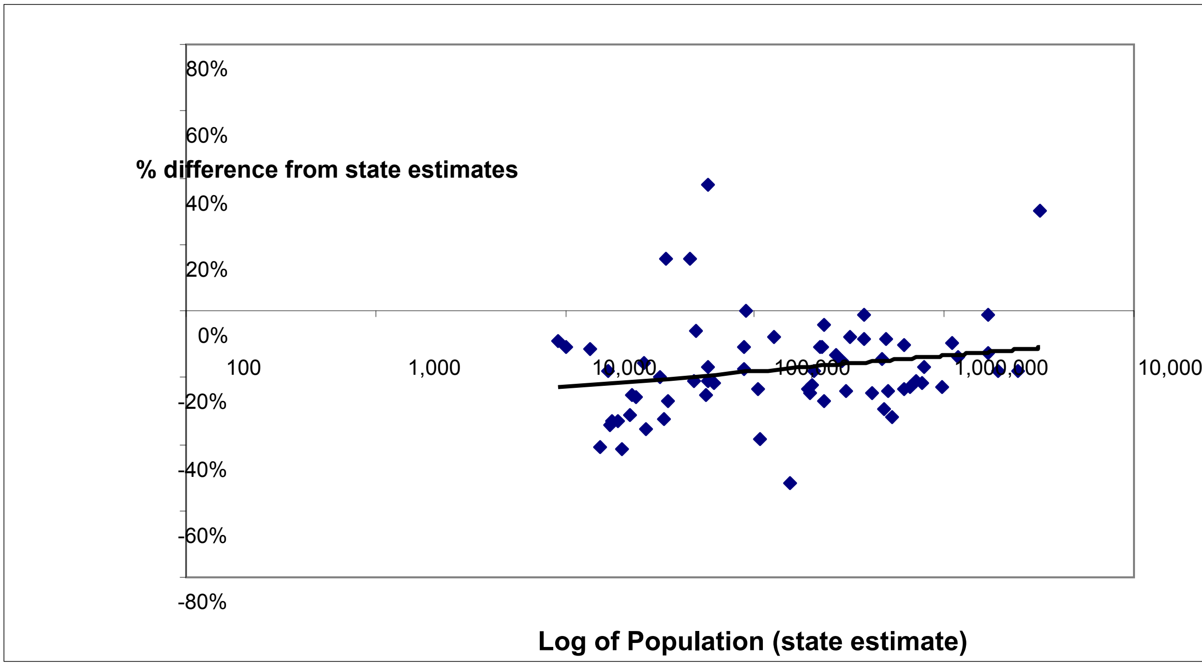


Figure 3-6: Comparison of Florida and ICLUS (base case) 2030 Projections

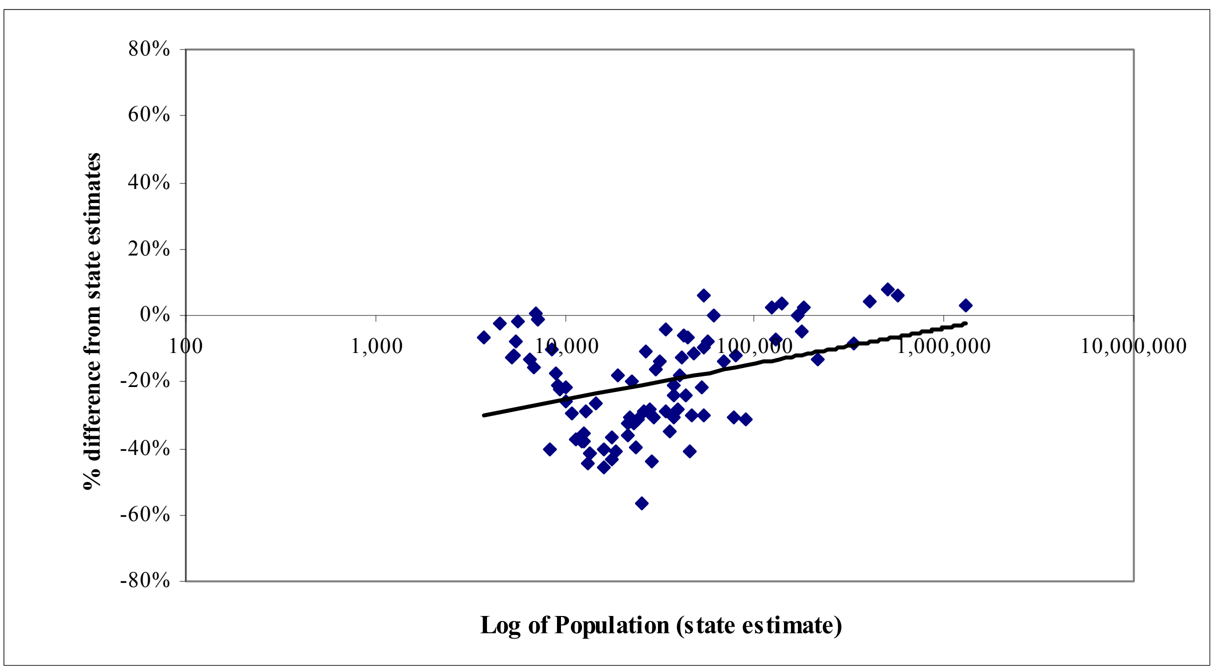


Figure 3-7: Comparison of Minnesota and ICLUS (base case) 2030 Projections

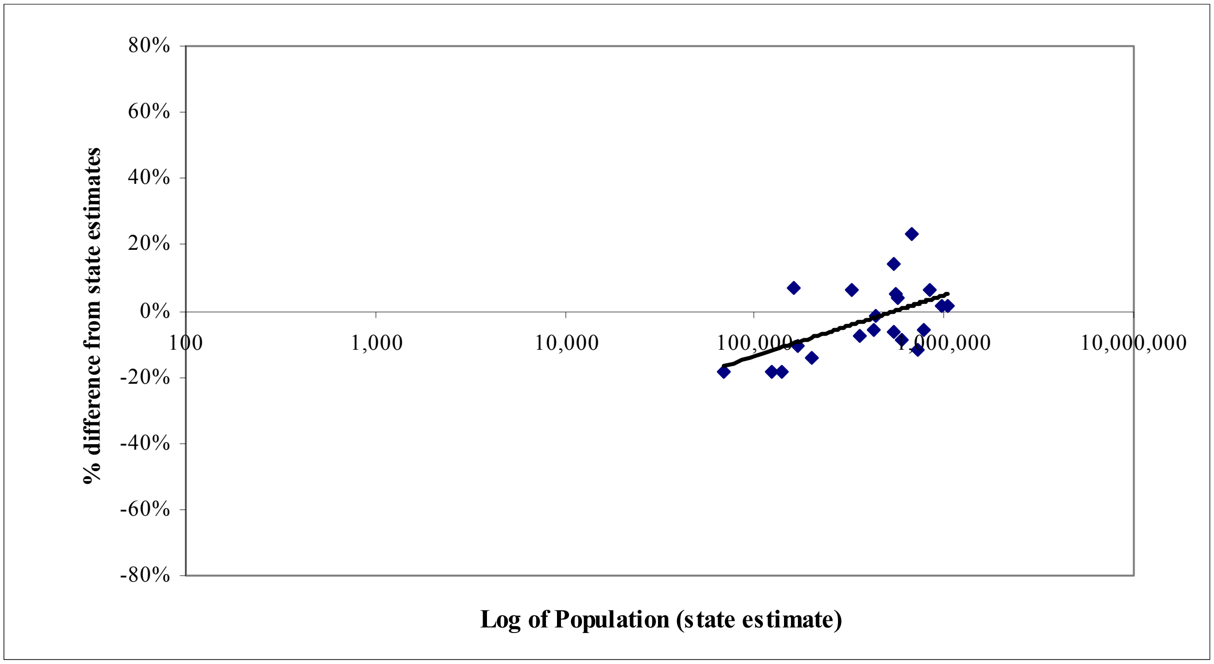


Figure 3-8: Comparison of New Jersey and ICLUS (base case) 2025 Projections

4 SPATIAL ALLOCATION MODEL

We selected a spatial allocation model to distribute the population into housing units across the country. SERGoM, or the Spatially Explicit Regional Growth Model (Theobald, 2005), was used to develop the land use projections for this effort. This section begins with a discussion of the reasons for selecting SERGoM, and continues with a discussion of SERGoM's methodology. We then conclude this section with a discussion of how the demographic model outputs were incorporated into SERGoM and how the model was adjusted for the SRES-compatible scenarios.

4.1 RATIONALE FOR THE SELECTION OF SERGOM

SERGoM, unlike the majority of land use change models, allocates a full continuum of housing density, from urban to rural. This allows a more comprehensive examination of growth patterns, since exurban/low-density development generally has a footprint 10 times as large as urban areas and is growing at a faster rate than urban areas (Theobald 2005). Hence, it is an important aspect of possible future growth scenarios. An advantage of modeling all types of housing density, especially low density rural development, is that links to GHG emissions by housing density can be made (Liu et al., 2003). In addition, SERGoM forecasts housing development by establishing a statistical relationship between neighboring housing density, population growth rates, and transportation infrastructure (Theobald, 2005). The model is dynamic in that as new urban core areas emerge, the model re-calculates travel time from these areas. For this modeling effort the expected changes in functional connectivity that would result from such emerging urbanization were not fed back into the functional connectivity calculations used to calculate domestic migration (Section 3.5.3 above). SERGoM also incorporates a detailed layer of developable/un-developable areas that incorporates public protected lands as well as private protected (e.g., through conservation easements) lands. Finally, SERGoM was designed to forecast housing density growth for large, broad (regional to national) extents. Population forecasts are a principal driver of SERGoM; in the model, population growth is converted to housing units, which are spatially allocated in response to the spatial pattern of previous growth and transportation infrastructure. An important technical advantage of this model is that it produces seamless, nationwide maps at 1 ha resolution. The benefit of this approach is that there are fewer (internal to coterminous United States) discrete differences across artificial analytical boundaries imposed by "piecing" individual model runs into a nationwide map, although the allocation of new housing units is restricted to counties. Growth rates and many model parameters are specified spatially-explicitly, so different regions (even census tracts or neighborhoods) have different parameters. Although not exercised in this project, some additional model parameters could be made spatially-explicit so they too could vary regionally – these might include different housing density thresholds for "urban" or "exurban" and relative changes in household size.

4.2 METHODOLOGY

The spatial database generated by SERGoM provides historical, current, and future estimates of housing density for the coterminous United States. That is, it represents residential land uses, which are the major types of development and intensification of land use related to urbanization in the U.S. (note that we also recognize and map commercial/industrial land use – however, these are static layers and we do not explicitly represent other "development" in the form of cropland or forestry developments). Housing density (number of housing units per acres) was computed for each 1 ha cell (100 m x 100 m raster; 2.47 acres). There are five main input spatial datasets used to estimate housing density:

1. **2000 Census Bureau** – Data were compiled from the 2000 census on the number of housing units and population for each block and the geography or polygon boundary for each census block using the 2000 Census geography (from the SF1 dataset). Block-groups, which are a coarser-level aggregation of block polygons, and attributes of the number of housing units built by decade were used to estimate the historical number of housing units in each block. An operating assumption in estimating historical housing units is that they have not declined over time, so that the number of housing units in any past decade (back to 1940) did not exceed the number of units in any subsequent decade (up to 2000). Reservoirs, lakes, and wide rivers that were identified as "water blocks" were also removed, so that no housing units were placed in these undevelopable areas.
2. **Undevelopable lands –** Spatial data on land ownership were compiled from a variety of sources to create the most current and comprehensive dataset – called the UPPT (unprotected, private protected, public protected, and tribal/native lands). The UPPT dataset was generated by starting from the Conservation Biology Institute's PAD v4 database (CBI 2008). We updated the PAD dataset with more current data for 21 states. The operating assumption is that housing units do not occur on publicly owned lands (e.g., national parks, forests, state wildlife areas, etc.) or on privately-owned, protected lands. Some state lands in the western United States (the so-called "school lands" sections, but not "stewardship" lands) were kept in the developable category because they are in practice sold to generate revenue for state school systems. Also, tribal lands are often considered federal (public), but here we included tribal lands as developable (except for known tribal parks). The portions of blocks that overlapped with public (and other non-developable lands) were deleted to create a modified or refined block. All housing units associated with each block are then assumed to be located in the refined (developable) portion of the blocks. Housing units were apportioned within the refined block using a dasymetric mapping approach described below. The final product is a raster

dataset that represents the developable and undevelopable lands for the SERGoM model, which is called dev20080306 and is available through the ICLUS tools.

3. **Road and groundwater well density –** The existence of major roads (interstates, state highways, county roads) was used to better allocate the location of housing units within a block. In a previous SERGoM model (v1, v2), housing units were spread evenly throughout the refined blocks. Here, in v3 of SERGoM, housing units were disproportionately weighted to areas according to fine-grained land use/cover data from NLCD 2001. Because major road infrastructure is included in the NLCD (actually burned in as values 21, 22, and some 23), road density *per se* was not included. Also, in the western US where the rural blocks are particularly large, groundwater well density was included to refine the allocation of units. Also, the analytical hierarchy process (AHP; Saaty 1980) was used to provide an estimate of logical consistency during the development of the weights (the consistency index was 0.035, which is less that then 0.15 threshold, showing that these estimates were logically consistent). Note also that these weights are applied in a relative, not absolute context. That is, the number of units that will be distributed in a given area is specified by the census block and so units are allocated in proportion to the weights found within a given block. This is robust in the face of potential misclassification of land cover types, because all the known housing units will be allocated to a given block, regardless of the land cover (but note that the undevelopable – water and public lands – portions of the blocks are excluded).
4. **County population projections –** Population projections for each county, discussed in Section 3, are used to drive the growth forecasts. Additional housing units were computed by determining the number of new housing units needed to meet the needs of the additional population, assuming the same (in 2000) population to housing unit ratio in each tract, using 2000 U.S. Census of Housing data.
5. **Commercial/industrial land use –** We also mapped locations with land uses that would typically preclude residential development (increased housing density), especially commercial, industrial, as well as transportation land uses. Using urban/built-up categories of NLCD 2001 (not open space developed), we identified locations (1 ha cells) that had >25% urban/built-up land cover but that had also had lower than suburban levels of housing density (because high-density residential areas would otherwise be included in the urban/built-up land cover categories). Although some re-development of central business districts ("gentrification") is occurring, SERGoM works from the operating assumption that these are relatively smaller portions of the landscape and typically brown-field settings.

These functional flow of the SERGoM model using data from these five sources is illustrated in Figure 4-1.

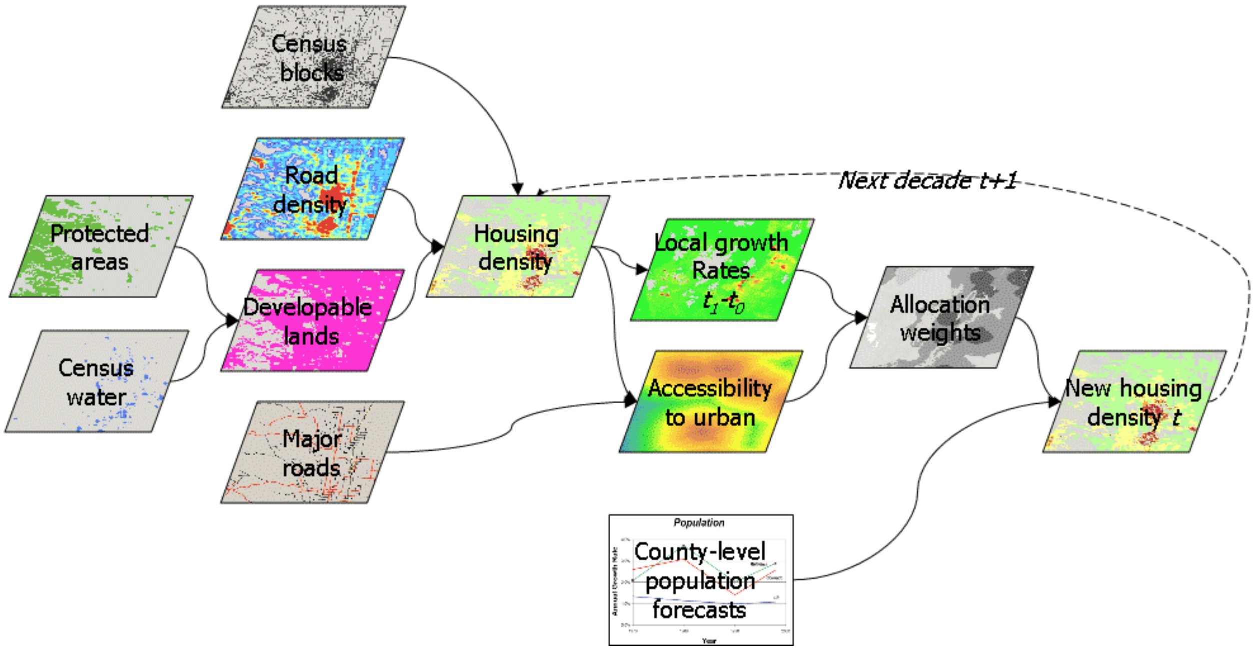


Figure 4-1: SERGoM Functional Flow

Housing density for each decade from 2010 to 2100 was forecast using the Spatially-Explicit Regional Growth Model (SERGoM) v3. SERGOM is a demand/allocation/supply model, where the number of new housing units needed for the next decade is computed to meet the demands of the projected population, computed here for each county (but could be other analytical unit boundaries). The average growth rate for each state-housing density class is computed from the previous to current time step (e.g., 1990 to 2000). These average growth rates are computed using a moving neighborhood (radius = 1.6 km, 500 m cell) for 16 development classes. These classes are formed by overlaying four housing density classes – urban, suburban, exurban, and rural – with four accessibility classes measured as travel time (minutes one way) from the nearest urban core along (existing) major roads: 0-10, 10-30, 30-60, and >60 minutes. The resulting combination creates a "surface" of raster values that reflect historical patterns of growth – called allocation weights – and are used to allocate the new housing units for a given time step.

Based on the Census definition of urban areas, we defined urban housing densities as less than 0.1 ha per unit and suburban as 0.1 – 0.68 ha per unit. We defined exurban density as 0.68 – 16.18 ha per unit (to 40 acres) to capture residential land use beyond the urban/suburban fringe that is composed of parcels or lots that are generally too small to be considered productive agricultural land use (though some high-value crops such as orchards are a notable exception). Rural is defined as greater than 16.18 ha per unit where the majority of housing units support agricultural production.

The strength of the SERGoM model is that it provides a comprehensive, consistent, and nationwide estimate of housing density. It uses the most fine-grained data set currently available, has performed reasonably well in assessments (79 to 99% accuracy rates), and compares favorably to parcel-level and aerial photography data during ad hoc analyses in a variety of locations in the United States (Theobald 2005). It assumes that growth rates and patterns are likely to be similar to recent times (1990s to 2000). The SERGoM outputs provide much more spatial detail as compared to the USDA Census of Agriculture[4], which are county-based and only provide data on land in farms. One other common datatset used to estimate the extent and trend of urbanization in the United States is the NRCS's Natural Resources Inventory (NRI)[5]. It is based on relatively fine-grained aerial photo analysis, but because they are sampled data, they are aggregated up to coarse analysis units (either county, watershed 8-digit HUC, or Major Land Resource Area). NRI also categorizes urban areas into only two classes – either as "small" or "large" development – resolving housing densities at urban and roughly 1 per 10 acre densities.

4.3 INCORPORATING U.S.-ADAPTED SRES INTO SERGOM

In addition to changes in population that resulted from the various demographic assumptions associated with each SRES-compatible scenario developed for the ICLUS project, the spatial location of growth was modified using SERGoM in two ways, through household size and travel time (Table 4-1). With SERGoM, household size is expected to reflect demographic changes due to changes in fertility and socioeconomic changes that affect household formation. Travel time from urban "central city" locations is used to help express how the evolution of the urban form might by affected by changing priorities and increases in the cost of transportation. Table 4-1 also shows how travel times are translated into this urban form. Housing units are allocated to a surface and the allocation is weighted by the accessibility to the transportation network, thereby influencing urban form over time to create a more "compact" form of development when allocations near urban centers are weighted more favorably.

The first SERGoM modification changed assumptions about households, particularly household size (roughly family size), defined as the number of people living in a single housing unit. Population projections from the U.S. Census assume that the ratio of population per unit, computed at the tract level from the 2000 U.S. Census data, is static. We modified this ratio to reflect assumptions in the SRES scenarios to adjust for assumed changes in demographic characteristics. For example, SRES A1 and B1 assume smaller household sizes (reduction by 15%), whereas scenarios B2 and baseline are not changed and A2 assumes a 15% increase in household size (Jiang and O'Neill, 2007). The changes in household size correspond to changes in fertility rates that are assumed under the different storylines. Under A1 and B1, where fertility is lowest, smaller average household sizes are also expected. Conversely, A2 has the highest fertility rates, so an increase in household sizes is expected. In B2, which uses the medium fertility rates, household sizes are not changed.

The second modification involves changing travel times by adjusting weighting values as a function of distance away (travel time) from urban cores. Urban area (<5 minutes) weights can be lowered by a given percentage to reflect a carrying capacity or saturation of an area, specified by zoning perhaps; or raised to reflect increased desire for urban living (lofts, gentrification, etc.). Exurban area weights (~30-60 minutes) can be lowered to reflect assumptions of lower rates of development due to increased fuel prices or can be used as a surrogate for lower land availability because of increased conservation purchases (or easements). It can also be raised for exurban areas to reflect increased "urban flight" of baby-boomer retirees and rural amenities. This weighting surface is re-computed at each time step. We modified the weights of travel times for the B1 and B2 storylines to model a "compact" growth scenario (see Table 4-1). Given the environmental orientation of the B1 and B2 storylines, we assumed that growth patterns in these

[4] http://www.agcensus.usda.gov/
[5] http://www.ncgc.nrcs.usda.gov/products/nri/

scenarios would place a greater emphasis on promoting denser growth patterns closer to existing urban centers.

We parameterized SERGoM to reflect the SRES scenarios in the following ways. First, the A1 and B1 scenarios were modeled to reflect a 15 percent decline in average household size. A2 was modeled to show a 15 percent increase in average household size. B2 was modeled with no change in household size. Thus, the household size for each census tract was modified by 0.85 for A1 and B1 scenarios, and 1.15 for A2. Second, to model the "compact" growth scenarios for the B1 and B2 scenarios, SERGoM was run with modifications to the spatial allocation of new housing units as a function of travel time from urban cores (Table 4-1).

Table 4-1: Summary of Adjustments to SERGoM v3 for SRES scenarios

Scenario	*Household size*	*Travel time (minutes)* *<5; 10; 20; 30; 45; >45*	*Form*
		Weighting (in percent)	
A1	Smaller (-15%)	75; 75; 85; 90; 95; 100	NC
B1	Smaller (-15%)	90; 95; 85; 90; 95; 100	Slight compact
A2	Larger (+15%)	75; 75; 85; 90; 95; 100	NC
B2	NC	90; 95; 85; 90; 95; 100	Slight compact
Baseline	NC	75; 75; 85; 90; 95; 100	NC

NC = No change from the U.S. Census Bureau's estimates.

4.4 INTEGRATION OF DEMOGRAPHIC, SERGOM, AND IMPERVIOUS MODELS

The demographic inputs from each of the US-adapted SRES storylines were fed into the SERGoM model, along with the SRES-specific adjustments in SERGoM for a given SRES scenario. The outputs of the SERGoM models were then mapped for each decade from 2000 to 2100 (Appendix A). We also used the impervious surface model to convert the SRES housing density estimates to the total percent impervious surface cover (Section 5.3). Section 5 discusses some preliminary analyses and potential future developments of the ICLUS modeling framework.

5 IMPACTS AND INDICATORS ANALYSIS

5.1 RATES OF GROWTH IN DIFFERENT REGIONS

The growth rates of the different regions of the United States under the various SRES storylines provides some interesting insight into the potential relative growth patterns in the coming decades. For this analysis of regional growth patterns, we used the U.S. Census regions (listed in Table 5-1). A separate analysis using EPA regions is presented in Appendix D. The populations of each of the Census regions and scenarios for 2005, 2030, 2060, and 2090, as well as the growth rates for each intervening period are presented in Table 5-2. These data are then displayed graphically to compare the different regions and scenarios (Figure 5-1 to Figure 5-14).

Table 5-1: U.S. Census Regions

Census Region	States
Northeast	Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont
Midwest	Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin
South	Alabama, Arkansas, Delaware, District of Columbia, Florida, Georgia, Kentucky, Louisiana, Maryland, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia, West Virginia
West*	Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, Wyoming

* Alaska and Hawaii were excluded from the West region in this analysis.

Table 5-2: Projected Regional Populations and Growth Rates

	Population				Growth Rate (%)		
Census Region	2005	2030	2060	2090	2005-2030	2030-2060	2060-2090
Base Case							
Northeast	54,679,292	63,384,211	70,279,618	79,600,361	16%	11%	13%
Midwest	65,936,398	71,250,888	73,287,983	76,745,425	8%	3%	5%
South	108,981,468	134,649,231	158,547,450	187,417,301	24%	18%	18%
West	64,973,375	81,705,117	96,926,417	114,073,784	26%	19%	18%
A1 Storyline							
Northeast	54,679,292	66,910,792	73,137,911	76,159,296	22%	9%	4%
Midwest	65,936,398	69,265,132	65,378,806	59,355,485	5%	-6%	-9%
South	108,981,468	140,717,741	162,287,975	174,443,647	29%	15%	7%
West	64,973,375	82,571,676	91,877,085	94,284,391	27%	11%	3%
A2 Storyline							
Northeast	54,679,292	64,718,449	78,041,141	101,339,355	18%	21%	30%
Midwest	65,936,398	71,810,622	80,335,490	98,476,101	9%	12%	23%
South	108,981,468	141,466,245	186,892,292	262,941,111	30%	32%	41%
West	64,973,375	85,129,358	111,597,232	153,721,857	31%	31%	38%
B1 Storyline							
Northeast	54,679,292	68,481,437	76,906,738	82,327,874	25%	12%	7%
Midwest	65,936,398	72,973,243	72,166,976	67,641,537	11%	-1%	-6%
South	108,981,468	136,176,035	152,179,001	159,582,292	25%	12%	5%
West	64,973,375	81,468,120	90,471,745	93,288,362	25%	11%	3%
B2 Storyline							
Northeast	54,679,292	64,097,466	72,006,459	82,638,846	17%	12%	15%
Midwest	65,936,398	73,134,039	77,070,686	82,236,752	11%	5%	7%
South	108,981,468	132,513,626	153,888,715	179,498,472	22%	16%	17%
West	64,973,375	81,182,232	96,254,307	113,554,597	25%	19%	18%

Figure 5-1 through Figure 5-5 compare the population in the four Census regions under each of the four SRES storylines and the base case. In all five sets of population projections, the South region remains the most populous region, while growing faster than most other regions in most scenarios. The West region, which begins with approximately the same population as the

Northeast and Midwest regions, outpaces those two regions in all scenarios except for B1. Across the board, all regions experience growth in all scenarios, with the exception of the Midwest region in scenarios A1 and B1.

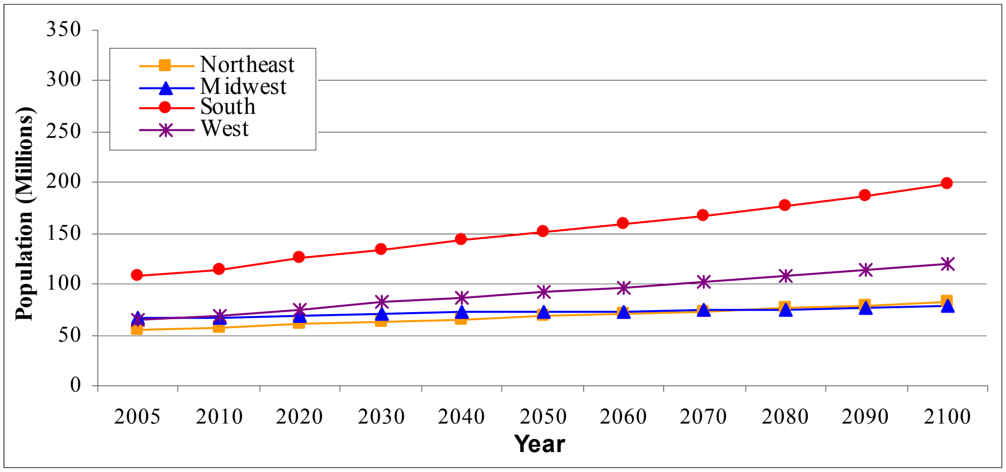


Figure 5-1: Base Case Population by Census Region

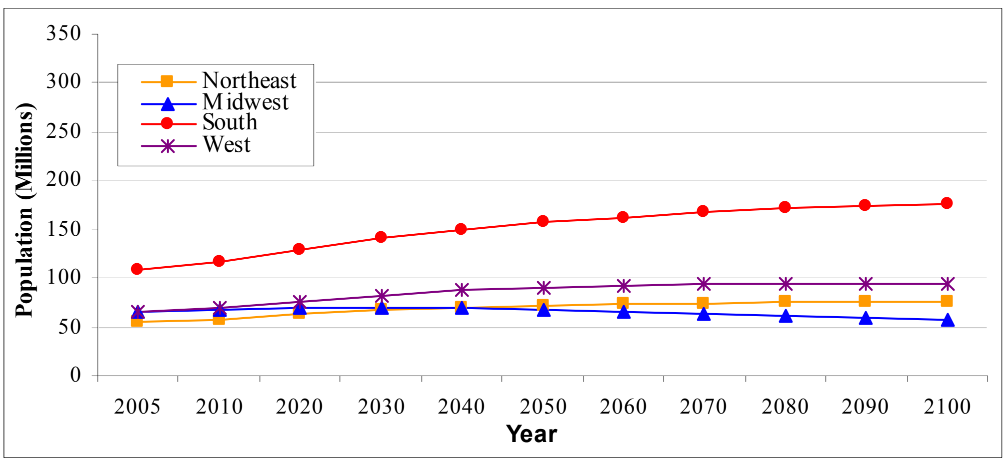


Figure 5-2: A1 Storyline Population by Census Region

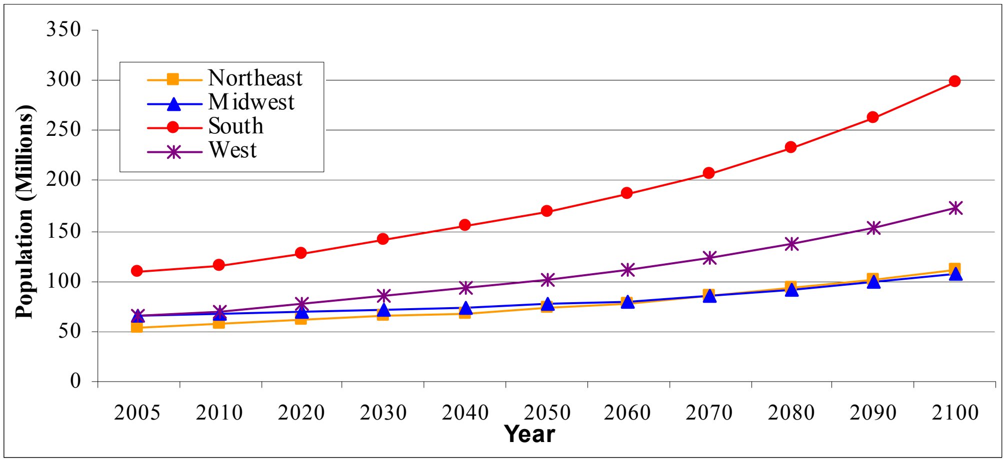


Figure 5-3: A2 Storyline Population by Census Region

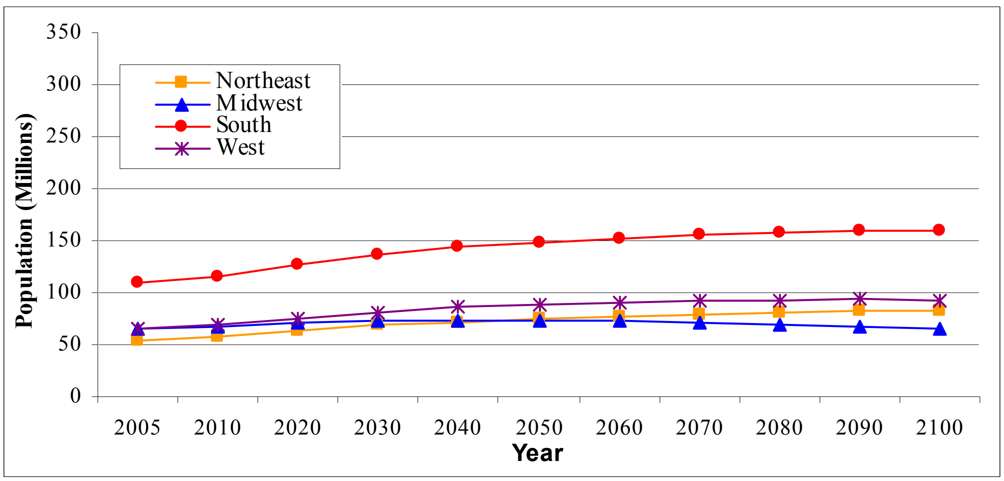


Figure 5-4: B1 Storyline Population by Census Region

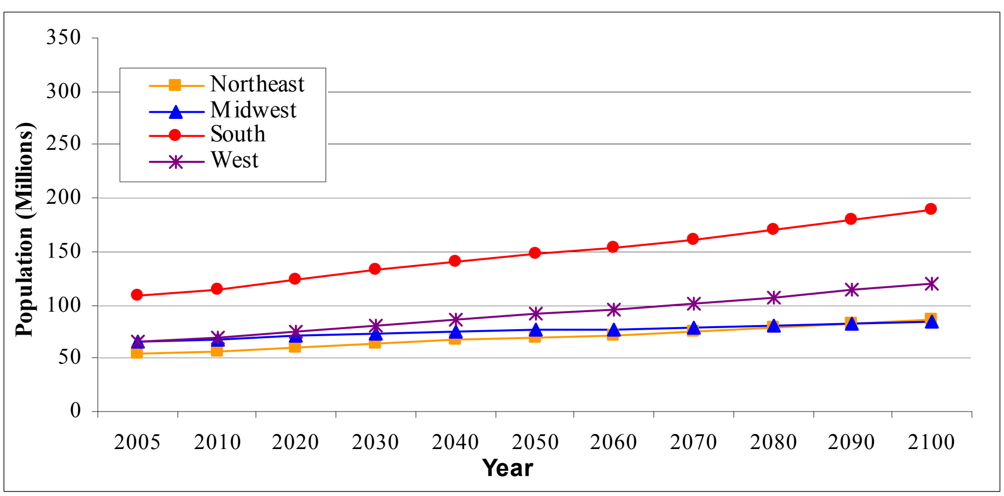


Figure 5-5: B2 Storyline Population by Census Region

Figure 5-6 through Figure 5-10 compare the average annual growth rates during each modeled decade under the different scenarios (e.g., a growth rate of 1.01 indicates growth of 1 percent). Under the base case and B2 storyline, population growth rates are highest during the first time period, then level off for the remaining two periods. The A1 and B1 storylines, by comparison, generally decline in growth rate throughout the 21st century. The A2 storyline, which has the highest overall population growth, is the only one that exhibits steady increasing rates of population growth over the next century.

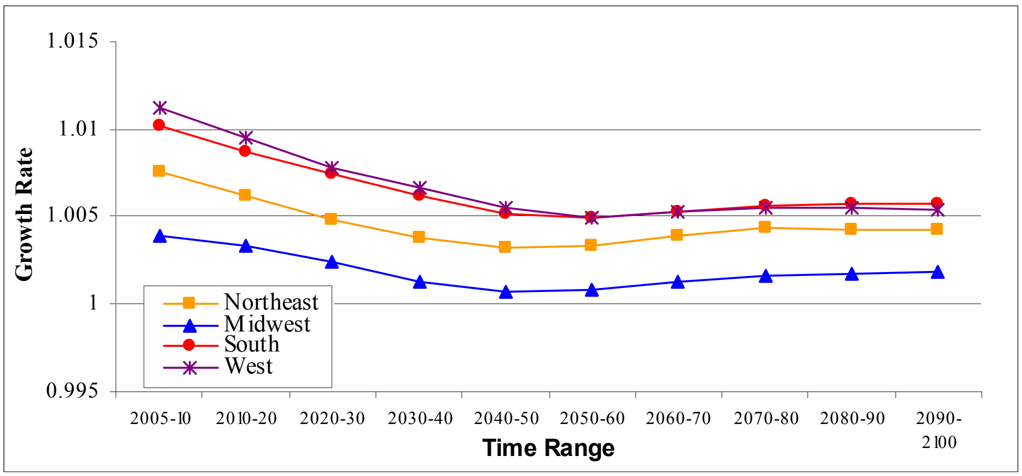


Figure 5-6: Base Case Annual Population Growth Rates by Region

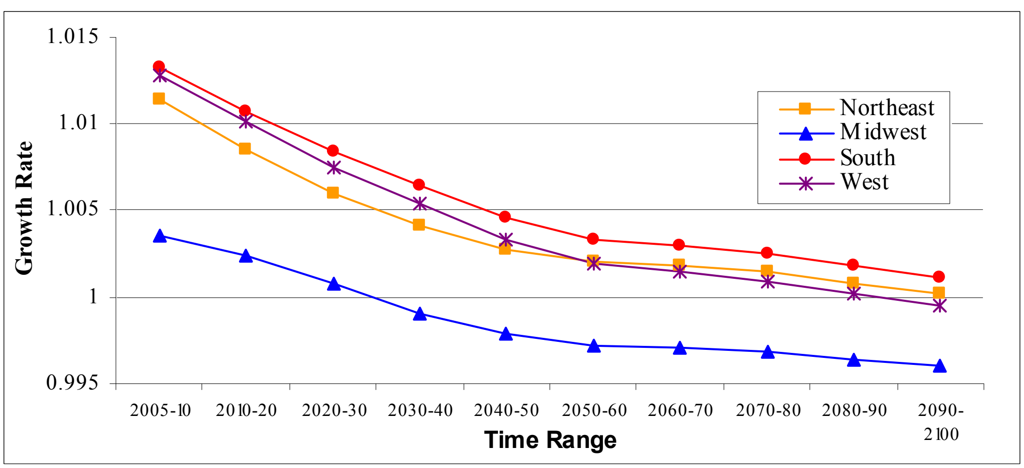


Figure 5-7: A1 Storyline Annual Population Growth Rates by Census Region

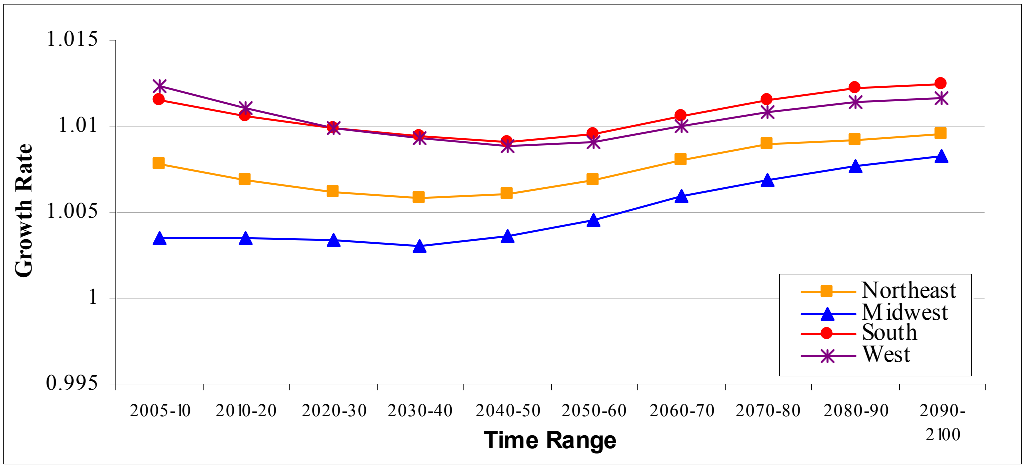


Figure 5-8: A2 Storyline Annual Population Growth Rates by Census Region

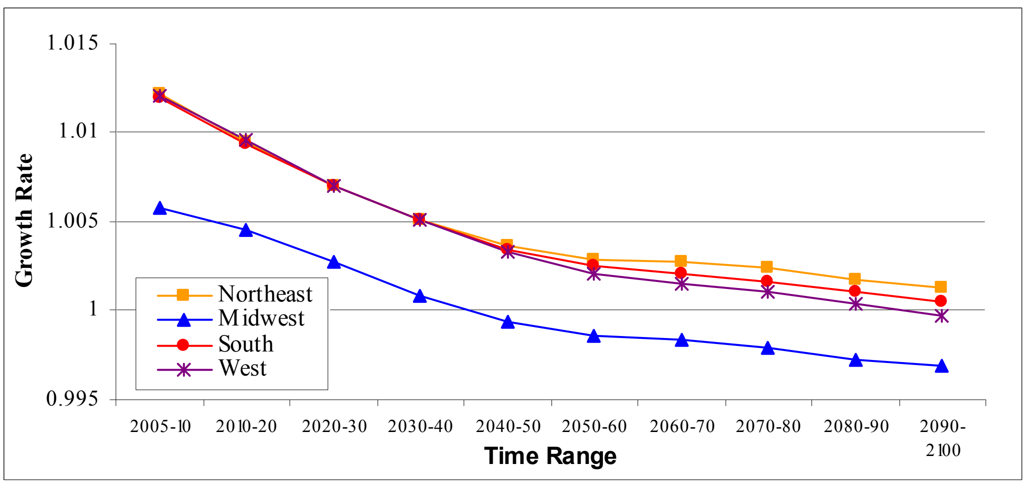


Figure 5-9: B1 Storyline Annual Population Growth Rates by Census Region

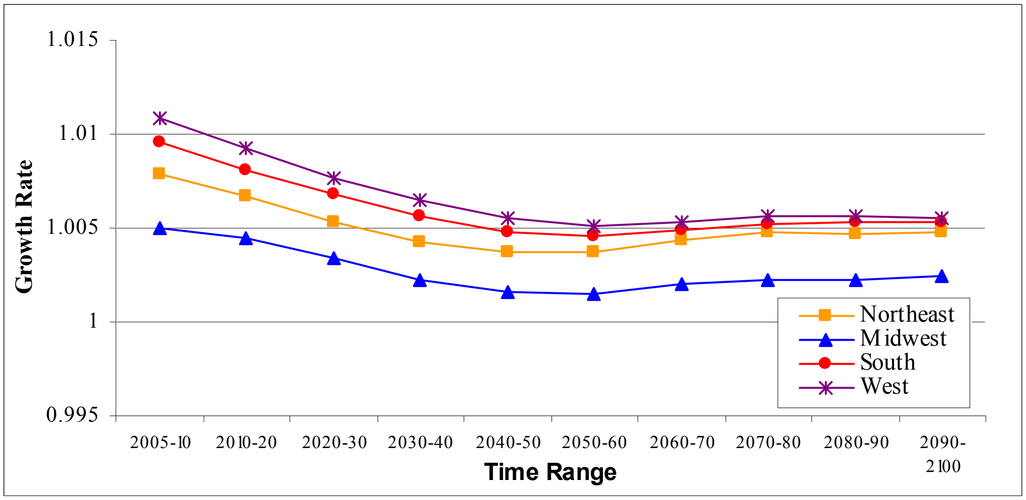


Figure 5-10: B2 Storyline Annual Population Growth Rates by Census Region

Figure 5-11 through Figure 5-14 provide comparisons of the storylines for each of the four Census regions. A2 produces the highest population in each region, confirming our expectations based on our interpretation of the SRES storylines. A1 produces the lowest population in the Northeast and Midwest regions, while B1 produces the lowest population in the South and West regions. This is because domestic migration, which is expected to continue to trend toward the South and West (and away from the Midwest and Northeast), is set to “high” under A1 and “low” under B1. Again, all regions grow under all scenarios, with the exception of the Midwest region under A1 and B1.

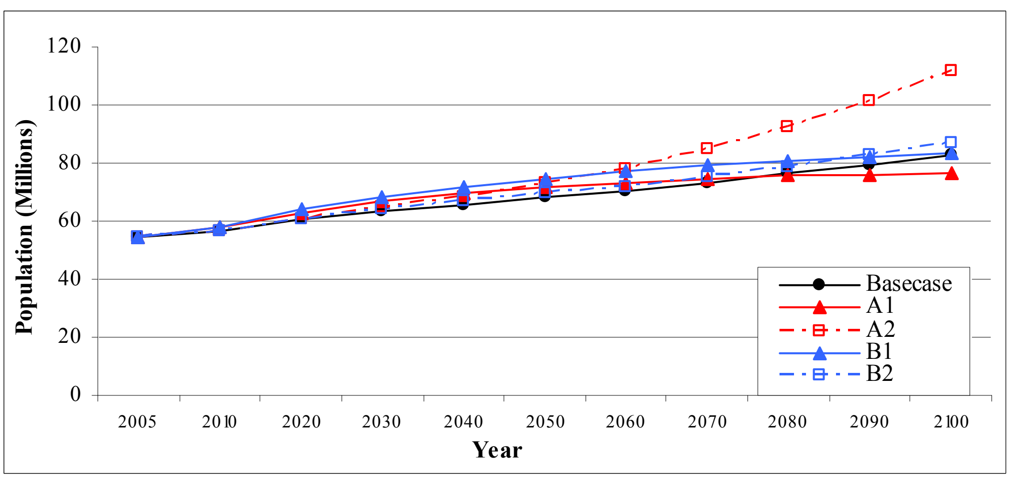


Figure 5-11: Northeast Region Population by Storyline

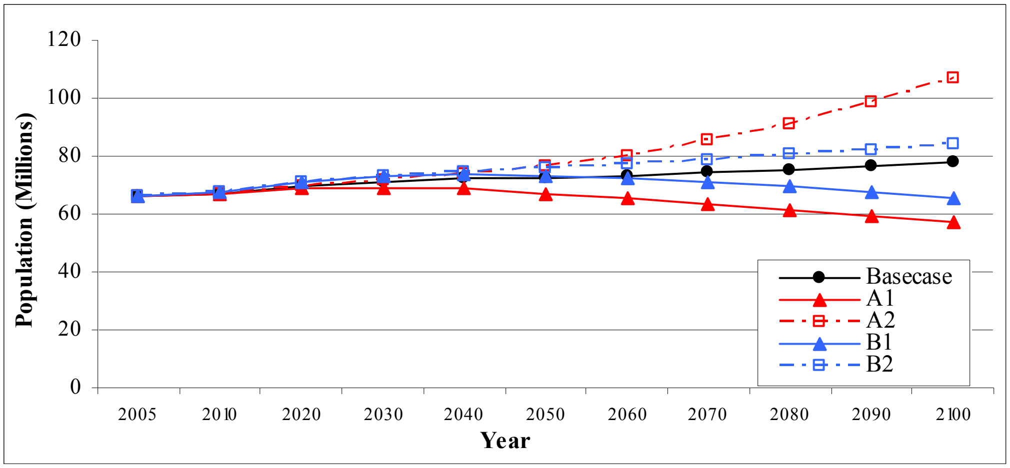


Figure 5-12: Midwest Region Population by Storyline

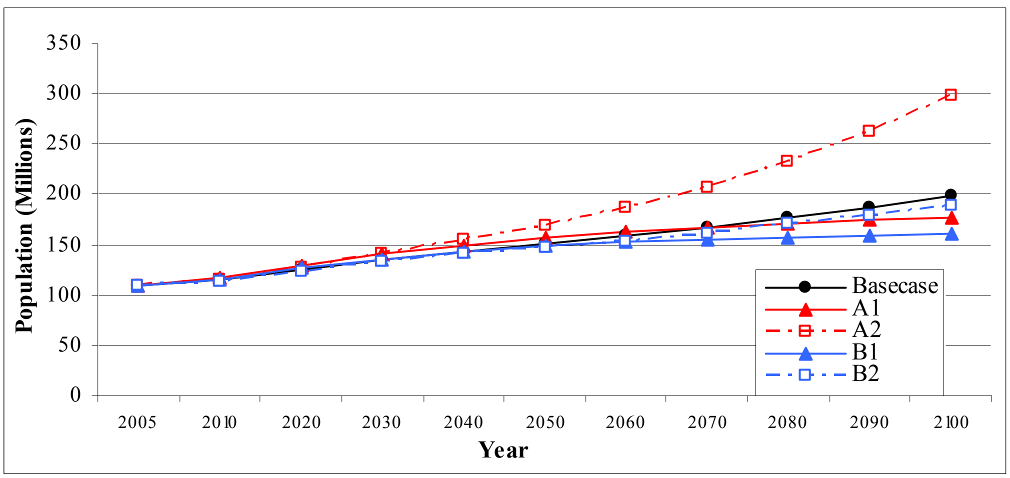


Figure 5-13: South Region Population by Storyline

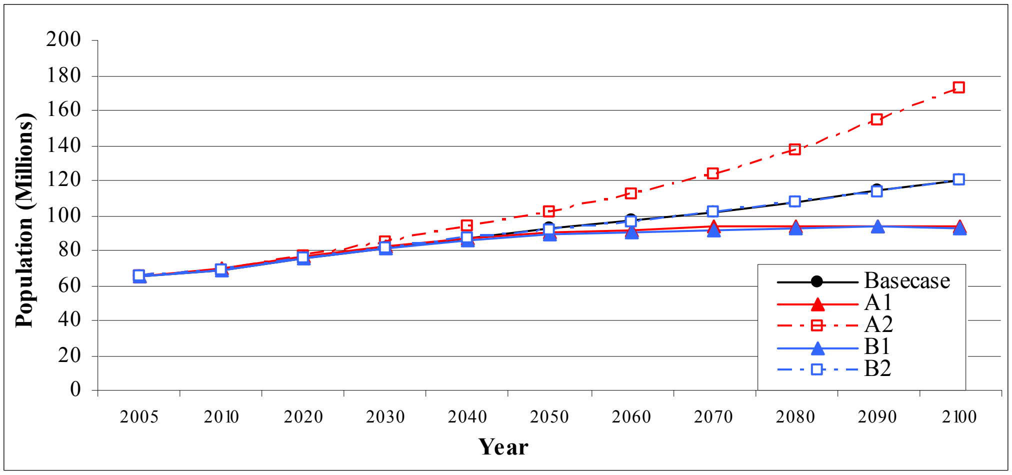


Figure 5-14: West Region Population by Storyline

5.2 HOUSING DENSITY TRENDS

The projected growth in population and housing density is anticipated to lead to corresponding impacts on environmental attributes such as water quality and air quality. Since the challenges are expected to be greater in urban and suburban areas, we used the model outputs to estimate the growth in these higher density areas. Under all modeled scenarios, urban and suburban areas are expected to increase between 56 and 156%. For this analysis, urban and suburban areas are defined as those areas with at least 0.6 units per acre (or less than 1.6 acres per unit). This land class is expected to increase the most in the A2 scenario, adding over 185,000 km^2 over the next century, or 156% more than 2000 levels (about 120,000 km^2) for a total of over 300,000 km^2 of urban/suburban area in 2100 (Table 5-3). Other increases are expected to be significant, but more moderate than the A2 scenario, with B1 having the smallest increase (56%) (Table 5-3; Figure 5-15). The non-intuitive result that B2 has a higher amount of urban/suburban area as compared to the base case may be the result of the net trade-off of negatively weighting growth in regions beyond suburban areas (i.e., exurban and rural areas); this growth results in a greater extent of the land surface containing urban/suburban densities, compared with the base case where those housing units are more frequently in exurban or rural categories. Note that we do not include in our estimates of urban/suburban housing densities the over 32,300 km^2 of estimated commercial/industrial land cover for 2000.

We also examined what broad land cover types were likely to be most affected by the projected development patterns (Table 5-4). To do this, we quantified the spatial overlap of the urban, suburban, and exurban housing densities (>1 unit per 40 acres) on the existing major land cover type as characterized by NLCD 2001 Anderson Level I coding. The largest impacts for all scenarios, both in terms of percentage and total area, are estimated to be on agricultural (cropland) cover where approximately 33% of area is converted into housing in these scenarios. Although wetlands cover less land area, our scenarios convert 30-36% of wetlands to housing. Shrublands are similar in total area converted, although the scenarios present more of a range in the amount converted (25-34%).

Table 5-3: Projected Urban and Suburban Area Increases in Modeled Scenarios, 2000-2100 (km^2)

Scenario	2000	2050	2100	% Increase, 2000-2100
Base case	119,422	181,897	212,657	64%
A1	119,422	182,425	208,551	75%
A2	119,422	188,824	305,279	156%
B1	119,422	170,856	186,388	56%
B2	119,422	172,972	225,857	89%

Table 5-4: Projected area (km^2) effects of Urban, Suburban, and Exurban Housing Densities on NLCD Land Cover Types in Modeled Scenarios for 2050

Scenario	Forest	Shrubland	Grassland	Agriculture (cropland)	Wetland
Current	400,118	47,943	70,066	269,290	44,007
Total area change between current and 2050					
Base Case	-40,477	-15,612	-16,289	-90,452	-15,721
A1	-34,232	-12,234	-13,580	-88,890	-14,150
A2	-36,628	-16,340	-15,441	-90,620	-15,140
B1	-35,513	-14,743	-13,867	-89,443	-13,366
B2	-39,833	-15,303	-14,411	-89,496	-14,687
Percent change between current and 2050					
Base Case	-10.1%	-32.6%	-23.2%	-33.6%	-35.7%
A1	-8.6%	-25.5%	-19.4%	-33.0%	-32.2%
A2	-9.2%	-34.1%	-22.0%	-33.7%	-34.4%
B1	-8.9%	-30.8%	-19.8%	-33.2%	-30.4%
B2	-10.0%	-31.9%	-20.6%	-33.2%	-33.4%

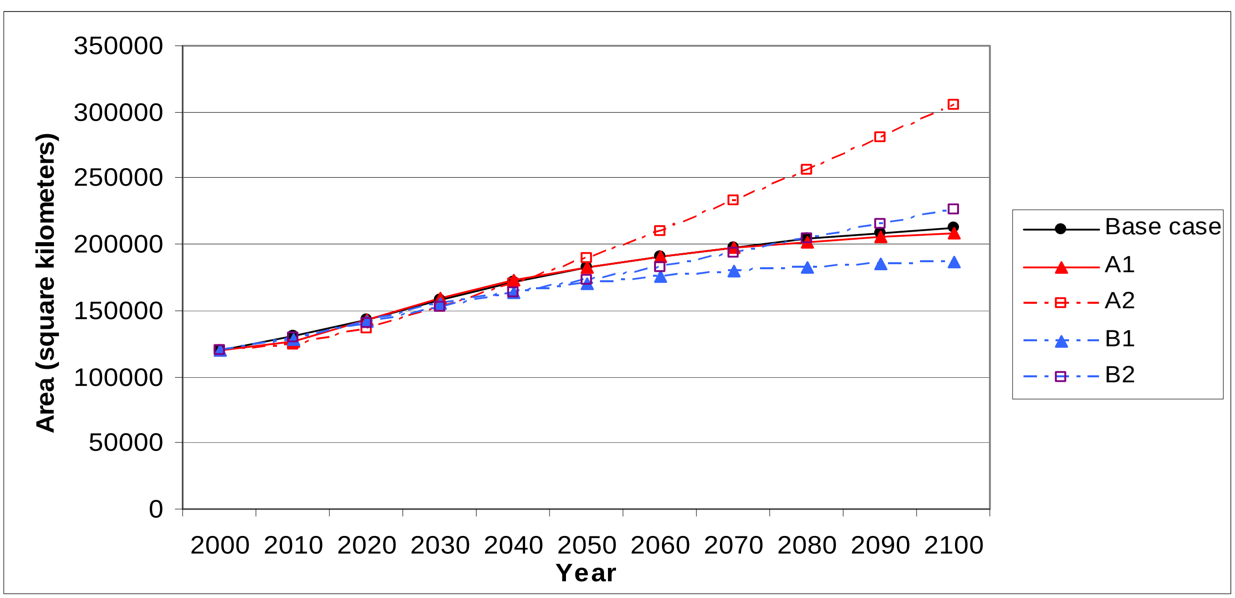


Figure 5-15: Urban/Suburban Housing Land-use Trends for ICLUS SRES Scenarios

5.3 IMPERVIOUS SURFACE CALCULATIONS

Impervious surfaces such as pavement and roofs degrade water quality, and by collecting pollutants, increasing run-off during storm events, and absorbing heat they also contribute to the heat island effect (Frazer, 2005). To develop national estimates of likely future impervious surface (IS), we developed a statistical relationship between 2000 housing density and the NLCD 2001 Percent Urban Imperviousness (IS_{PUI}) data set (MRLC 2007). We aggregated the 30 m IS_{PUI} data set to 900 m^2 cells and then resampled using bilinear interpolation to 1 km^2 resolution. We aggregated the SERGoM 1 ha housing density up to 1 km^2 as well. Based on a spatially-balanced random sample of 200,000 points from across the coterminous United States, we developed a relationship using the *cv.tree* function in S-Plus (Insightful Corporation, Seattle, WA) between IS_{PUI} and HD_{2000}. To generate a map of IS based on the housing density (IS_{HD}), we converted the tree into a set of if-then-else conditional statements in ArcGIS. A brief comparison of our modeled IS to existing fine-grained (from high-resolution photography) validation datasets resulted in an R^2=0.69 (Elvidge et al. 2004) and R^2=0.69 and R^2=0.96 for Frederick County, Maryland and Atlanta, Georgia (Exum et al. 2005). Because our estimates of IS are produced on a per 1 km^2 pixel basis, we were able to roughly compare our estimates to Exum et al.'s (2005) by averaging pixels that fell within their 10-12 digit HUCs. It would be useful to compare our results to other aerial-photography-based estimates, but to our knowledge the spatial datasets of these estimates of IS are not readily obtainable. The detailed methods and results are described in Theobald et al. (in press) and in 6Appendix C.

5.3.1 Percent of Watersheds over Stressed (>5%) Impervious Threshold

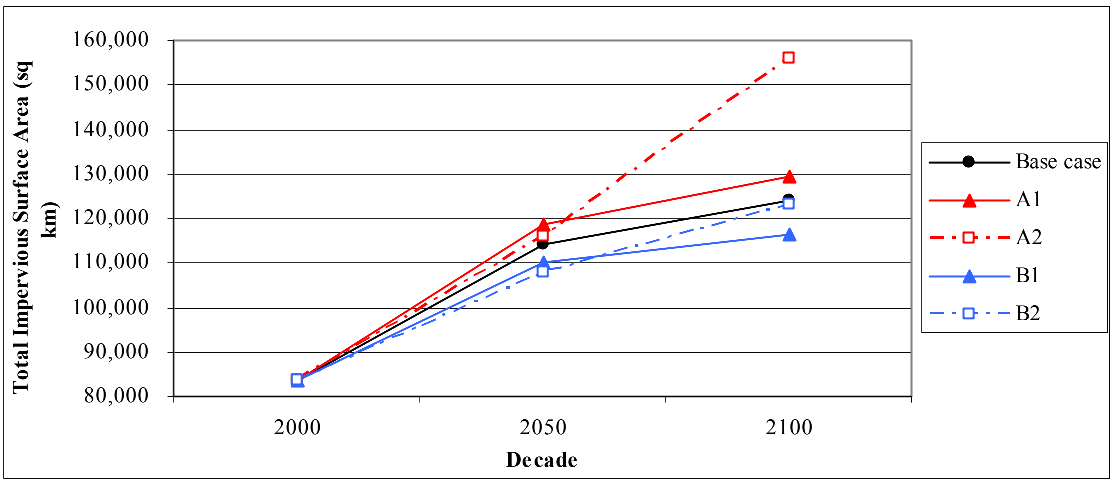
The total percent impervious surface (computed at 1 km^2) for the United States in 2000 was 83,749 km^2. We developed a regression model (described in Appendix C) that relates housing density estimates in 2000 to estimates from the Percent Urban Impervious from the NLCD 2001 dataset. Based on that statistical relationship, we were able to forecast likely changes to impervious surface for different future patterns of land use that reflect our SRES growth scenarios (Table 5-5; Figure 5-16). We classified impervious surface estimates into 5 classes: unstressed (0-0.9%), lightly stressed (1-4.9%), stressed (5-9.9%), impacted (10-24.9%), and degraded (>25%), following Slonecker and Tilley (2004) and Elvidge et al. (2007) and Theobald et al. (*in press*). Note that our estimates here do not include impervious surface for known commercial/industrial lands (in 2000) – that added an additional 13,430 km^2 of impervious surface area. All housing density classes were included when estimating the impervious surface. In 2000, urban/suburban areas (< 1.6 acres per unit) comprised 49.6% of the total impervious surface (accounting for different percent IS), exurban areas (1.6-40 ac per unit) comprise 34.1%, and rural comprised 16.3%. We estimate that in 2000 there were 113 8-digit HUCs that were stressed or higher (at least 5% IS), and this will likely increase to between 180 to 206 in 2050 and to between 197 and 290 in 2100 – a doubling to nearly a tripling.

In general, there are fairly large differences between the amount of impervious surface that likely will result from different growth scenarios – from a 3.8% increase (A1) from base case to a 6.1% decline (B2) from base case in 2050. Figure 5-17 to Figure 5-26 show the impervious surface patterns for each U.S.-adapted SRES scenario and the relative differences between these scenarios and the base case.

1 **Table 5-5: Impervious surface estimates for SRES scenarios. "Stressed" level is defined as**
2 **at least 5% impervious surface.**

	Year 2050		**Year 2100**	
SRES	**Total impervious surface (km^2)**	**Number of stressed 8-digit HUCs (of 2127)**	**Total impervious surface (km^2)**	**Number of stressed 8-digit HUCs (of 2127)**
Base case	114,320	195	124,190	216
A1	118,670	204	129,322	227
A2	115,800	206	156,100	290
B1	110,176	185	116,344	197
B2	107,765	180	123,255	217

3



4

5 **Figure 5-16: Impervious surface area estimates, 2000-2100**

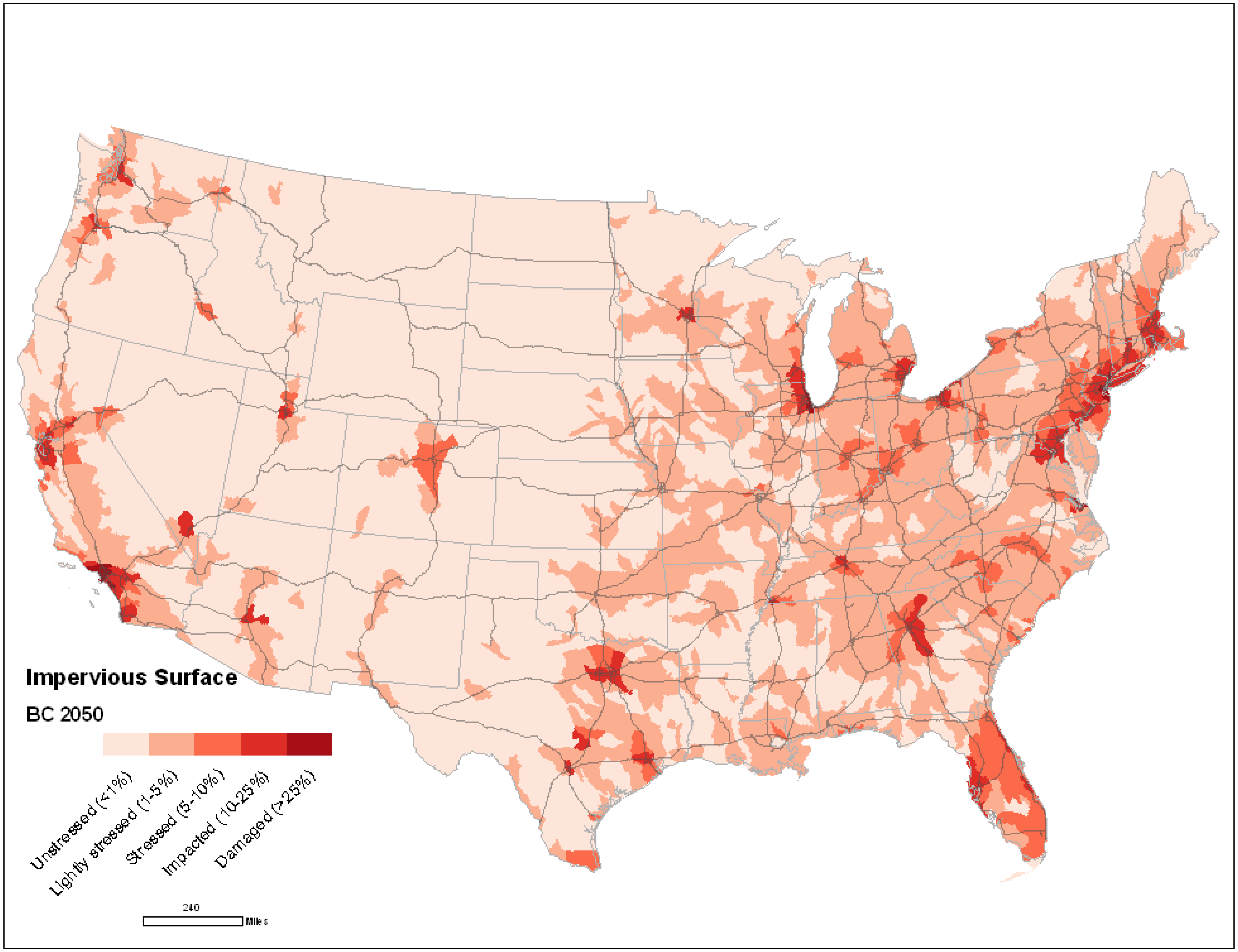


Figure 5-17: 2050 Impervious Surface, Base Case

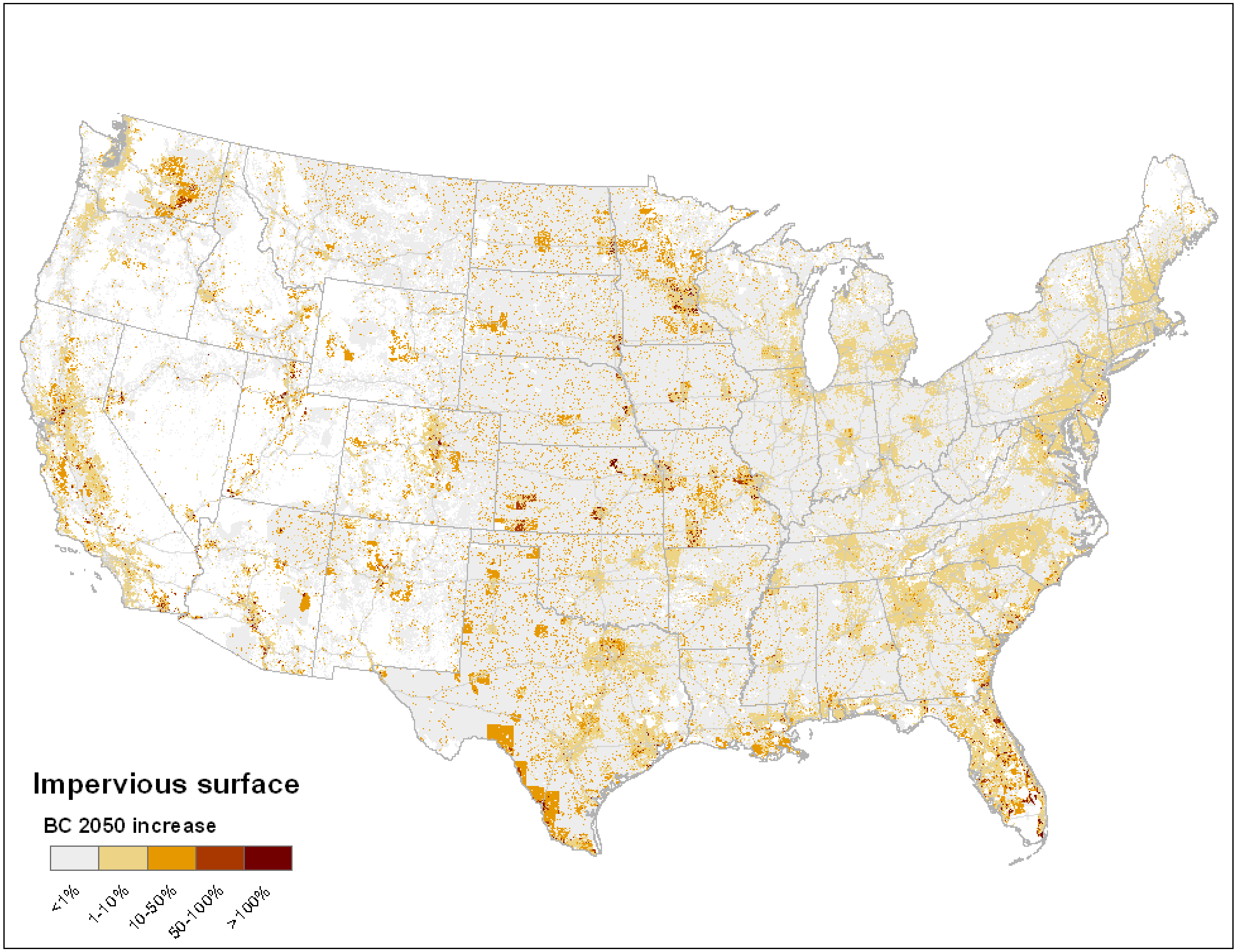


Figure 5-18: 2000-2050 Relative Change in Impervious Surface, Base Case

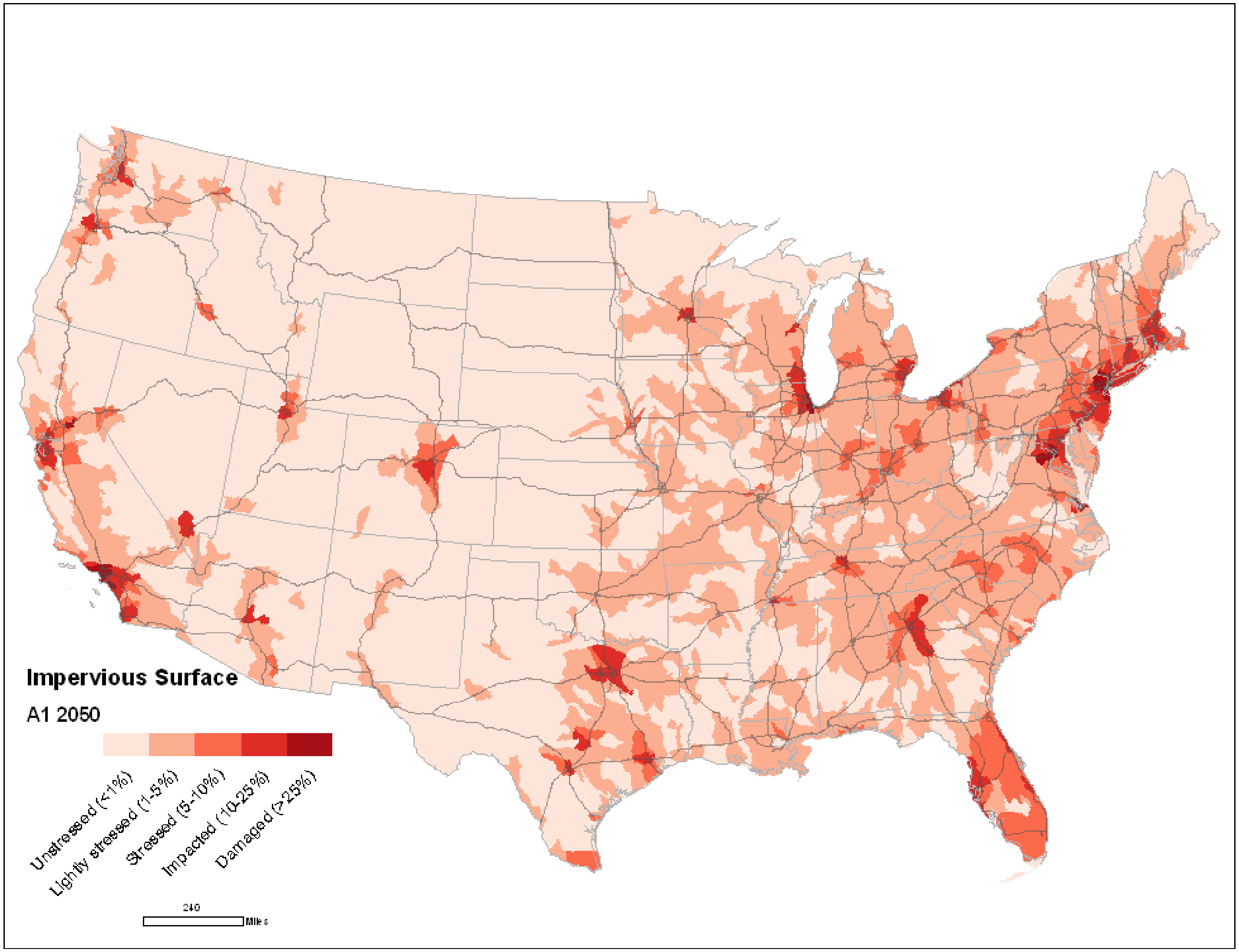


Figure 5-19: 2050 Impervious Surface, A1 Storyline

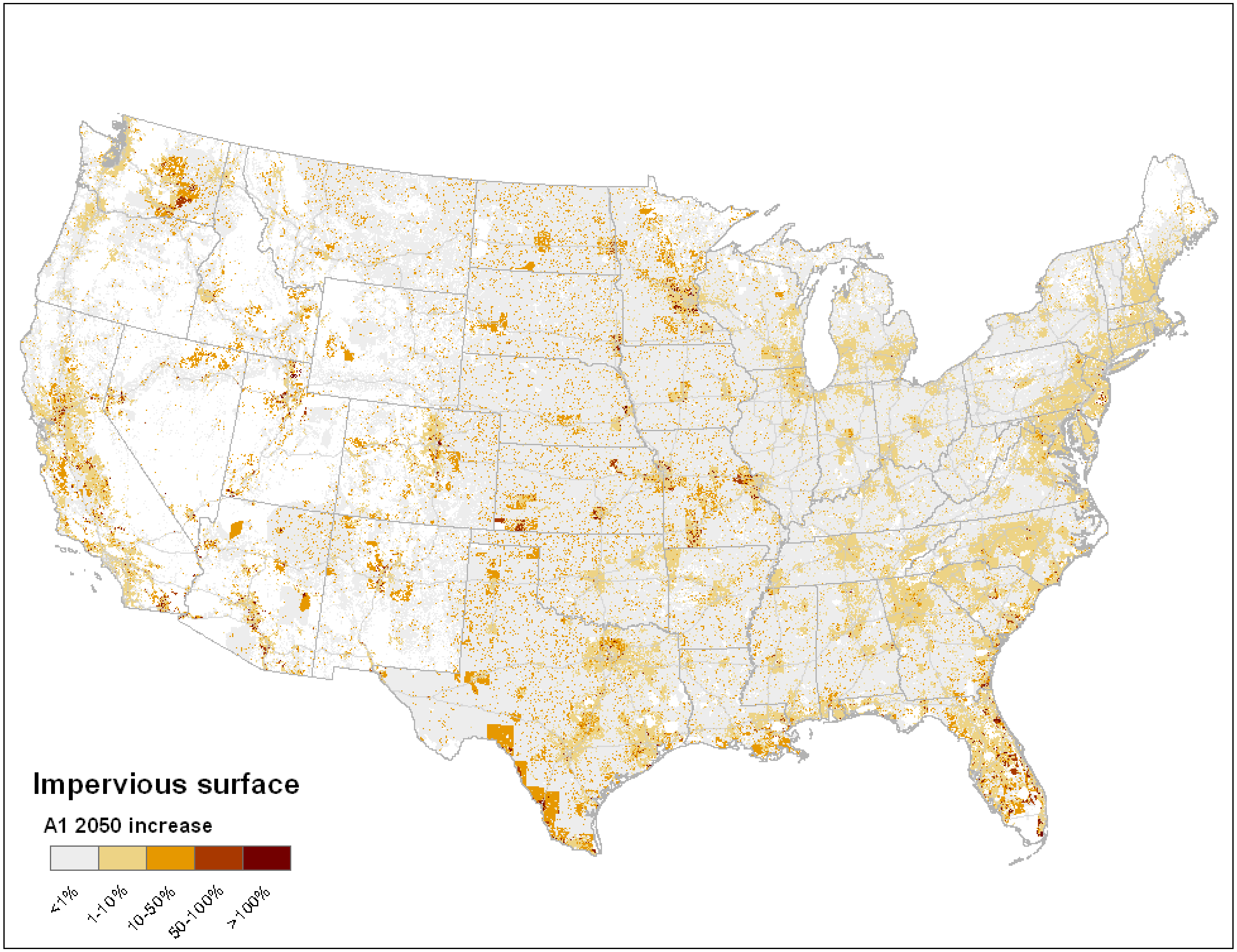


Figure 5-20: 2000-2050 Relative Change in Impervious Surface, A1 Storyline

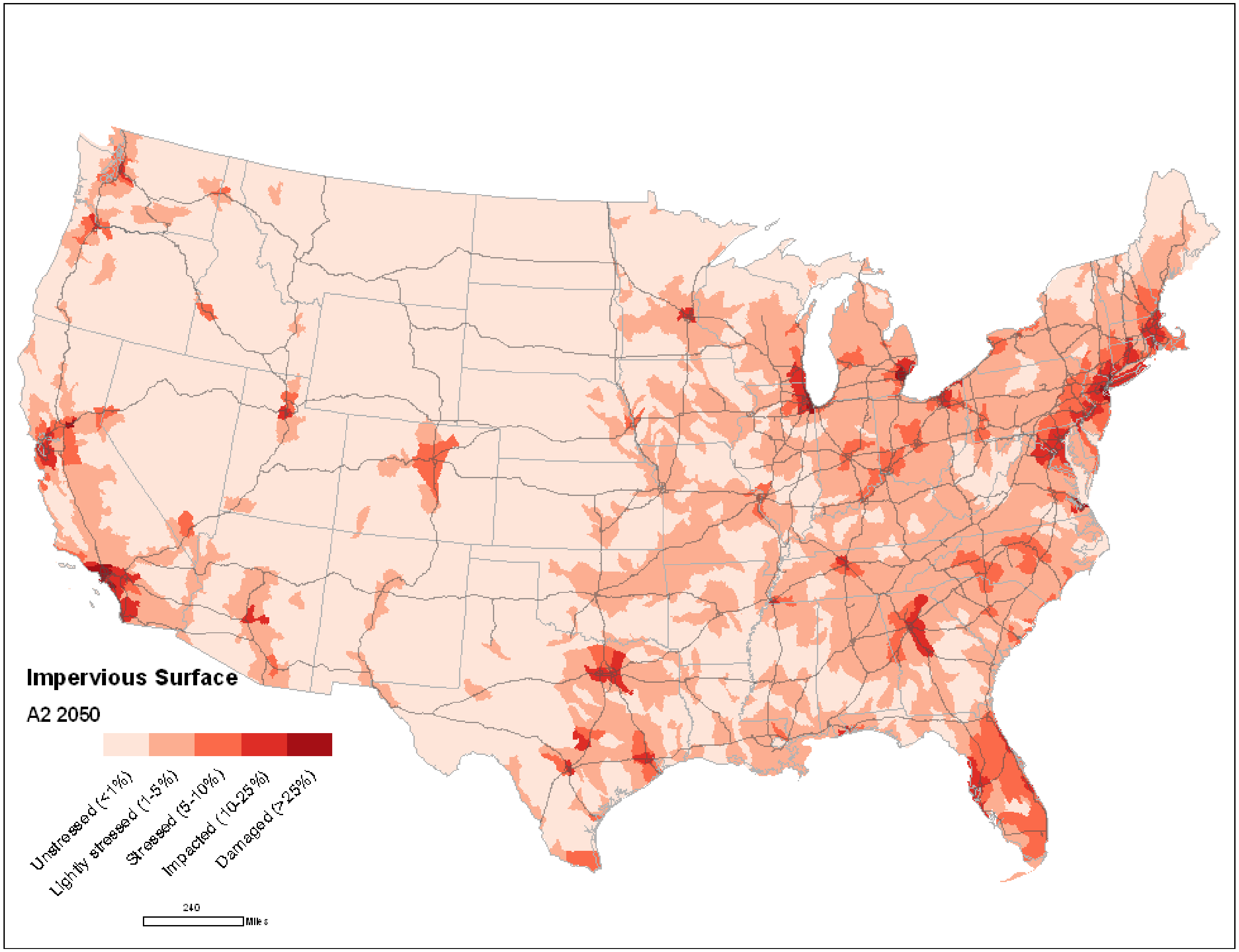


Figure 5-21: 2050 Impervious Surface, A2 Storyline

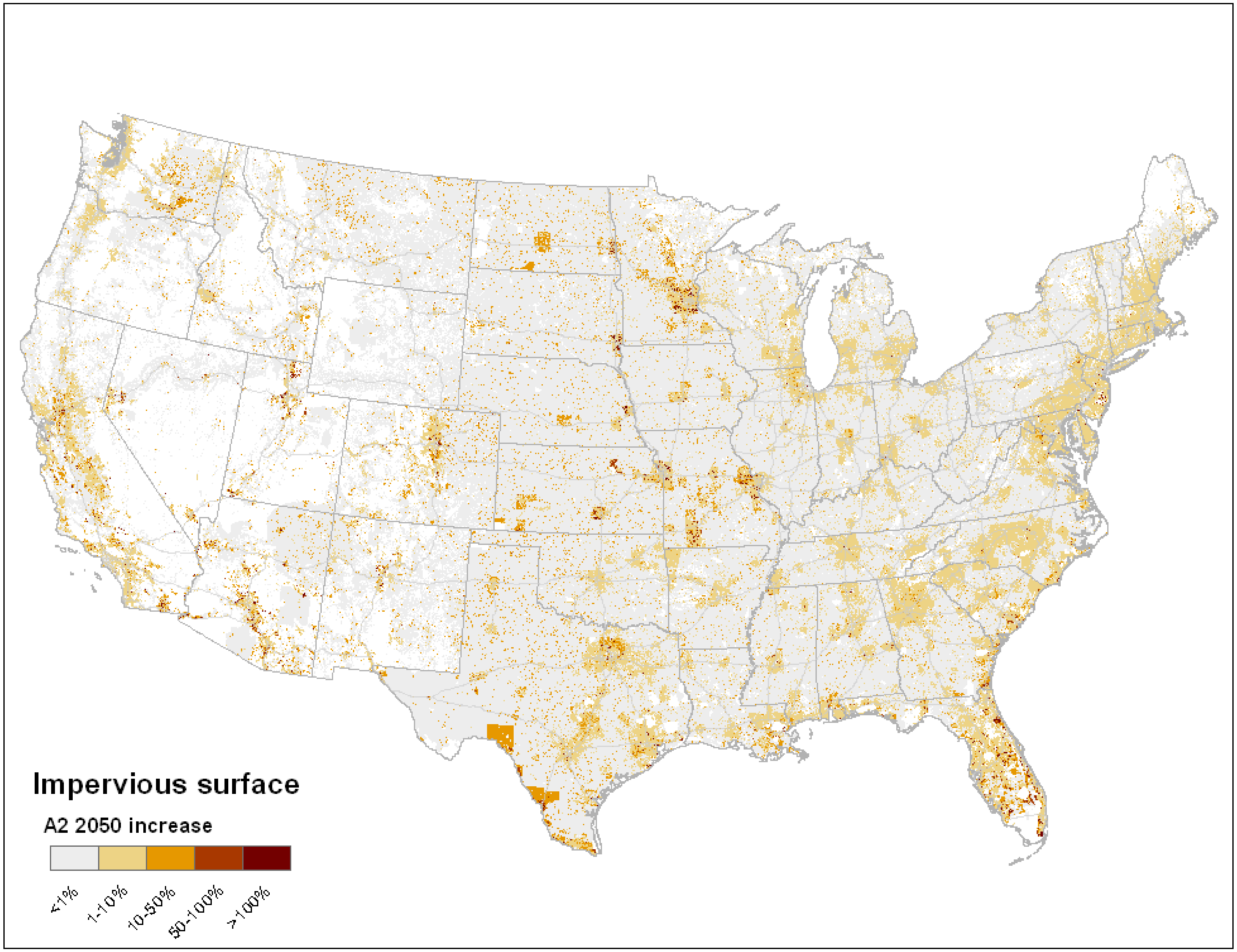


Figure 5-22: 2000-2050 Relative Change in Impervious Surface, A2 Storyline

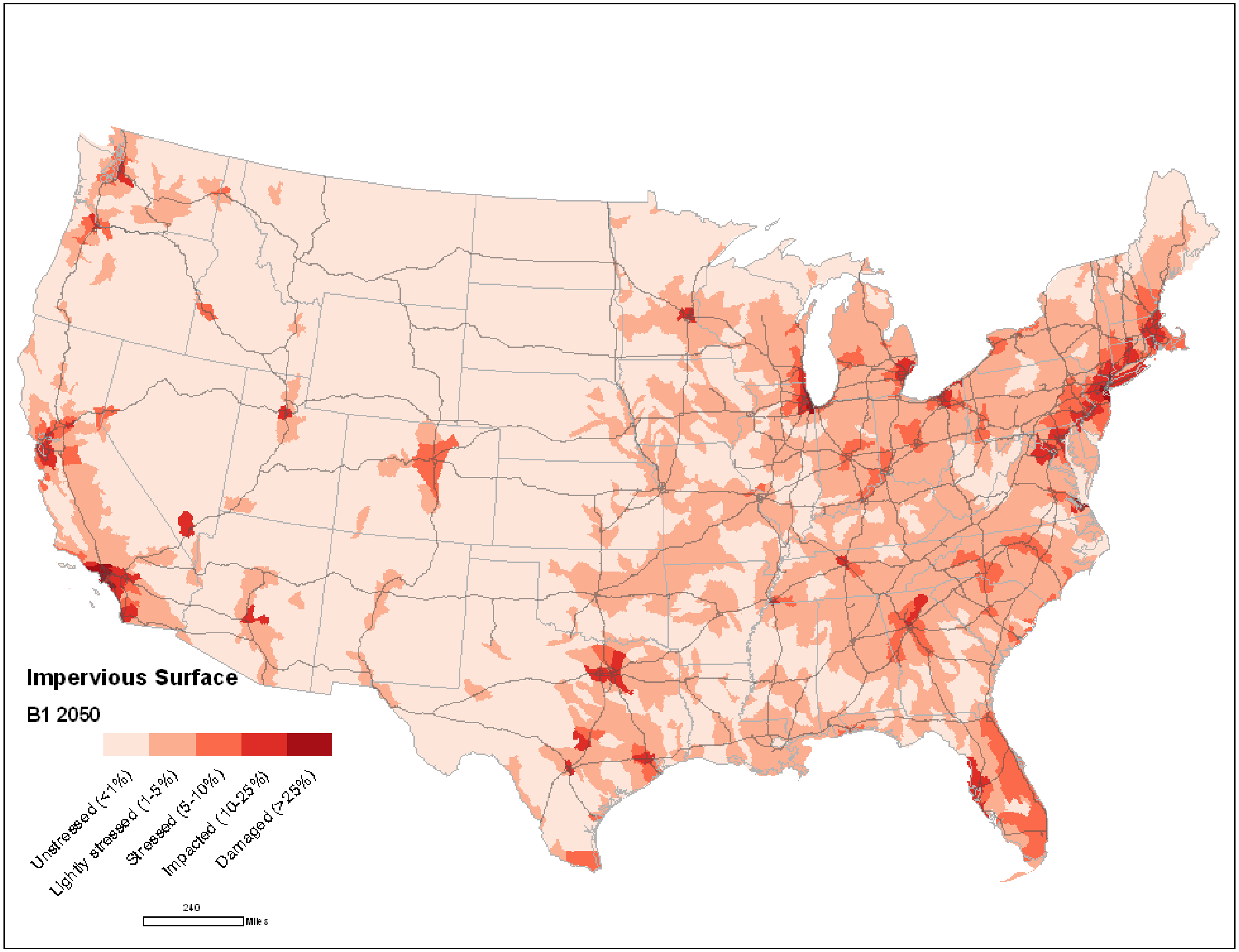


Figure 5-23: 2050 Impervious Surface, B1 Storyline

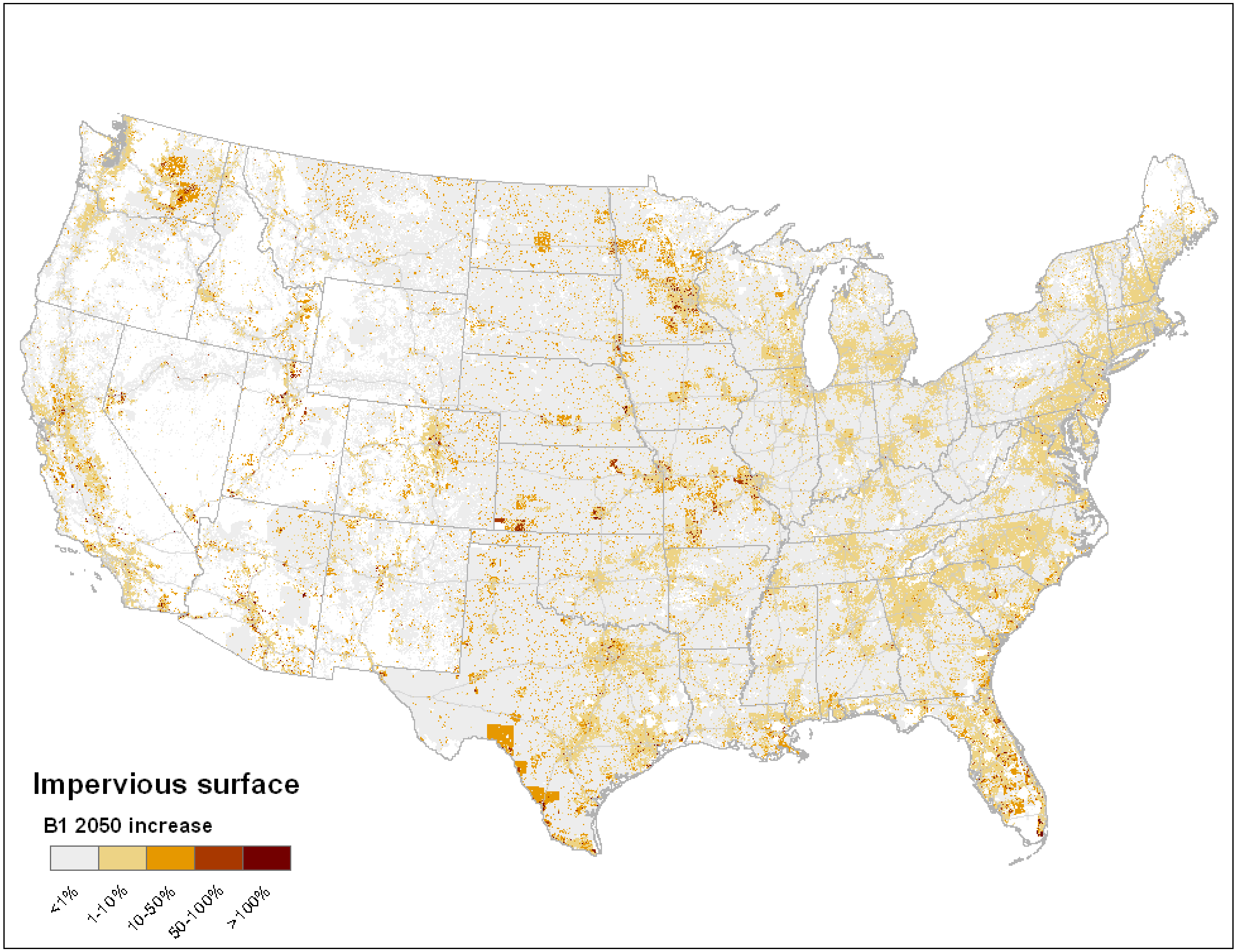


Figure 5-24: 2000-2050 Relative Change in Impervious Surface, B1 Storyline

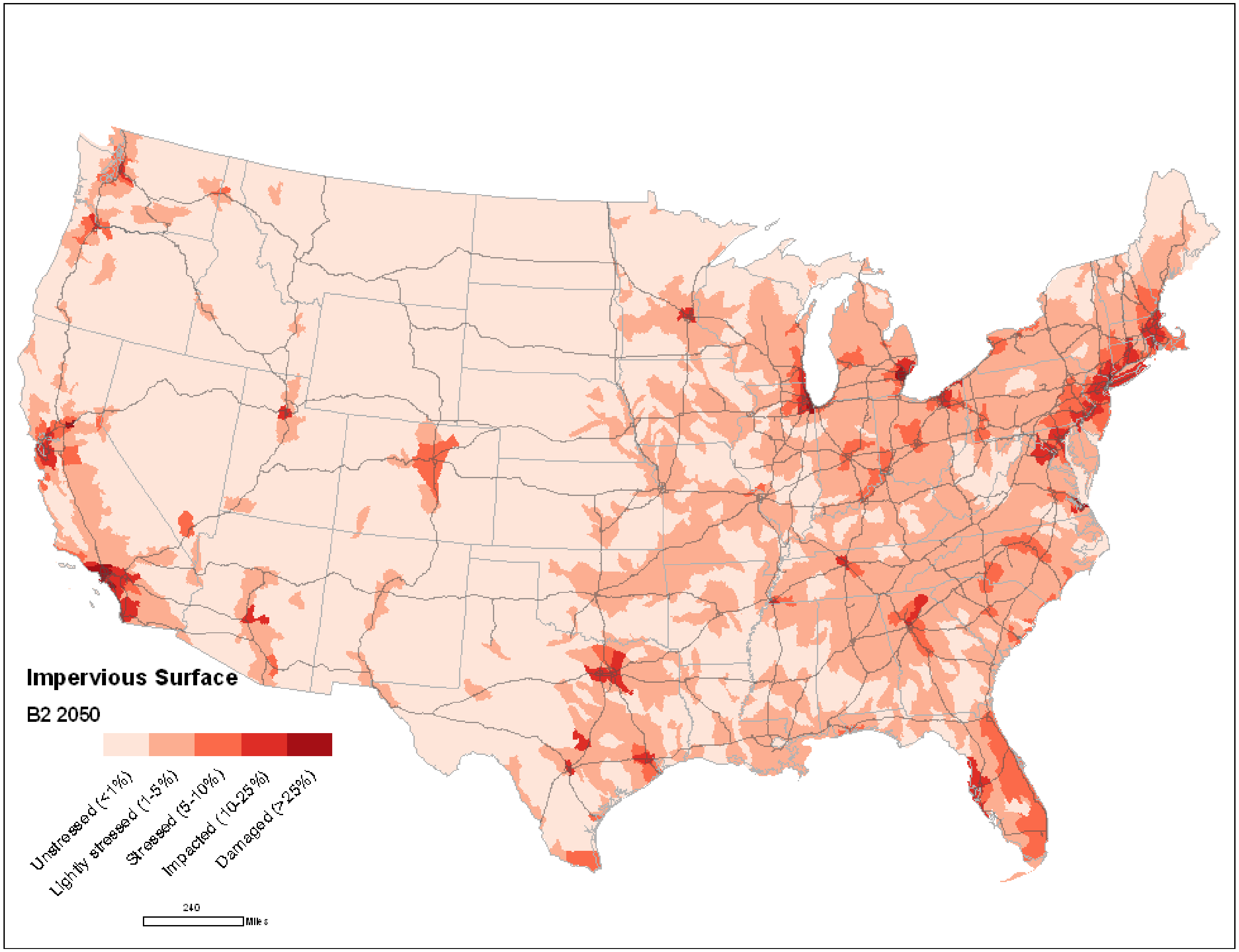


Figure 5-25: 2050 Impervious Surface, B2 Storyline

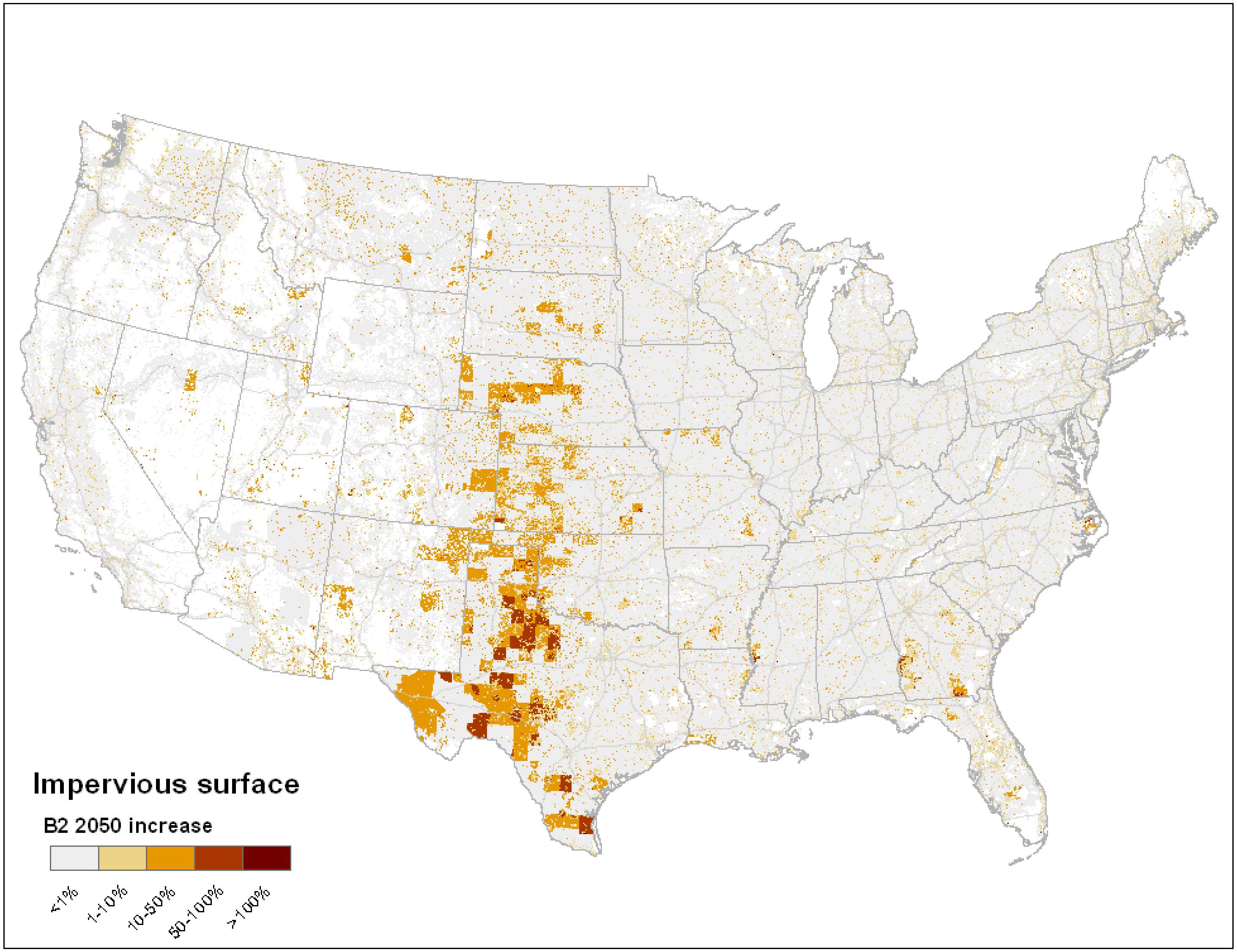


Figure 5-26: 2000-2050 Relative Change in Impervious Surface, B2 Storyline

5.4 OPTIONS FOR FUTURE STUDY

Impervious surface calculations and regional growth rates are just the first set of many possible analyses using results from this project. The housing density and population projections can inform modeling exercises that consider such diverse areas of research as traffic volumes, air quality, and water quality. Additionally, the demographic and housing allocation models can be further modified to incorporate climate change variables, incorporate additional factors affecting population change and housing patterns, or consider specific policy responses such as an emphasis on Smart Growth development patterns.

The current set of scenarios does not reflect the effects of climate change on development patterns. Some climate change effects, e.g., sea level rise, are likely to have significant impacts on development patterns. By integrating projected changes in sea level, projected population growth, and land development patterns, the resulting scenarios would provide valuable information to planners interested in coastal development, transportation infrastructure vulnerability, housing density, water quality (e.g., salt water intrusion), and other endpoints of concern. Such integration is a likely next step in the development of this project in order to begin to incorporate climate change variables into the models to facilitate more comprehensive assessments of the combined effects of climate change and land use change. Additional options for incorporating climate change variables include modifications to the gravity model to allow climate variables to change over time.

Another possible modification might examine changes in housing density regionally. Current housing density class ranges are static and the same throughout the country. This can be easily modified geographically, particularly west vs. east to explore different development patterns regionally, such as larger ranches or farms in the western U.S. (e.g., 10-40 acres exurban vs. ~2-10 acres exurban in the east). Also, the amount of developable land is currently assumed to be static, but that could be modified to remove additional protected lands. However, an approach would first need to be developed to identify where these specific lands may be protected and what the relationship to new housing allocations and densities might be.

The driving factor in SERGoM is population, so that forecasts are exogenous variables that are input to the model. Other population scenarios could also be modeled. In the current version of SERGoM housing units do not move across boundaries if an analytical unit is saturated. One reason for this is that it would require coupling the SERGoM model with the demographic model (that is, at each decade SERGoM would have to pass back to the ICLUS demographic model the actual number of people/households that were placed in a county). Rather, we endeavored to make the ICLUS demographic model more responsive to broader-scale (county and up) trends by using the amenity-based gravity model. A future refinement could be to couple the demographic and SERGoM models to ensure explicit distribution of people/houses. Another way to handle this challenge, if data were available and assumptions were reasonable, is to estimate the “build-out” (or carrying capacity) of a county based on zoning, for example.

Housing density currently is spread from one location to another (even across county or state analytical units) as a function of distance away (travel time) from urban core areas. Urban “core areas” are identified by a high housing density level (e.g., urban) of a size/population/area to approximate providing general services. In the ICLUS scenarios these parameters are specified by two user-defined values that do not vary across the study area (e.g., nationwide model). These could be easily changed so that they are spatially-explicit parameters, which would allow regional variation to occur. Also note that as growth continues through time, eventually some new urban core areas will "emerge", creating a new "hot spots" or concentrations of growth. Currently these new core areas do not feedback into the functional connectivity matrix that influences domestic migration in the demographic model.

Some options for future research include:

- *Identify new urban clusters.* Currently, new urban core areas are modeled by SERGoM in the spatial allocation process. An analysis of the detailed SERGoM outputs would help identify new or expanded urban clusters. Such new urban clusters would likely experience dramatic changes in air quality, water quality, and traffic. Identifying these growth areas could help improve regional analyses and planning.
- *Estimate traffic demands.* Vehicle miles traveled (VMT) can be estimated for each grid cell based on the number of housing units and available estimates on the number of automobile trips generated per day that vary based on housing density class. When combined with average trip lengths, these projections can be used to estimate fuel consumption, travel demand, and other factors. Combining the housing density maps with the road network layer of SERGoM can allow more sophisticated traffic analyses.
- *Model air quality changes.* The VMT outputs above, along with other layers of data about stationary emissions sources, can be used with existing air quality models to estimate projected air quality under the various scenarios.
- *Analyze effect of impervious surface on water quality.* The impervious surface analysis can be used to consider the quality of stormwater runoff and its impact on water quality in key watersheds. Groisman et al (2005) suggest that one potential impact of climate change is an increase in the intensity of individual storm events. Since these events are responsible for the majority of impacts to water quality from stormwater runoff, examining the possible extent of impervious surfaces become even more important given the anticipated impacts of climate change.
- *Develop alternative Smart Growth scenarios.* Alternative SERGoM runs could be used to project housing density under alternative development patterns that reflect Smart Growth goals. One example would be to model denser development along existing transportation infrastructure. The results could also be combined with some of the other suggested analyses to estimate the performance of such strategies. Another use would be to examine the amount of growth that could be accommodated in brown/greyfield sites, vs. greenfield sites.
- *Analyze effect of urban vs exurban growth on impervious surface thresholds.* Another interesting question to ask in the future would be the degree to which growth in urban/suburban vs. exurban classes is the main cause for watersheds to cross over a threshold (e.g., >5%) into the stressed impervious surface classification. It would also be interesting to explore the consequences of assumptions about how population per housing unit would vary both between urban and rural areas, and through time.

6 DISCUSSION AND CONCLUSIONS

The IPCC emissions storylines were adapted to the U.S. by modifying Census demographic projections, by incorporating county-to-county connectivity and amenity variables, and by modifying the spatial growth pattern of housing. The resulting scenarios provide benchmarks for possible future housing density patterns. The comparison of our demographic projections at the county level with selected state estimates shows that our model is in the range of other projections, and therefore can be used to generate plausible population scenarios. The differences also underscore that there are many approaches that can generate scenarios, and that these approaches may use more detailed or finer-scale information. However, the EPA-ICLUS methodology does produce demographic results within the range projected by other efforts and is therefore useful in benchmarking scenarios within established GHG emissions scenarios.

The preliminary results presented in this report call attention to the expected spatial variability of land-use effects and their possible intersection with regional climate changes. For examples, population growth rates in the South and West may increase the vulnerability of these regions to water quantity and quality issues if precipitation decreases. This is one way that these land-use scenarios can facilitate integrated assessments of climate change and land-use change.

Our preliminary results also show differences in the impacts on various land-cover classes, which, along with increases in impervious surface cover, will translate to effects on air quality, human health, water quality, and ecosystems. Further assessments of these effects, including more detailed spatial analyses of which watersheds and regions may be more vulnerable to these changes; which wetland types and in which watersheds and regions may be more impacted by land conversion; and which regions may benefit more from policies and planning that includes Smart Growth development patters, will be important next steps. The explicit integration of climate change into the next phase of modeling will further facilitate these assessments.

In conclusion, the U.S.-adapted SRES scenarios produce a range of outcomes both in the demographic model of the EPA-ICLUS project and in the spatial allocation model. The range of population projections, housing densities, and impervious surface cover allows for a broad examination of trends and impacts to a variety of endpoints. The ICLUS methodology also allows for future modifications that can incorporate more explicit climate-change information, feedbacks to domestic migration patterns from emerging growth centers, and a variety of regional changes to housing densities and allocation preferences. The current outputs from the EPA-ICLUS project can be used in a variety of assessments that include effects on air quality, water quality, and any other endpoints that are modeled using either population or land use as an input.

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Appendix A - MAPS FOR ICLUS SCENARIOS

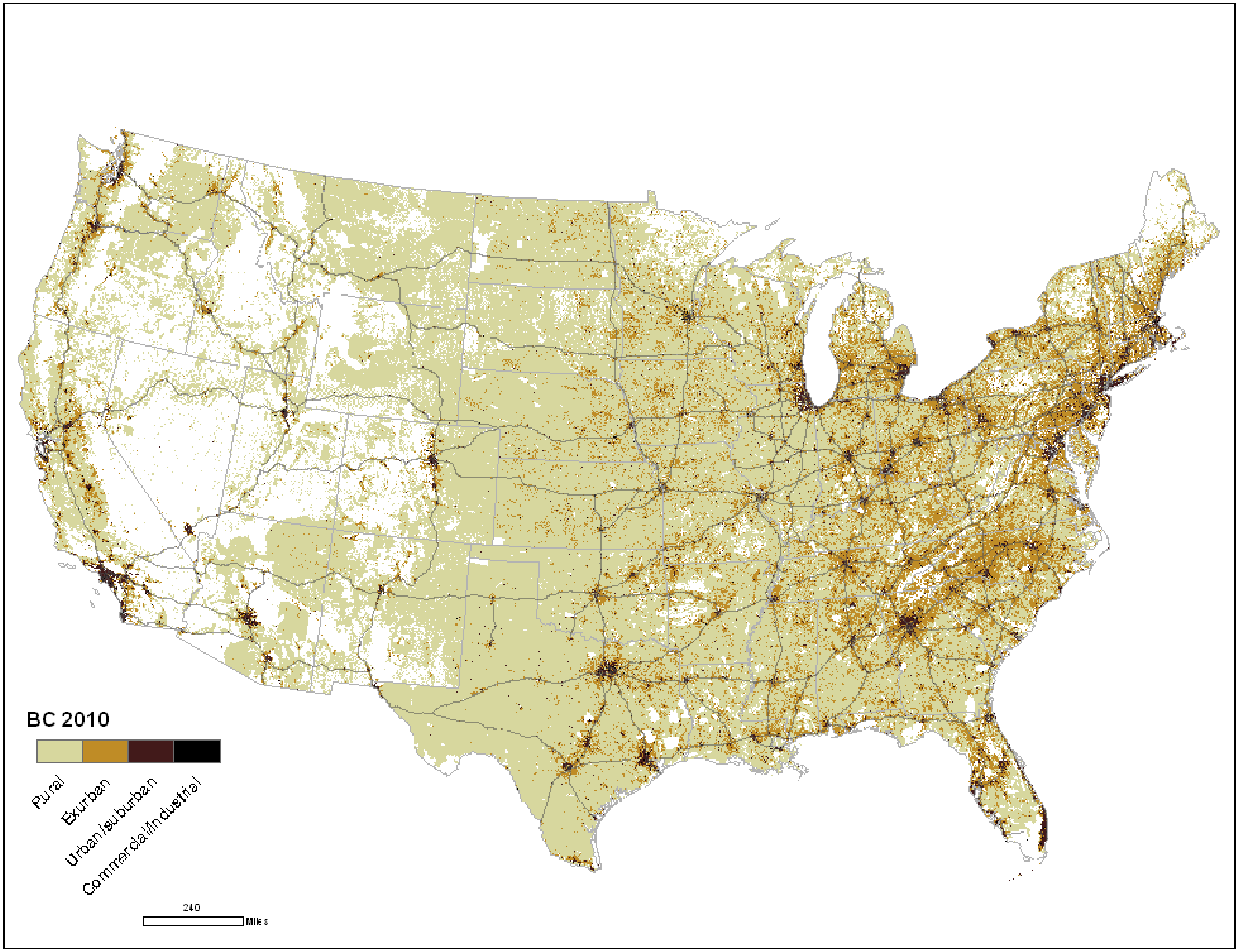

Figure A-1: Base Case, Year 2010 Housing Density Map

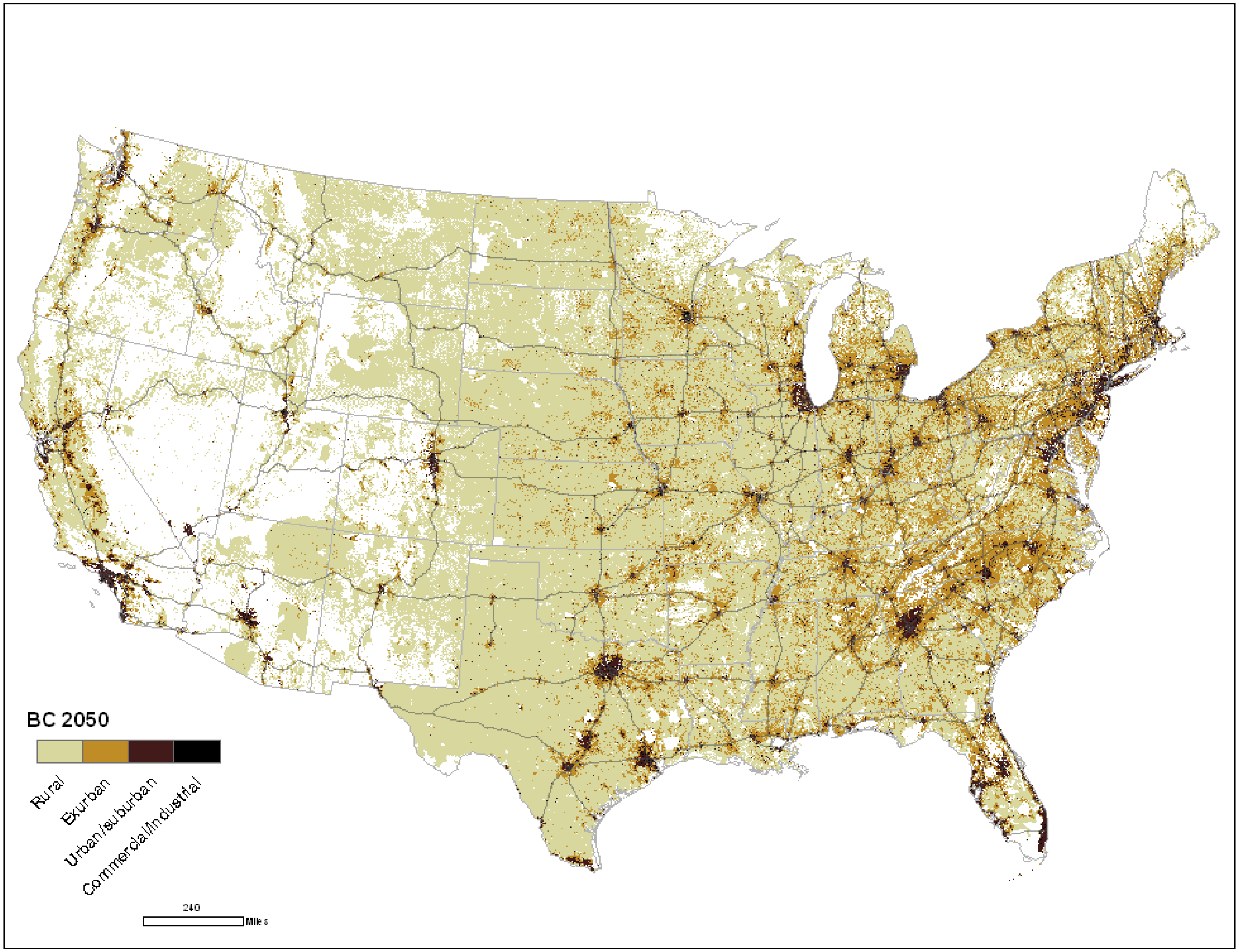

Figure A-2: Base Case Storyline, Year 2050 Housing Density Map

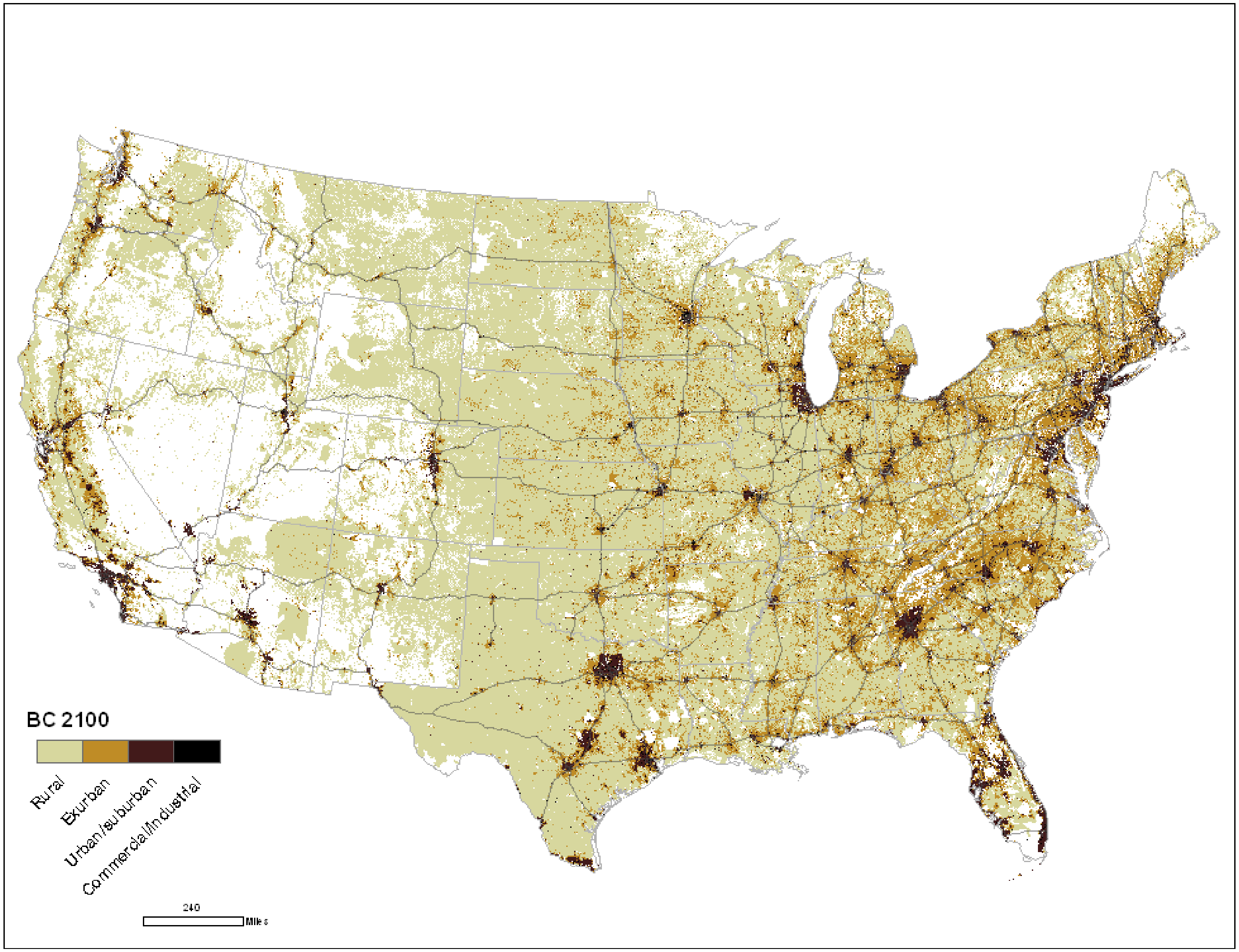

Figure A-3: Base Case, Year 2100 Housing Density Map

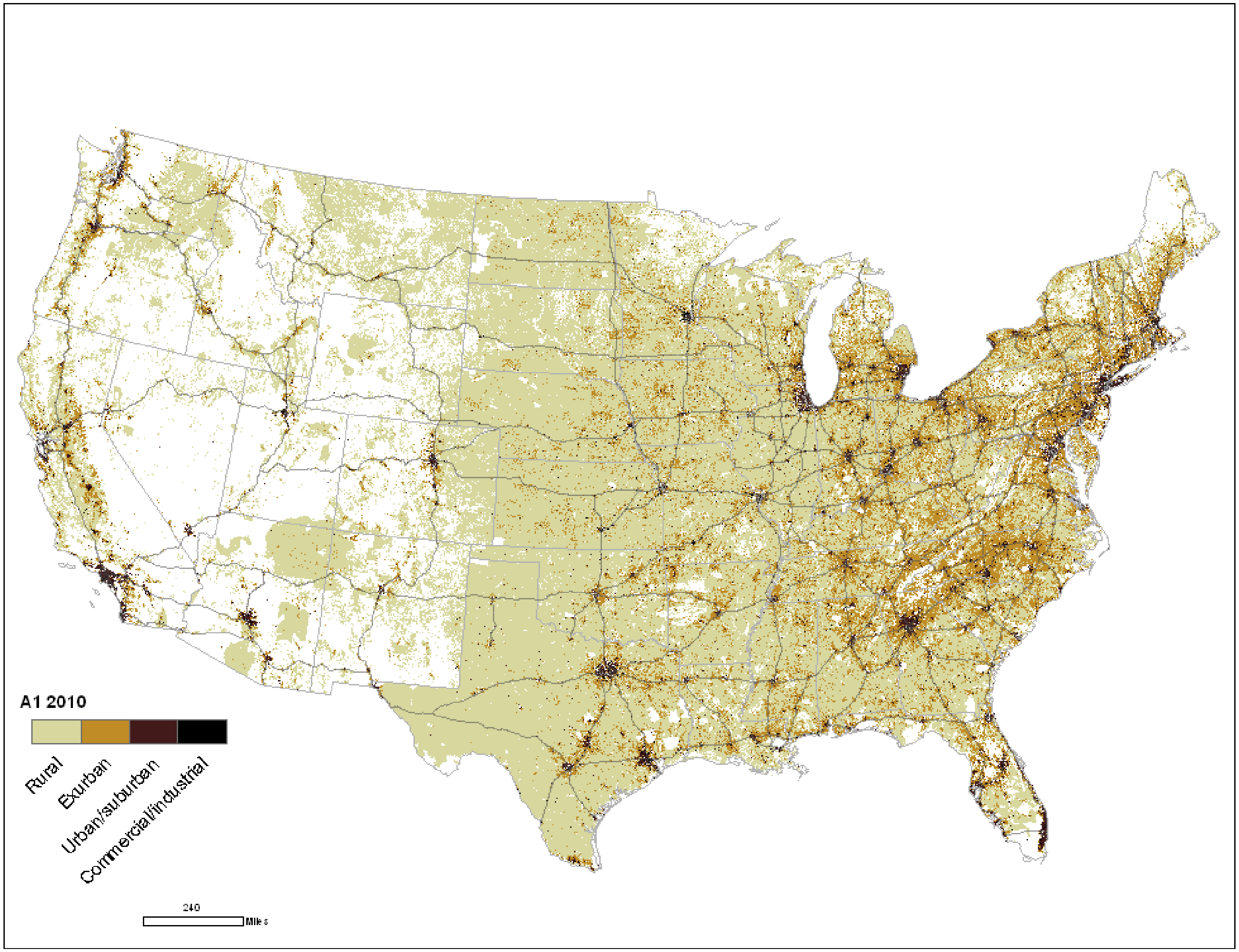

Figure A-4: A1 Storyline, Year 2010 Housing Density Map

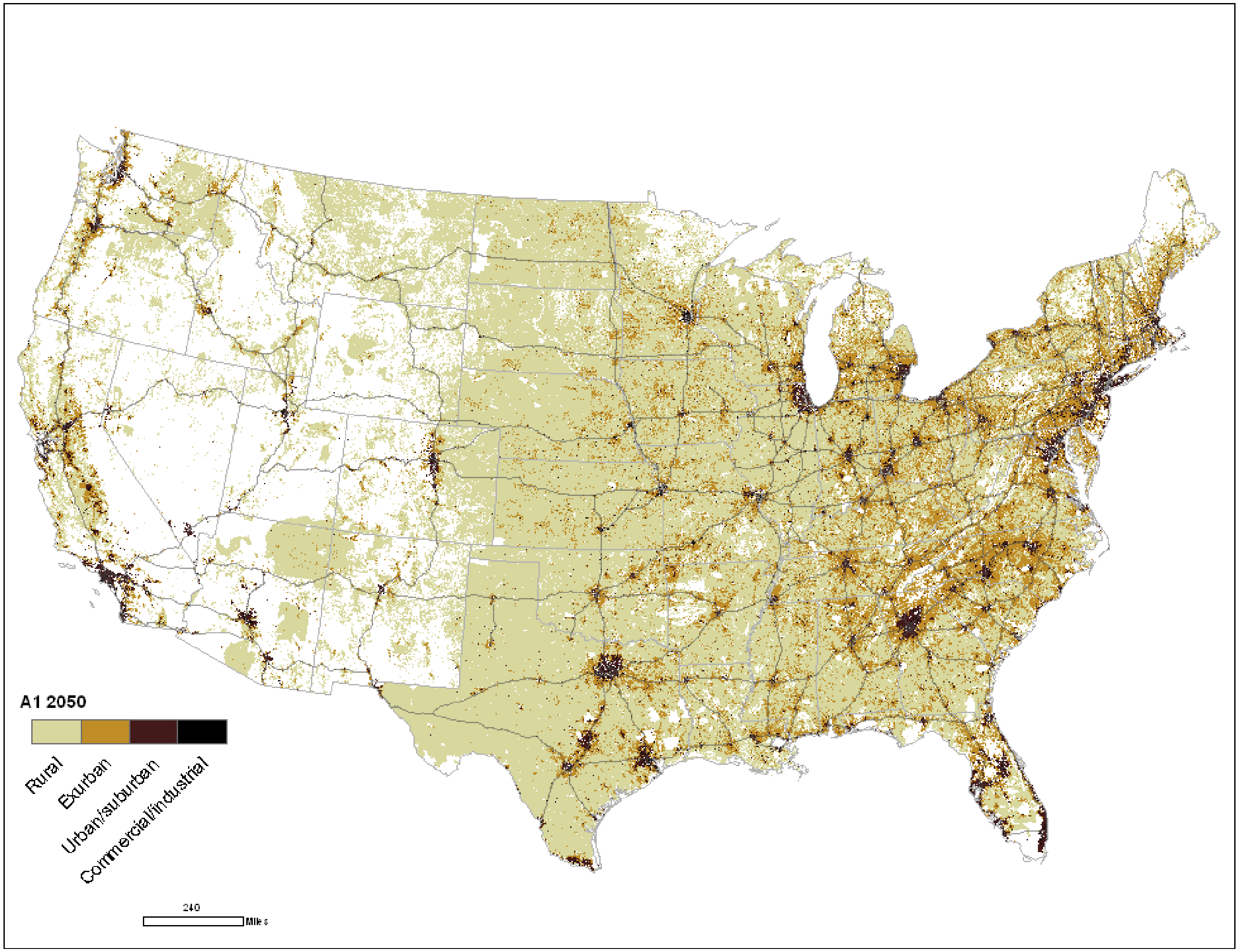

Figure A-5: A1 Storyline, Year 2050 Housing Density Map

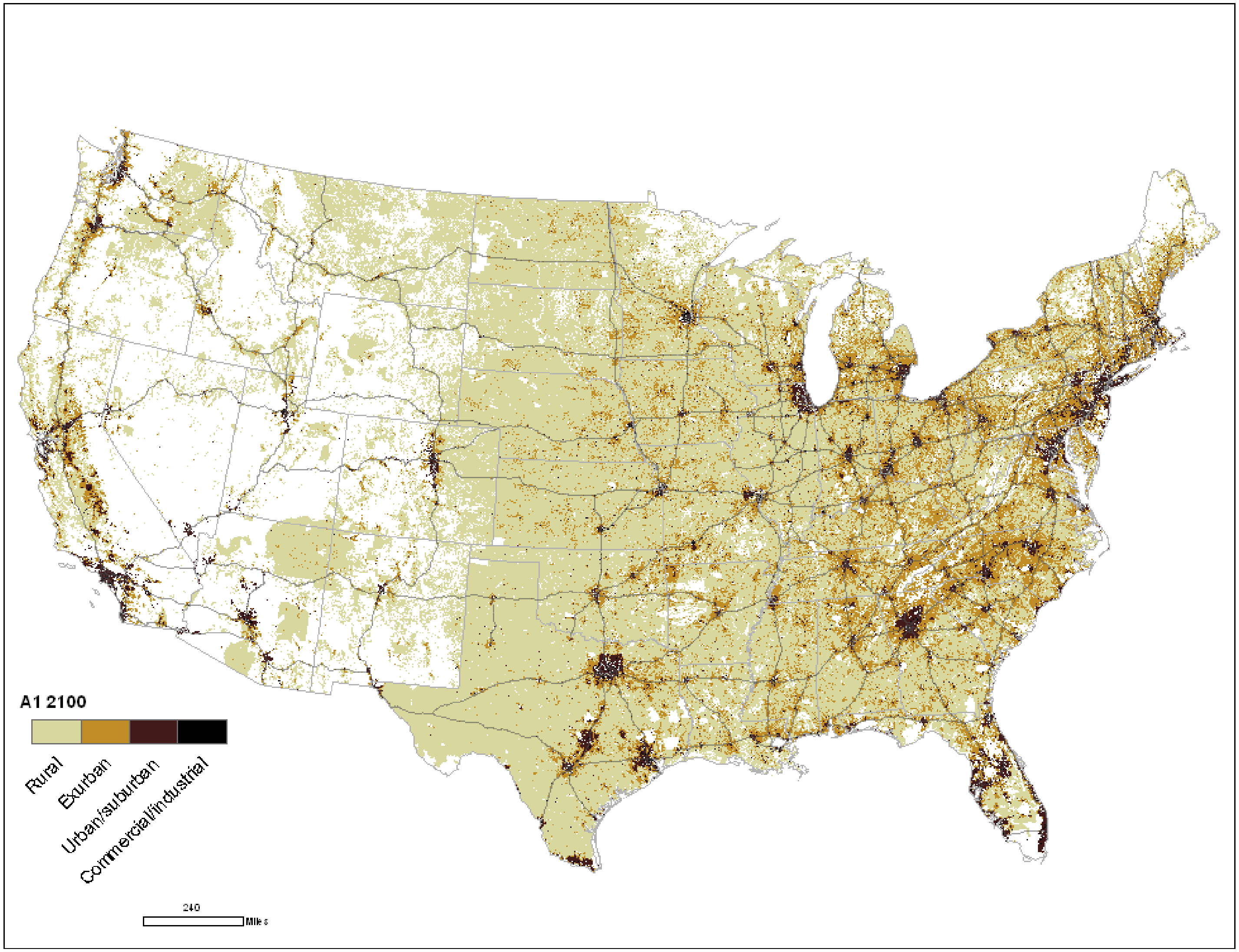

Figure A-6: A1 Storyline, Year 2100 Housing Density Map

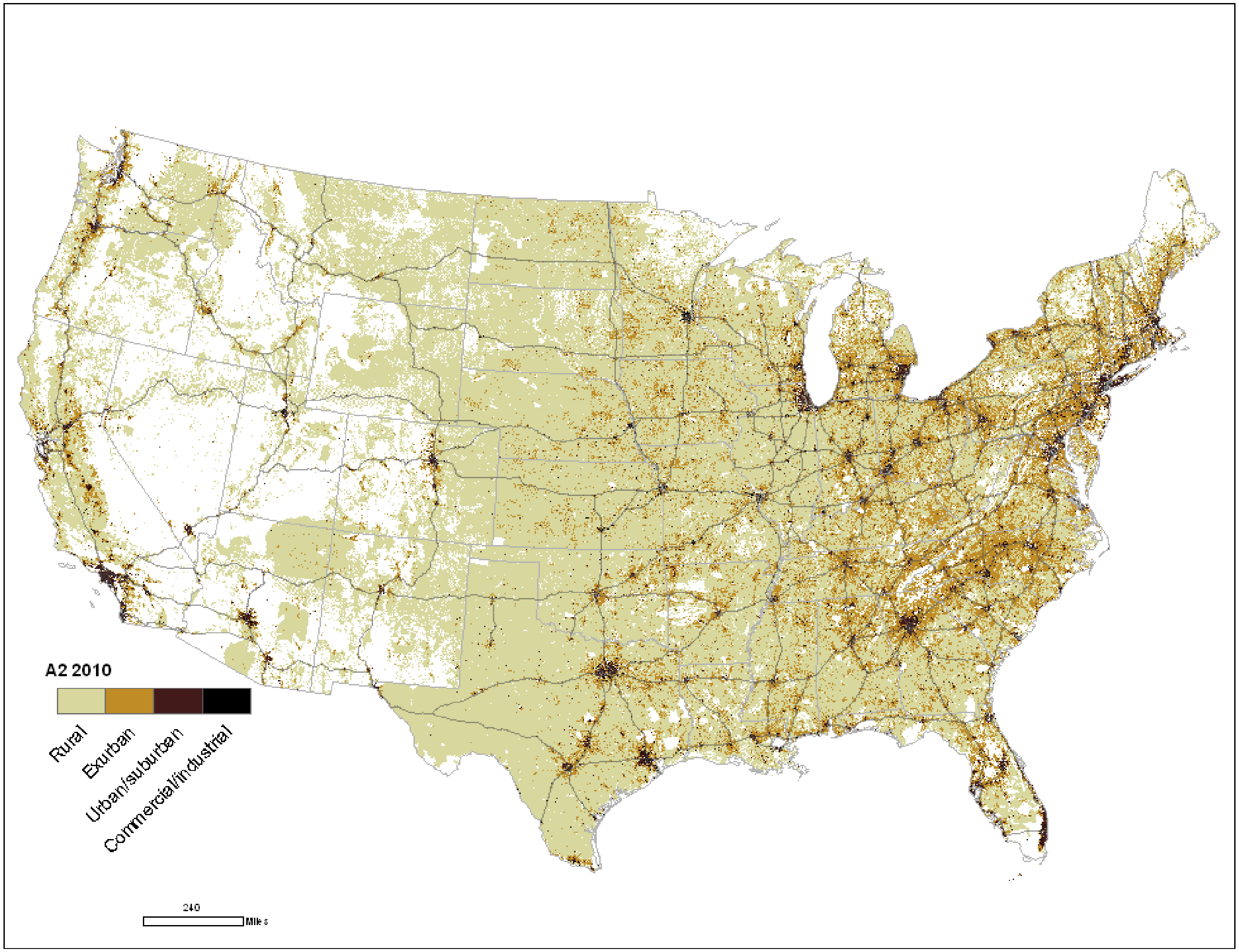

Figure A-7: A2 Storyline, Year 2010 Housing Density Map

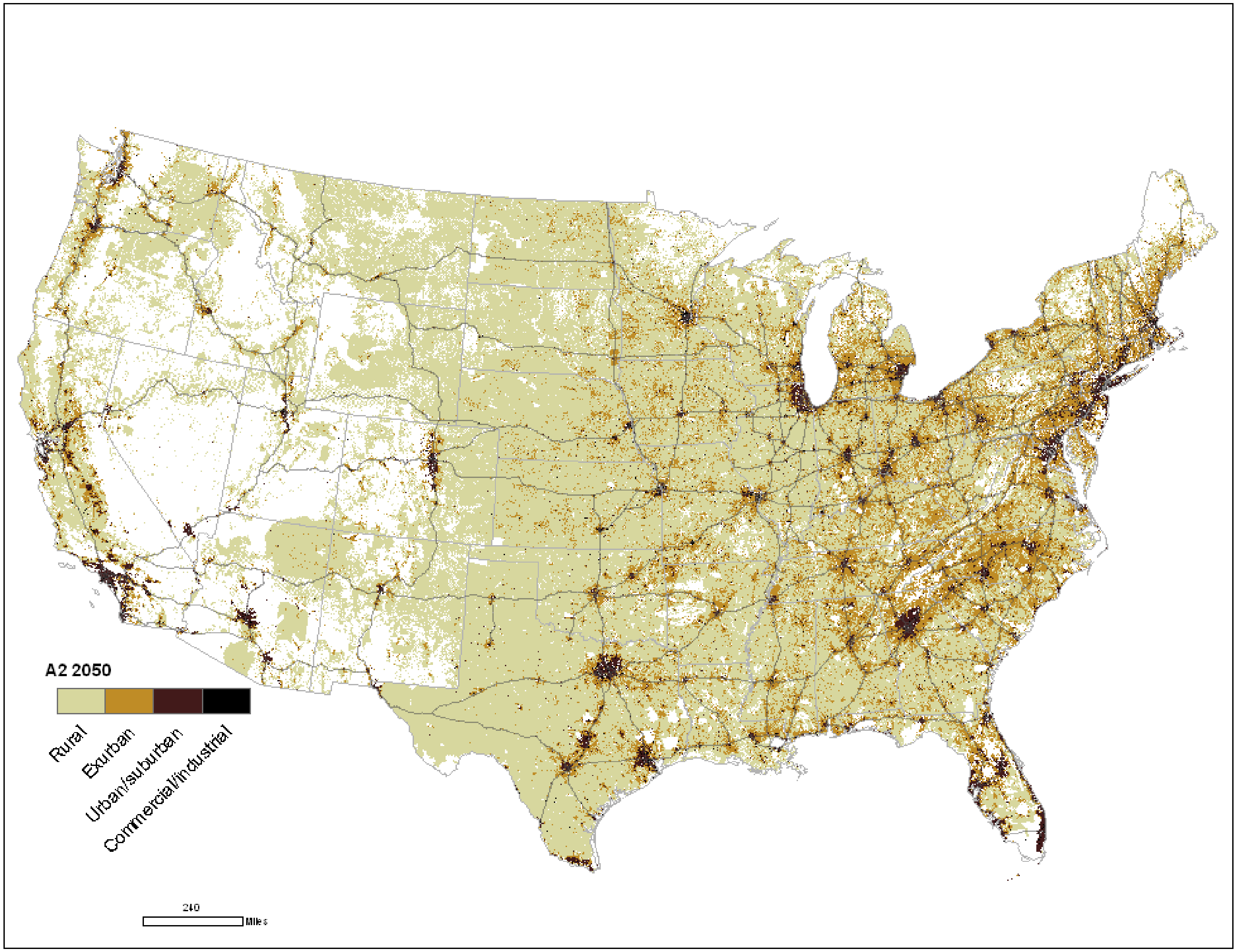

Figure A-8: A2 Storyline, Year 2050 Housing Density Map

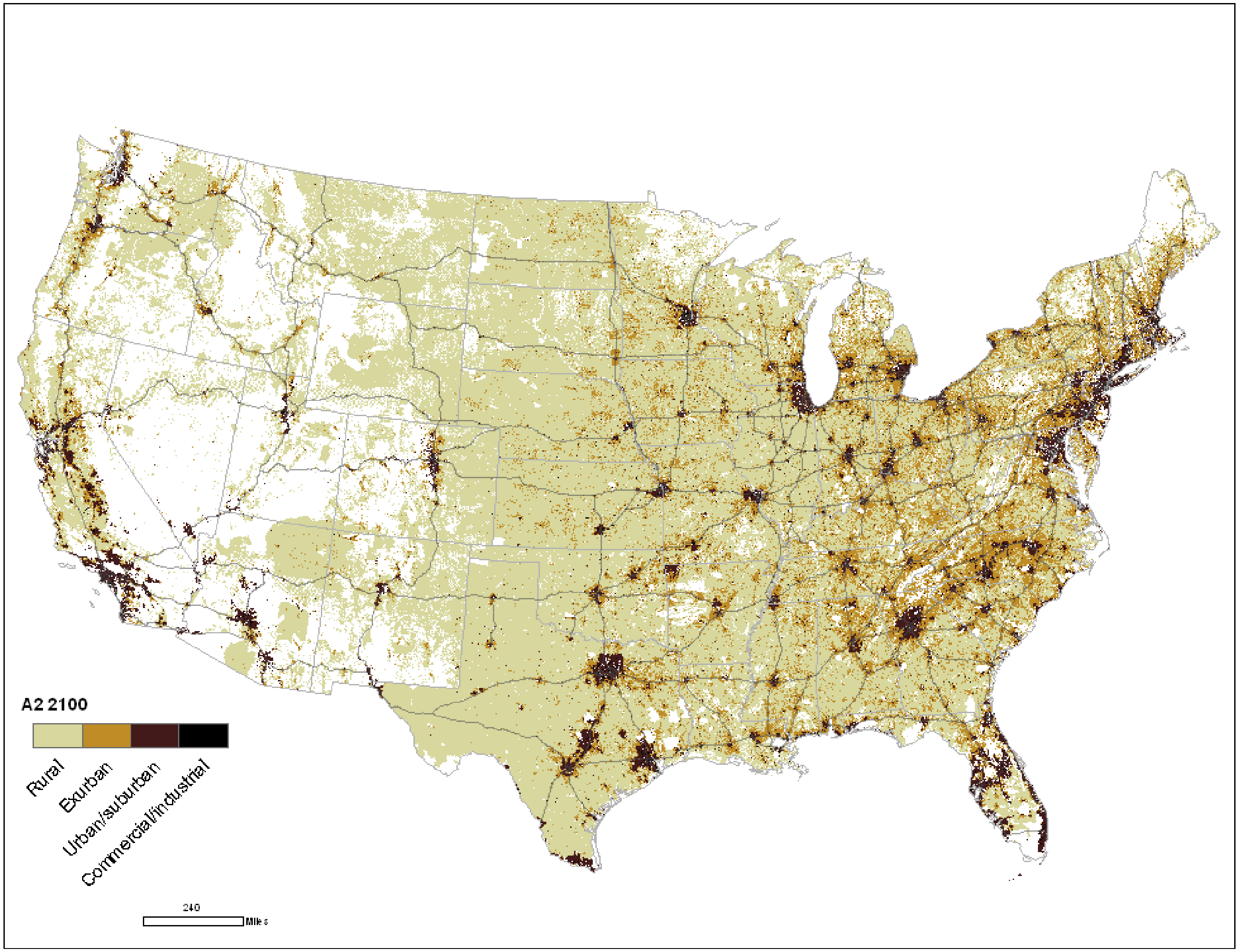

Figure A-9: A2 Storyline, Year 2100 Housing Density Map

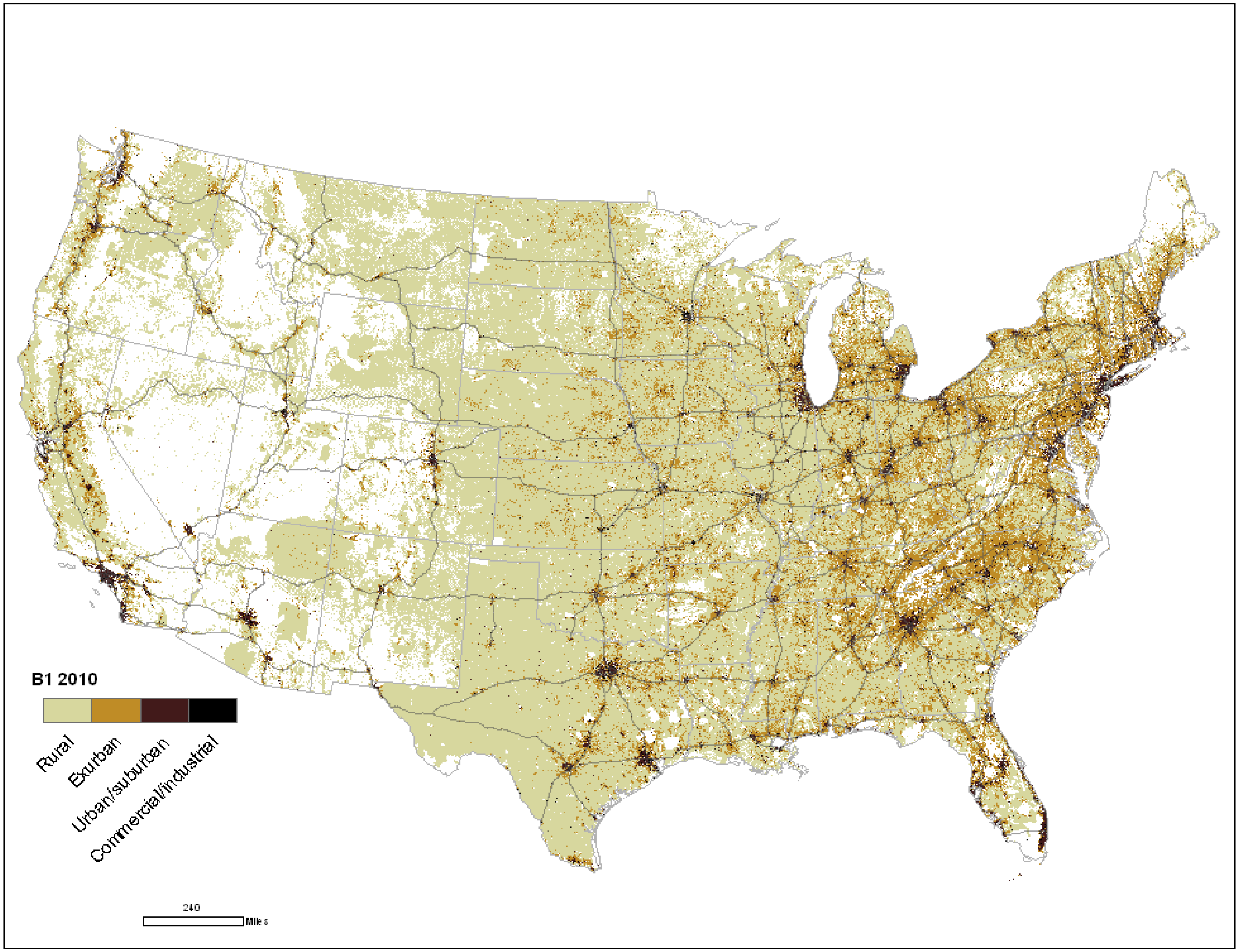

Figure A-10: B1 Storyline, Year 2010 Housing Density Map

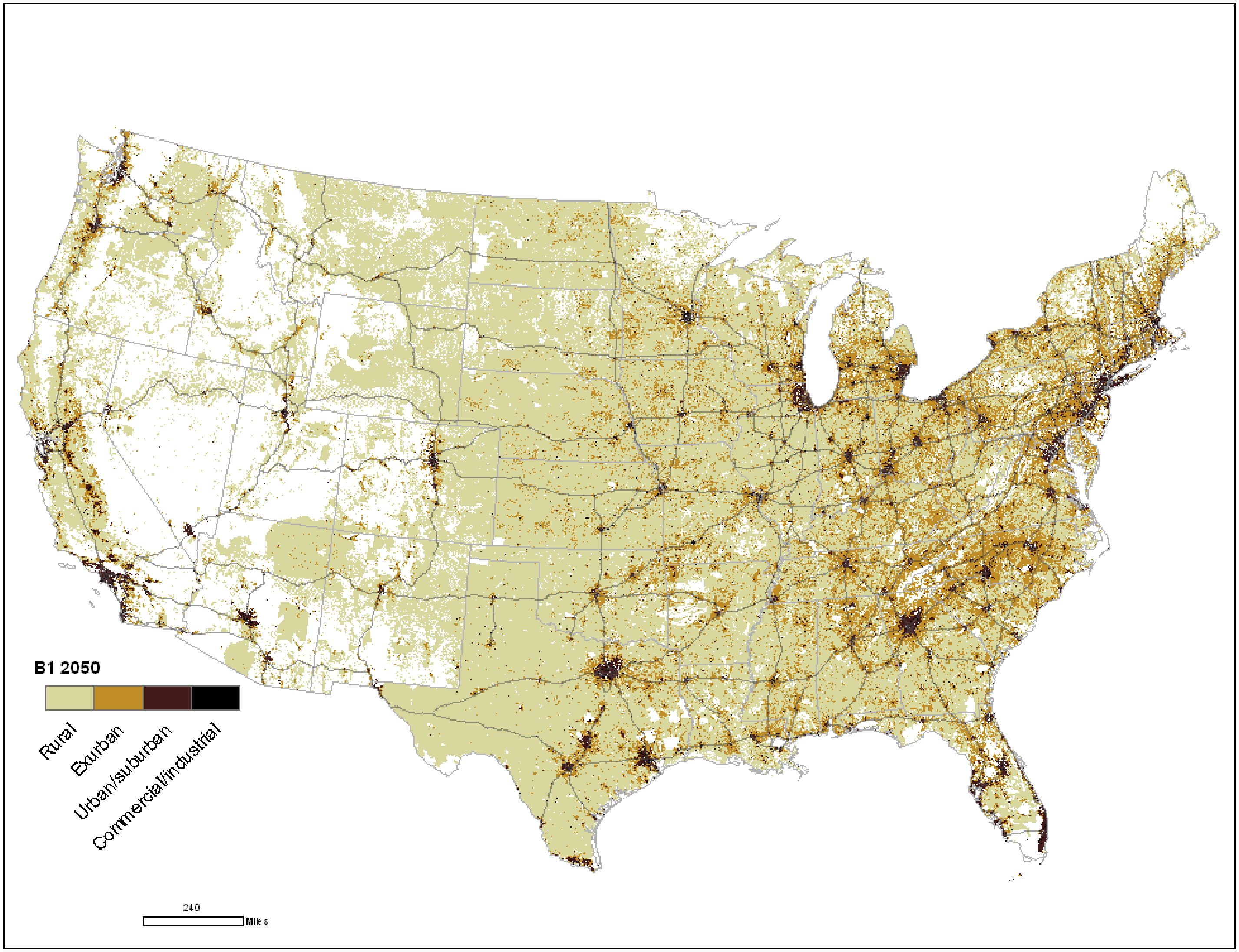

Figure A-11: B1 Storyline, Year 2050 Housing Density Map

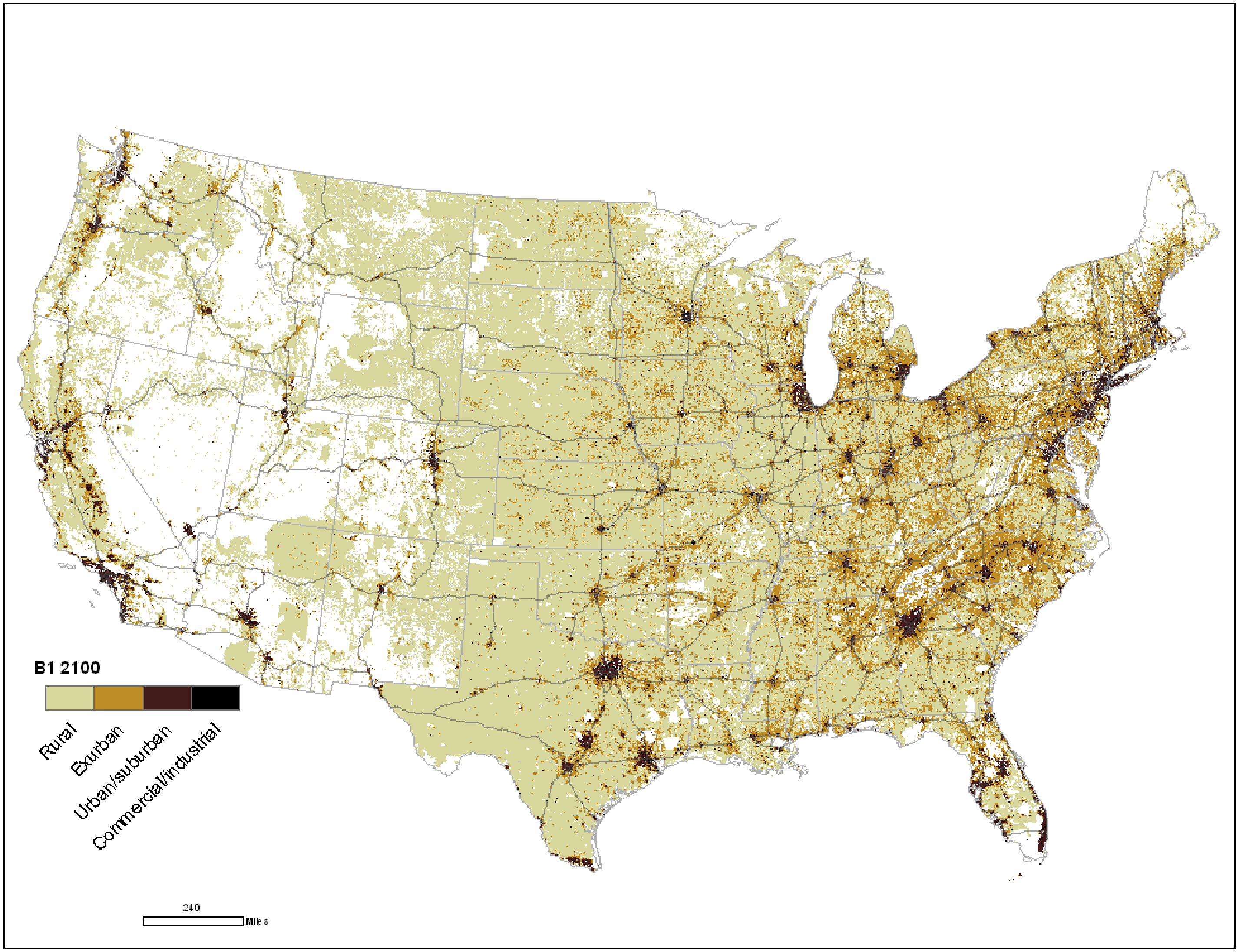

Figure A-12: B1 Storyline, Year 2100 Housing Density Map

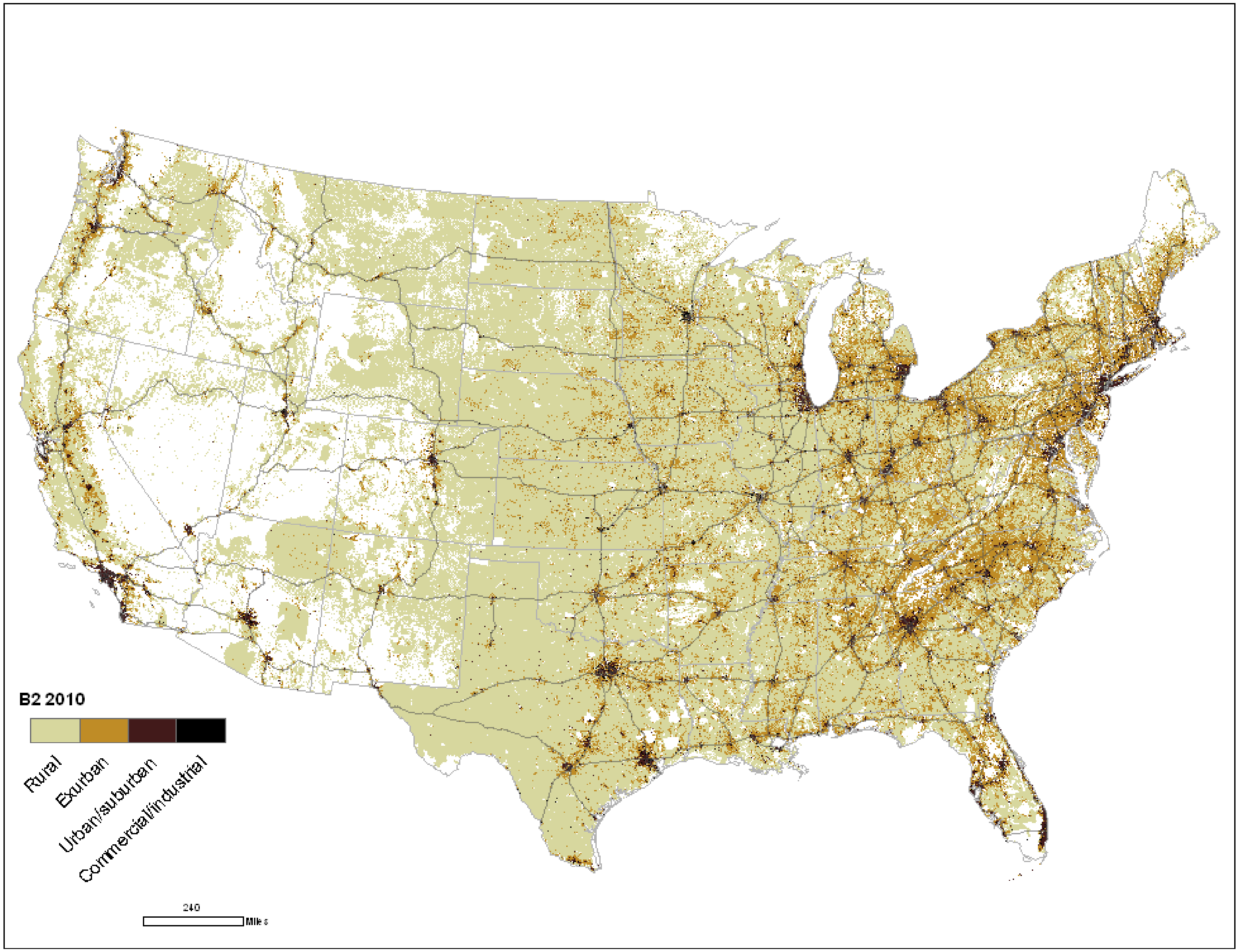

Figure A-13: B2 Storyline, Year 2010 Housing Density Map

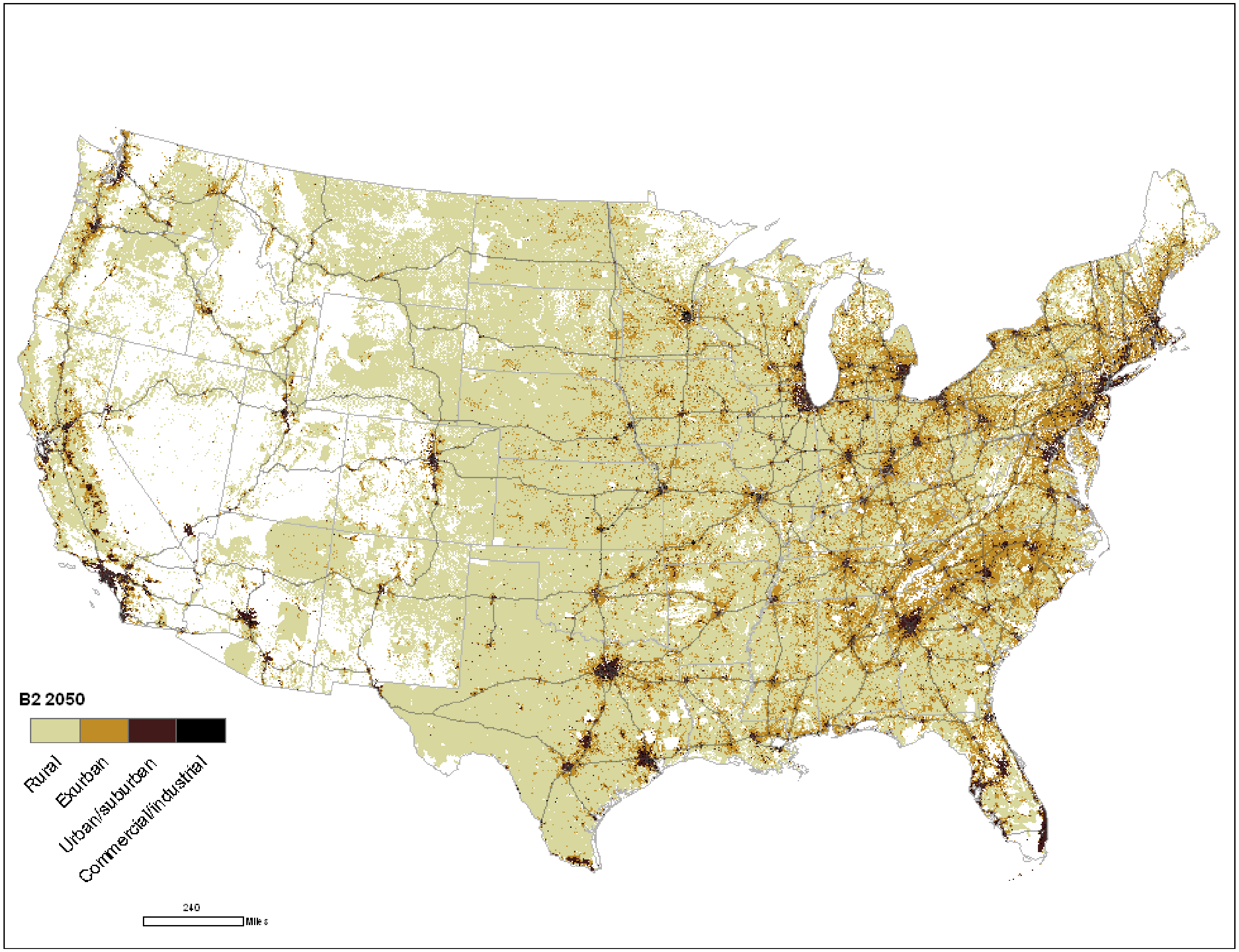

Figure A-14: B2 Storyline, Year 2050 Housing Density Map

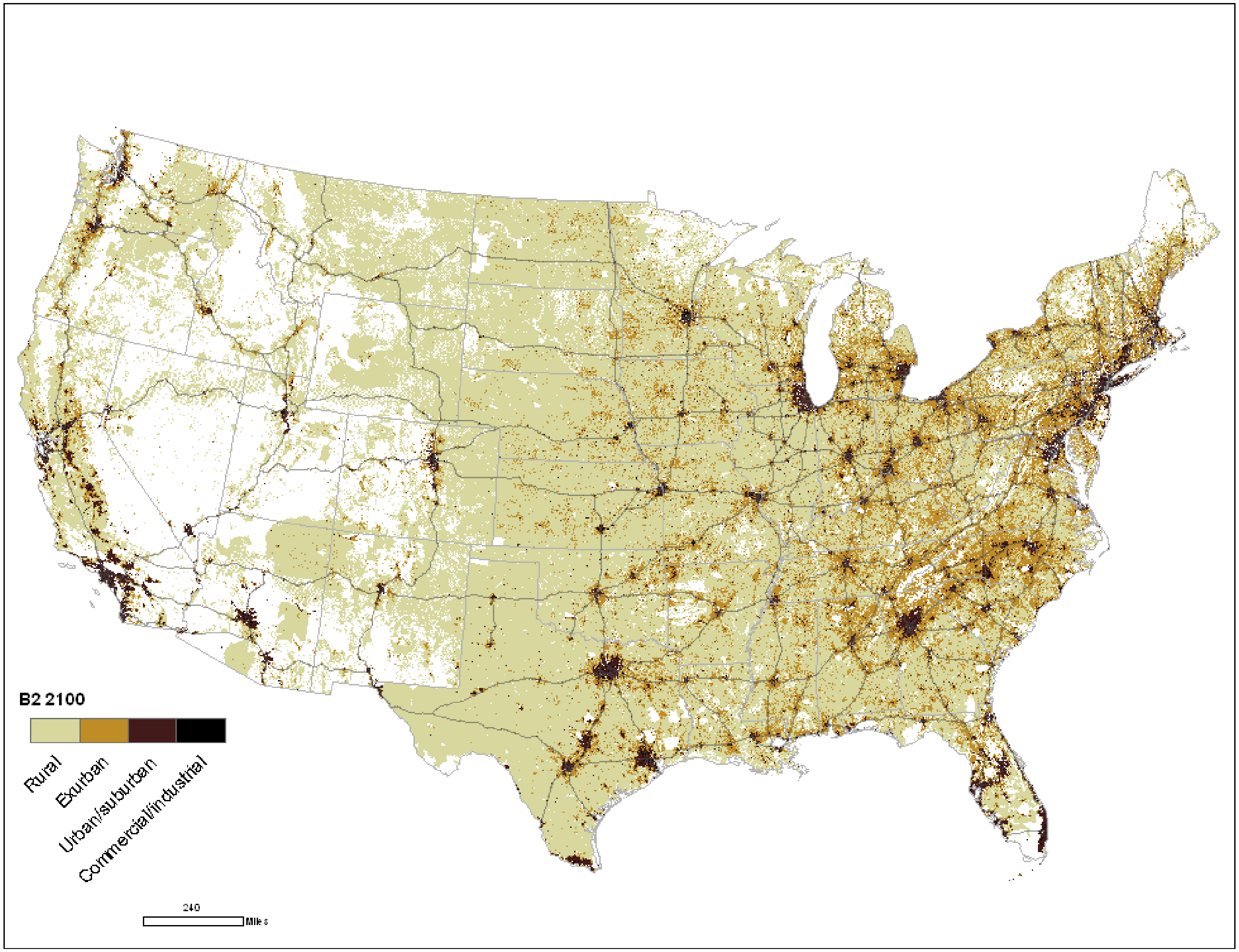

Figure A-15: B2 Storyline, Year 2100 Housing Density Map

Appendix B - Demographic Model Sensitivity Testing

In order to explore the demographic model's response to changes to its inputs and a variety of potential scenarios, we ran a series of sensitivity tests that paid particular attention to the behavior of the gravity model. These tests were used to improve the model, as well as to develop the downscaling approach to the SRES scenarios. We also compared the outputs for several states to county-level projections produced by those states. While this project could not expect to match the level of detail and state-specific methodology produced for each state's estimates, this did provide us with a useful benchmark for comparison with the ICLUS outputs.

The first set of testing involved the fertility rate. International migration was held at medium, while domestic migration was set to zero, since we were interested only in looking at total national population at this time. The model was then run using the low, medium, and high fertility rate scenarios provided by the U.S. Census Bureau. Figure B-1 below compares the impact of the fertility rate scenarios on national population. Under these settings, low fertility predicts a mid-century peak in population followed by a small decline, with the medium and high scenarios result in steadily rising population.

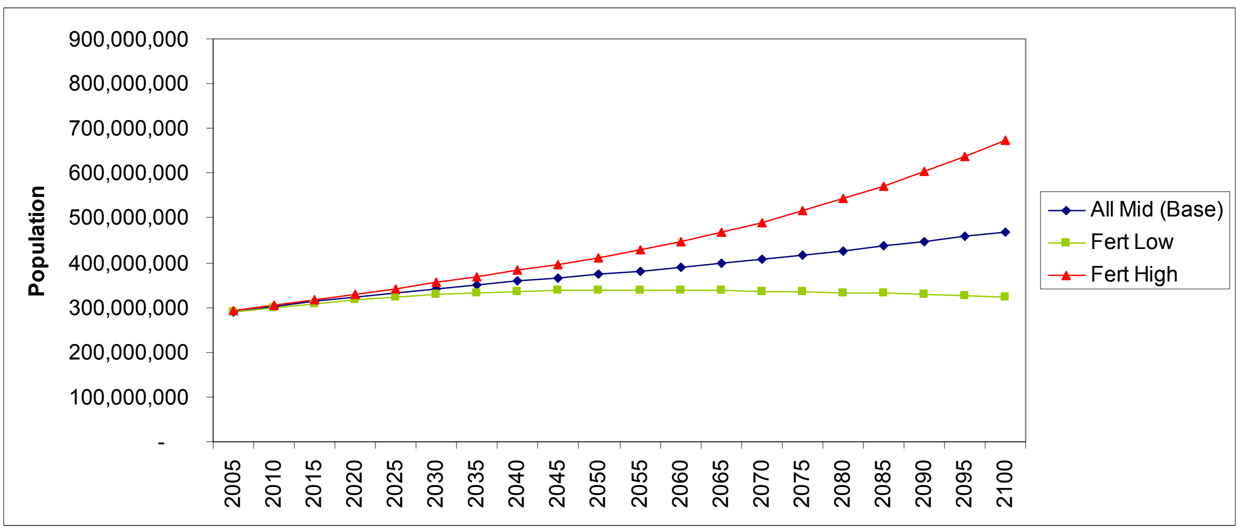

Figure B-1: Effect of fertility rate on national population

Next, we considered the impact of international migration on total population. This time, fertility was held constant at medium and domestic migration was set to zero. The model was run using the low, medium, and high international migration scenarios provided by the U.S. Census Bureau. Figure B-2 below displays the results of these scenarios. All scenarios result in steadily rising national population, but since medium fertility produces a small steady increase in the population, this increase is at least partially due to fertility. Figure B-3, which presents a wider range of scenarios, shows that the combination of low fertility and low international migration presents the lowest possible population trajectory given our current inputs. In Figure B-3, the outputs for the base case and four SRES-compatible scenarios are presented, as well as the maximum and minimum scenarios (calculated using high fertility and high immigration, and low fertility and low immigration, respectively).

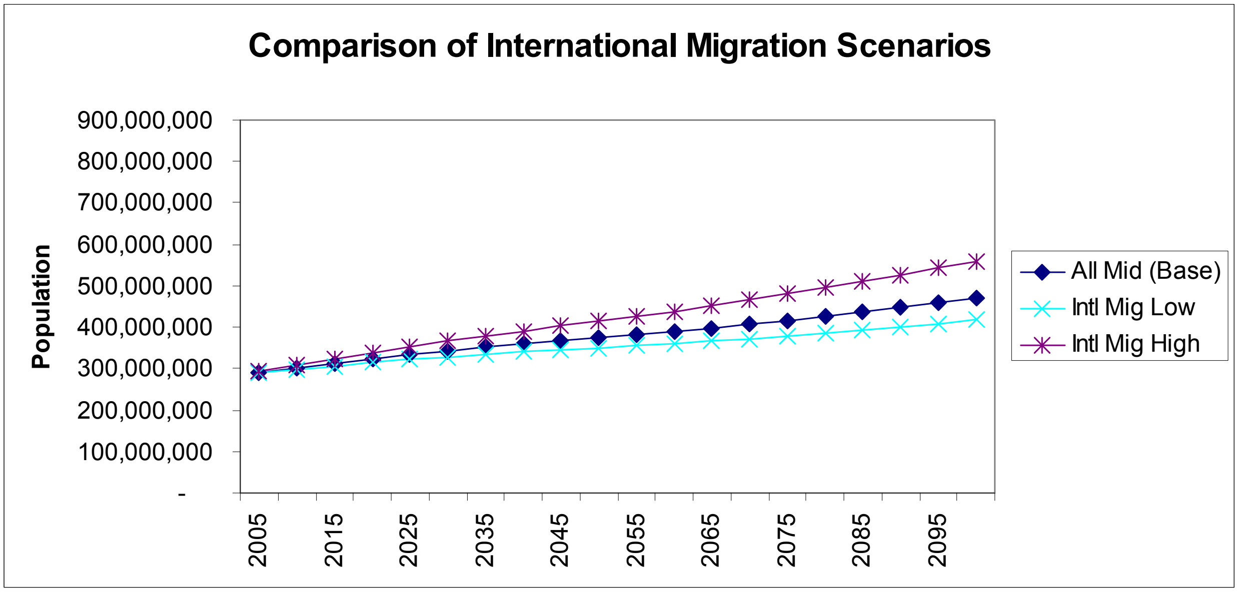

Figure B-2: Effect of international migration on national population

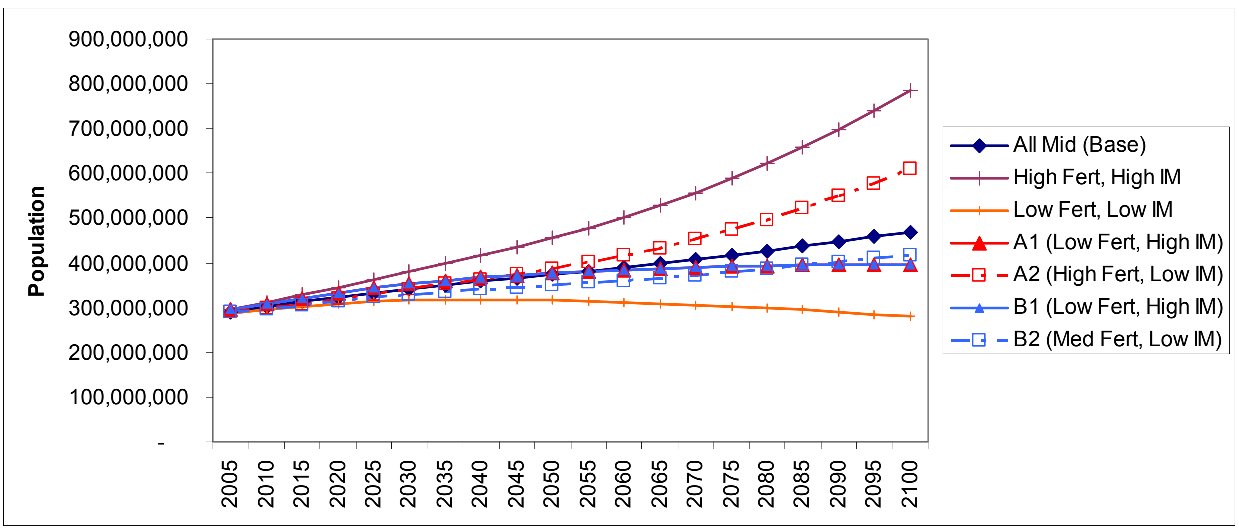

Figure B-3: Comparison of a broad range of scenarios

We also ran tests with the mortality rate, even though the only available data set for mortality rates was the Census middle case, and we elected to use this set in all SRES storylines. To explore the effect of mortality on national population, we used the Census middle case to create additional sets of mortality rates by adjusting the Census medium scenario by +/-1%, +/-1.5%, and +/-2% per decade so that by 2100, the high cases were 10, 15, and 20 percent higher than middle and the low cases was 10, 15, and 20 percent lower than middle, respectively. Each was run with fertility and international migration set to medium and domestic migration set to zero.

As Figure B-4 shows, the effect of even the strongest change was relatively small compared to changes in the other components of change.

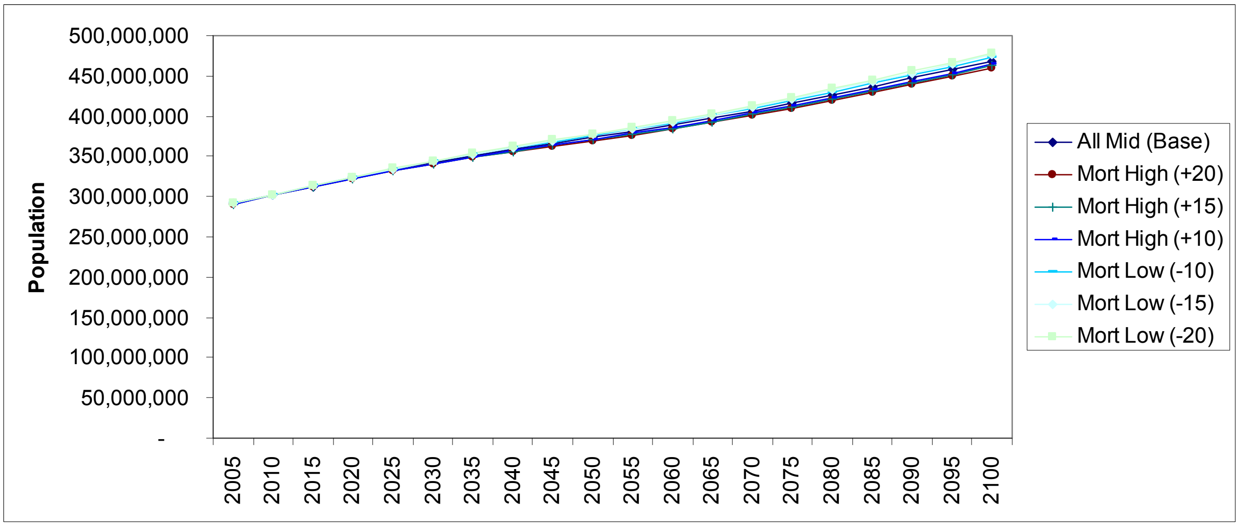

Figure B-4: Effect of mortality on national population

Due to the complexity of the gravity model, there were many possible adjustments that could be made to change the magnitude of domestic migration. The simplest change involved the introduction of a scaling factor. Under this adjustment, the gravity model calculations would proceed as normal, but all calculated migrations would be scaled upward or downward. For example, if the normal model estimated 10 migrations from county A to county B, with a 50% scaling factor to cut migrations in half, only 5 migrations would occur. Other approaches could involve adjusting the model coefficients and/or y-intercept. These approaches would allow more fine tuning by increasing the attraction of large cities or increasing the friction of distance, for example.

In this analysis, we ran the gravity model with the following nine alternative scenarios:

1) Scaling all migrations by 50%. This has the practical effect of reducing migrations.
2) Scaling all migrations by 150%. This has the practical effect of increasing migrations.
3) Increasing the production population coefficient by 20%. Since the production population coefficient is positive, this has the practical effect of increasing migrations.
4) Decreasing the production population coefficient by 20%. Since the production population coefficient is positive, this has the practical effect of decreasing migrations.
5) Increasing the attraction population coefficient by 20%. Since the attraction population coefficient is positive, this has the practical effect of increasing migrations.
6) Decreasing the attraction population coefficient by 20%. Since the attraction population coefficient is positive, this has the practical effect of increasing migrations.
7) Increasing the distance coefficient by 20%. Since the distance coefficient is negative, this has the practical effect of reducing migrations.

8) Decreasing the distance coefficient by 20%. Since the distance coefficient is negative, this has the practical effect of increasing migrations.

9) Increasing the 1980-2000 growth rate coefficient by 20%. Since the growth rate coefficient is positive, this has the practical effect of increasing migrations. We did not analyze a similar decrease because adding this coefficient was deemed to be a model improvement and the areas of concern so far have been in the rapidly growing counties.

Because domestic migration can only be considered from a county perspective, we compared the outputs from five states with state projections and the revised base case projections from October. The five states—California, Colorado, Florida, Minnesota, and New Jersey—were selected for their geographic diversity and availability of suitable county-based projections. We compared the 2030 state projections (2025 for New Jersey) with the ICLUS base case projections and with outputs from the scenario tests.

We used the outputs of these tests to help refine the demographic projections. For example, early runs showed that urban counties were growing much faster in the ICLUS projections than anticipated by state projections. This led to changes in how we modeled the attraction of migrants to urban centers (see Section 3.5.4). We also found that counties currently identified by the states as fast-growing areas did not grow as quickly in the ICLUS model as they did in the state projections. Since the ICLUS model was designed to be a relatively simple national model, it was not possible to include some of the specialized local details that the states included in their projections. Therefore, divergences from the state projections were expected. This observation did lead us to include 1980-2000 growth rates as a term in the migration model. As a result, those fast-growing areas continued their relatively rapid growth rates in our projections.

Appendix C - Statistical Relationship between Housing Density and Impervious Surface Cover

Background

The goal of this analysis was to develop a model to statistically relate housing density estimated by SERGoM to impervious surface cover. To do this, we examined how impervious surface from the National Land Cover Database (NLCD) (MRLC 2001) related to housing density and ancillary variables including transportation (highways, secondary, local roads), and neighborhood density of urban/built-up land uses. Statistical relationships were developed by using regression tree models. We also investigated other regression-based approaches that estimate imperviousness from land cover (e.g., NLCD) and/or population data. We felt these were limited or not appropriate for our purposes primarily because they use population data rather than housing data, and because population is tied to primary residence, they underestimate the actual landscape effects of housing units. We also explored adding the locations of commercial/industrial land use from NLCD 2001 to the impervious surface estimates for housing density because they are likely to have very high impervious surface levels as well.

Methods

We downloaded the Percent Urban Imperviousness (PUI) dataset from the MRLC Consortium website.[1] The PUI dataset is produced using a Categorical Regression Tree that includes satellite imagery and roads (Homer et al. 2004). We aggregated the 30 m resolution to roughly 1 km^2 resolution (990 m) to compute the average PUI for each 1 km^2 cell. We then resampled the average PUI at 0.98 km^2 cell to 1 km^2 using bilinear interpolation. The 1 km^2 resolution is a commonly used resolution to develop national estimates of imperviousness (e.g., Elvidge et al. 2004).

We aggregated the housing density estimates for the year 2000 from the SERGoM model (Theobald 2005) from 1 ha to 1 km^2 resolution. This provided us with the average housing density (HD) for each 1 km^2. We generated a sample of 200,000 random points (generated in a spatially-balanced way using the Reversed Recursive-Quadrant Randomized Raster algorithm; Theobald et al. 2007) from across the coterminous US. We extracted the values of both the PUI and HD at each point, and used a Categorical and Regression Tree model to develop a regression equation to develop a relationship between PUI and HD.

We generated the percent impervious surface for current housing density using the *tree* function in S-Plus (Insightful Corp, Seattle, Washington). See Brieman et al. (1984) for a review of categorical and regression tree methods. The resulting regression tree (Figure C-1) was then evaluated using a cross validation (*cv.tree* S-Plus function) technique to investigate if the tree over-fitted the data. As the number of terminal nodes increase, the overall deviance decreases (Figure C-2), indicating that the original tree is not over-fitting the data. If the deviance were to start increasing after some point within the cross validation analysis, then the tree would need to be pruned to a size that would minimize deviance. Because this was not the case, we decided to develop the percent impervious surface with the original tree. The large tree size (58 nodes) can

[1] www.mrlc.gov; accessed 12 February 2007

be explained best by the relatively poor non-parametric relationship between PUI and HD (R^2 = 0.38), meaning that there was not a simple, linear fit, as shown in Figure C-3.

The model resulted in a Residual Mean Deviance (which is the sum of the square differences between the actual values and the predicted values divided by the sample size) of 4.671. This is equivalent to the standard error in linear regression, which is the spread of error (in impervious units) for a given observation. The distribution of the residuals (error associated with the impervious surface observations) has a minimum value of -62.35, a mean of -1.132e-14 (about 0), and a max value of 89.5. This distribution was not unexpected because there are areas where impervious values (independent variable) had values of 0 but have positive values of housing density (dependent, response variable). Figure C-1 shows the decision backbone of the full regression tree with the length of a limb indicating deviance. The top ten nodes within the tree minimized deviance the most, with the remaining nodes making small adjustments for non-parametric small grain instances. Figure C-4 shows the top ten nodes within the full regression tree and the housing density thresholds used to estimate percent impervious.

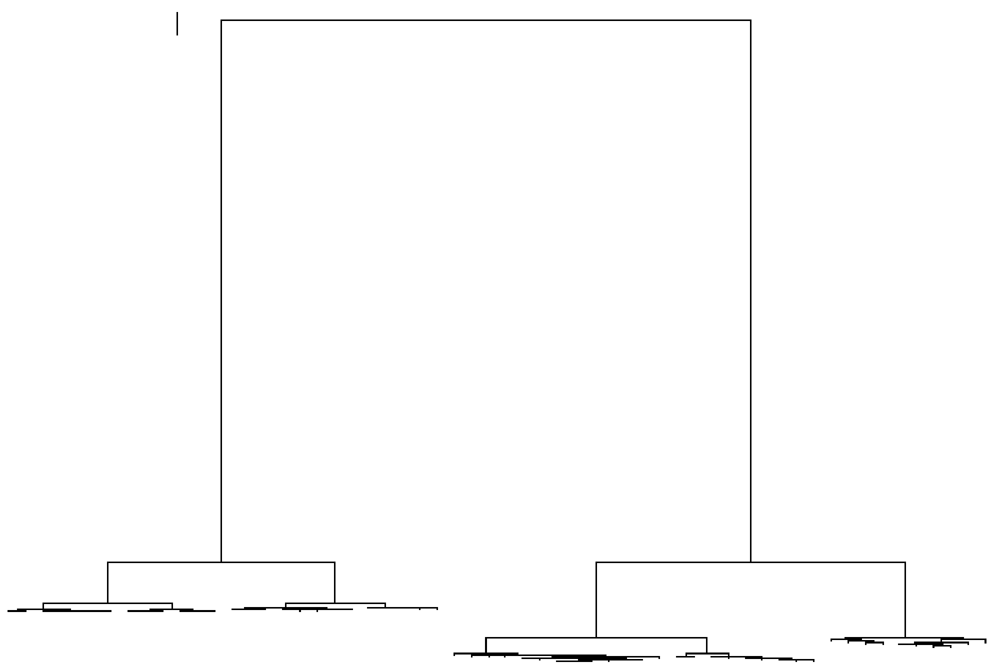

Figure C-1: Full regression tree backbone (58 terminal nodes) without labels

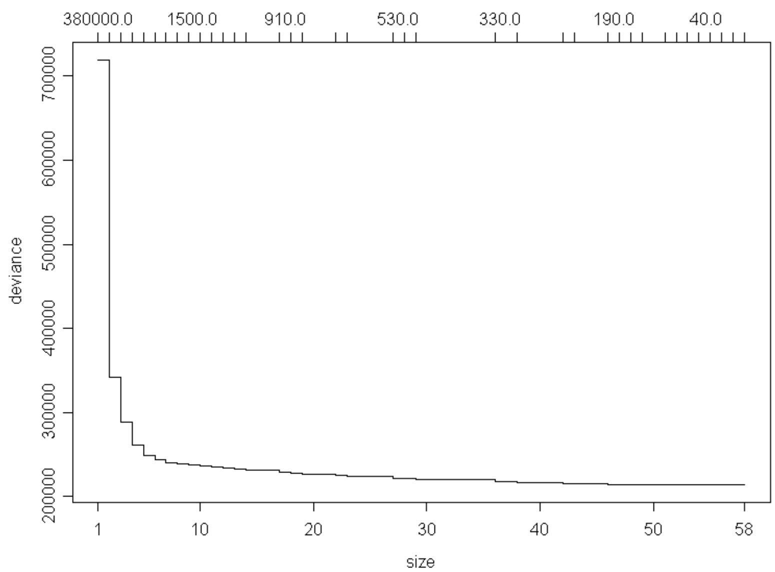

Figure C-2: Cross validation results for the full regression tree

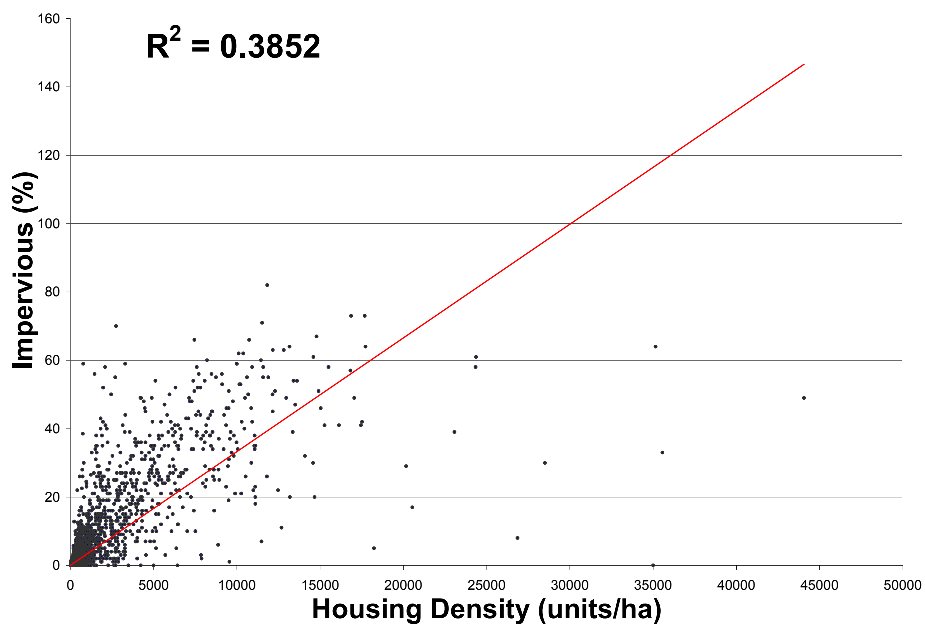

Figure C-3: The relationship between percent impervious and housing density

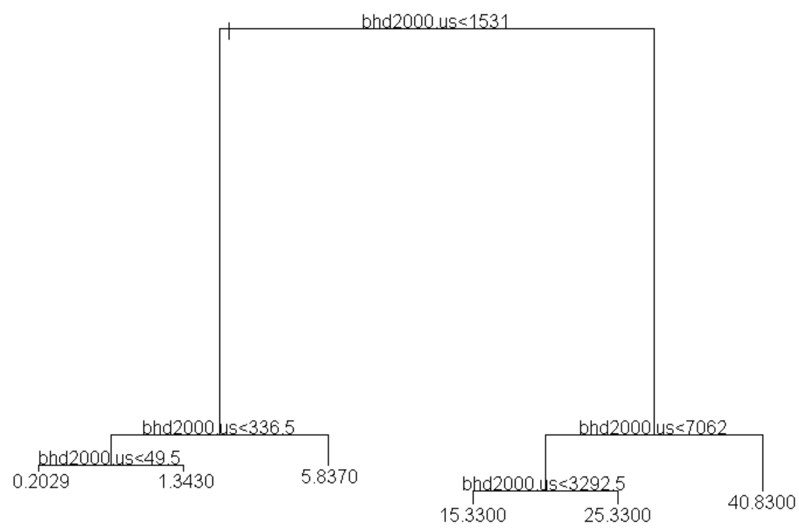

Figure C-4: Top ten terminal nodes within full regression tree with housing density labels and percent impervious estimates (terminal nodes)

We then converted the tree into a "con" (conditional) statement that can be input into ArcGIS as a Map Algebra statement. This statement then will then apply the regression model to generate a spatially-explicit map (note that HD is in units of housing units × 1000 per hectare; and *bhd* is the Block Housing Density raster dataset):

bhd_imperv = con(bhd < 1795.5, con(bhd < 354.5, con(bhd < 49.5, con(bhd < 1.5, con(bhd < 0.5, 0.1056, 0.2680), con(bhd < 12.5, 0.4103, con(bhd < 28.5, 0.5862, 0.7027))), con(bhd < 170.5, con(bhd < 107.5, con(bhd < 78.5, 0.9120, 1.1480), con(bhd < 147.5, 1.4070, 1.6870)), con(bhd < 292.5, con(bhd < 210.5, 2.0330, 2.4030), 3.0230))), con(bhd < 885.5, con(bhd < 542.5, con(bhd < 410.5, 3.6690, 4.3110), con(bhd < 687.5, 5.5750, con(bhd < 688.5, 11.7400, con(bhd < 865.5, con(bhd < 844.5, 6.5670, 7.9770), 5.3150)))), con(bhd < 1219.5, con(bhd < 1095.5, 7.9370, 9.5950), con(bhd < 1528.5, con(bhd < 1225.5, 15.3900, con(bhd < 1516, con(bhd < 1499.5, 10.5000, 15.5000), 7.4670)), 12.6500)))), con(bhd < 5528, con(bhd < 3109.5, con(bhd < 2501.5, con(bhd < 1799.5, 34.3900, con(bhd < 2084.5, 13.9300, con(bhd < 2117.5, 19.4400, 15.2300))), con(bhd < 2978.5, con(bhd < 2529.5, 20.6800, 17.2600), 19.5300)), con(bhd < 4083, con(bhd < 3114.5, 32.2000, con(bhd < 3136.5, 16.3600, con(bhd < 3983, con(bhd < 3562.5, 20.9700, 22.8700), 19.5300))), con(bhd < 4462.5, 24.4400, con(bhd < 5518.5, con(bhd < 5248.5, con(bhd < 4890, 28.0700, 25.0200), 28.6900), 17.8400)))), con(bhd < 11117, con(bhd < 6772.5, con(bhd < 5551.5, 39.6500, con(bhd < 6744.5, con(bhd < 6715, con(bhd < 6679.5, con(bhd < 6553.5, 29.7700, 32.5200), 23.5500), 39.1900), 22.3900)), con(bhd < 9423.5, con(bhd < 7552, 34.8700, con(bhd < 9184.5, con(bhd < 9146, 36.8200, 49.4300), 33.1500)), 39.6500)), con(bhd < 26946, con(bhd < 15496.5, 45.2100, 49.6600), 62.3500))))

RESULTS AND DISCUSSION

Using 2000 SERGoM v2 housing density, we estimated 88,887 km^2 of impervious surface (Figure C-5). (When we fill in areas with no housing density with NLCD 2001 urban imperviousness, the total impervious surface area increases to 92,639 km^2. That is, in many parts of central business districts within urban areas, there census data show no residential housing density, although the land there is quite built-up comprised of buildings, parking lots, etc.).

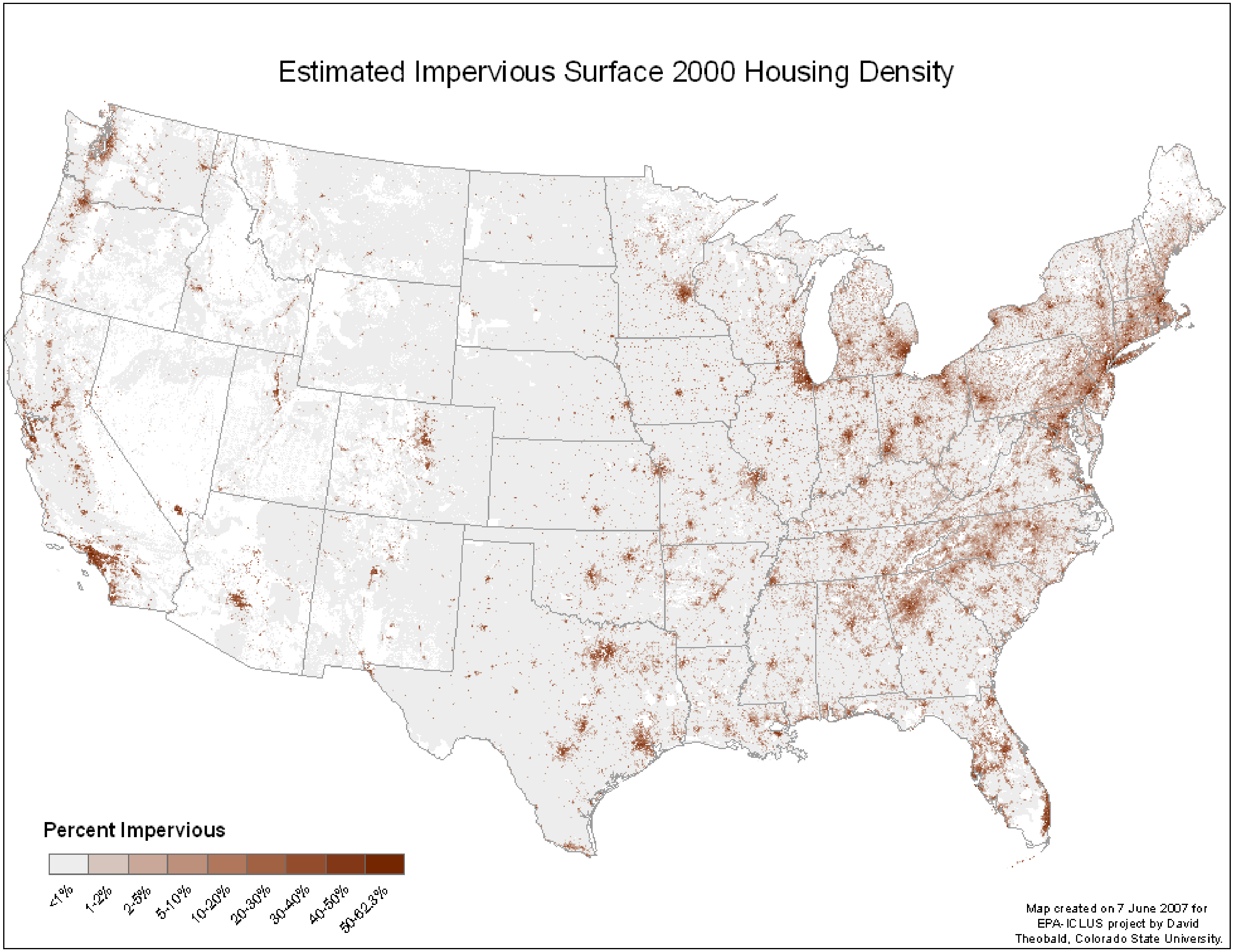

Figure C-5: Estimated National Impervious Surface, 2000

Using 2000 SERGoM v2 housing density, we estimated 88,887 km^2 of impervious surface. Our estimated extent of impervious surface (88,887 km^2) is fairly similar to other nationwide estimates. The NLCD 2001 Urban Imperviousness layer estimated an impervious surface of 95,746 km^2. The impervious correlation coefficient against a ground-truth dataset was .83, .89, .91 (Homer et al. 2004). Note that we were not able to develop "bracket" or "bookend" models that incorporate under- and over- estimations based on deviations around published error statistics because they were not provided for the NLCD 2001 impervious surface cover. Also, the precision of estimated PUI below 20% is believed to diminish so that low % PUI estimates from PUI were difficult to obtain (Homer et al. 2004).

Elvidge et al. (2004) estimated an impervious surface area of 113,260 km^2 (they actually report 112,610; +/-12,725 km^2) based on nighttime lights radiance, road density, and NLCD (1992) urban land cover classes. Thus, we were within 7% of NLCD 2001. Because SERGoM has NODATA values on public (non-developable) lands, there were some cases where impervious surface occurs on non-developable lands, such as military bases, airports, developed portions (visitor centers) of national parks, interstates, etc. When we filled in areas of the SERGoM-based impervious surface that had no housing density (mostly public lands) with NLCD 2001 urban imperviousness, the total impervious surface area increased slightly to 92,639 km^2. Thus, we recommend using this combination of datasets to better represent total impervious surface that gets at roads and commercial/industrial areas as well.

We also conducted an additional validation step by developing a simple linear regression of the SERGoM-based impervious surface against 80 data points generated from high-resolution aerial photography of 1 km^2 "chips" and used to generate the Elvidge et al. (2004) product. The resulting R^2 was 0.694. This result was better than expected, as the 80 data points were not randomly selected, rather purposively targeted to capture a gradient of urbanization, and as a result these points were selected to pick up much of the commercial and industrial land cover types.

We also generated a difference map to compare the NLCD-derived estimates against the SERGoM estimates (Figure C-6 through Figure C-8). In general, NLCD estimated higher imperviousness in urban areas (shown in red), and under-represented imperviousness in lower-density, suburban/exurban land use areas (shown in blue). Our estimates of imperviousness are likely underestimated in urban areas because they do not include commercial and industrial land uses. Because it is difficult for NLCD to identify low housing density land uses beyond the suburban fringe, it is likely that NLCD PUI slightly underestimates impervious surface in exurban and rural areas.

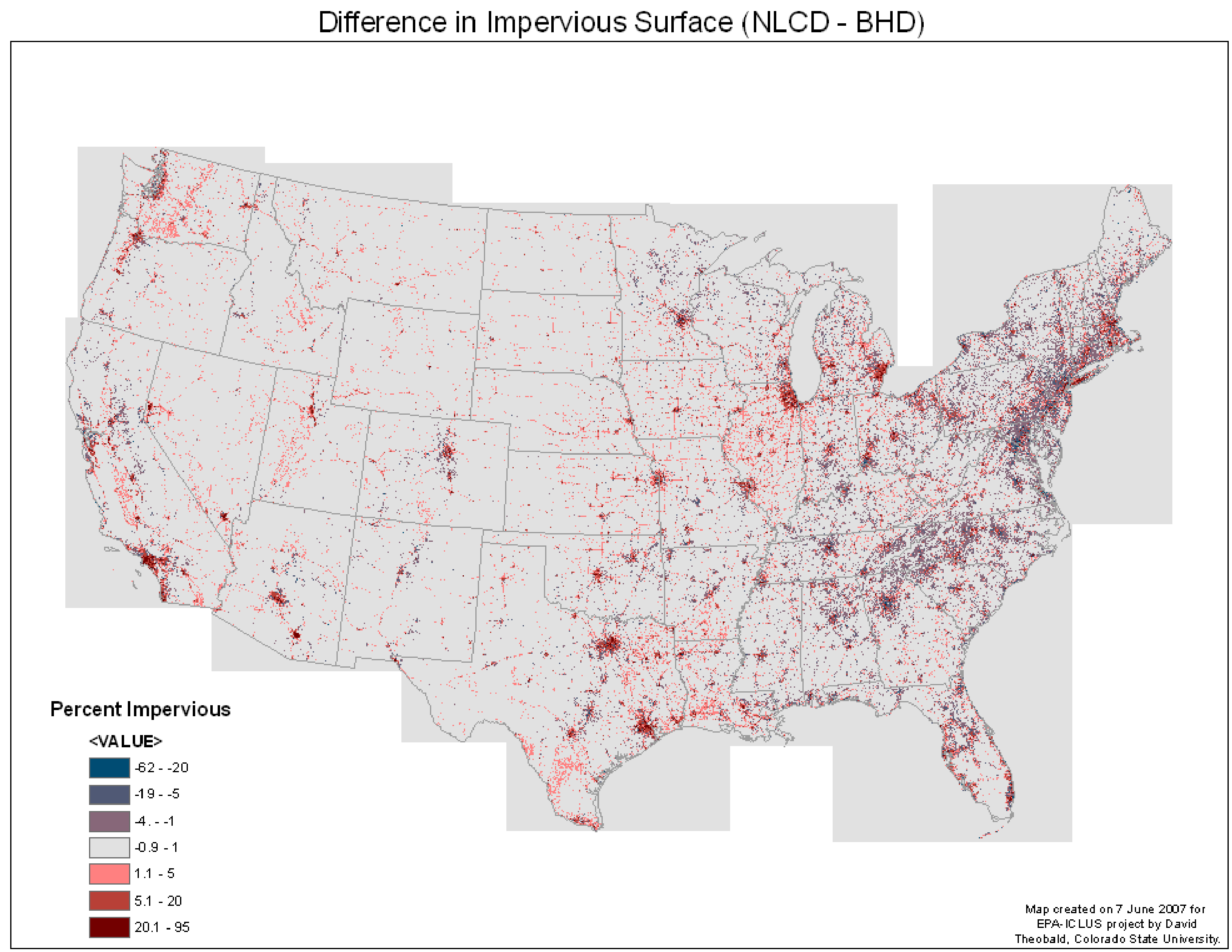

Figure C-6: Difference in Impervious Surface, United States

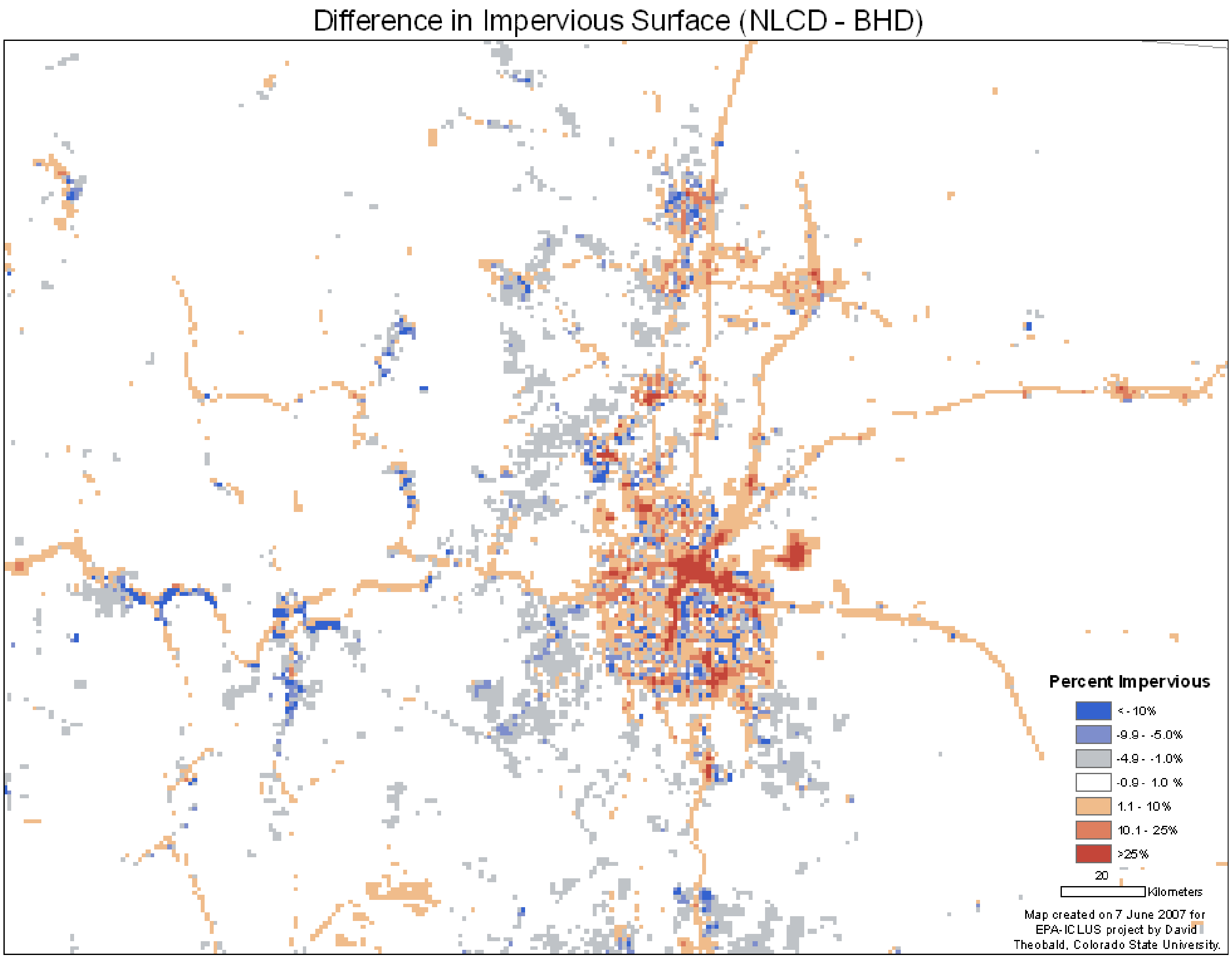

Figure C-7: Difference in Impervious Surface, Colorado

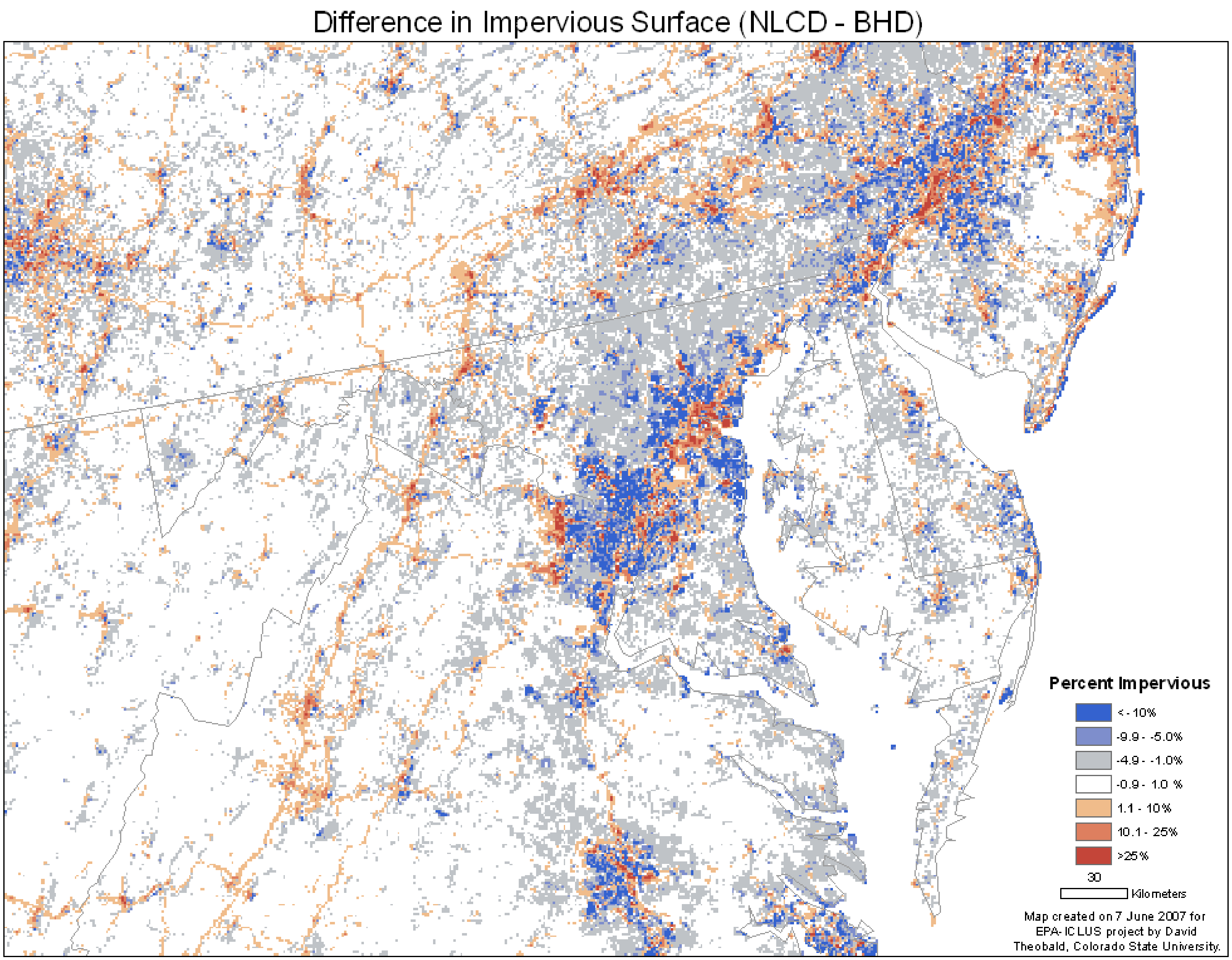

Figure C-8: Difference in Impervious Surface, Mid-Atlantic Region

Finally, in Figure C-9 we show the results of using the SERGoM housing density projections for 2030 – base case and the estimated impervious surface as a function of housing density. We will need to consider how to incorporate commercial/industrial contributions to impervious surface estimates for future projections. For now, we recommend reporting just housing density-based impervious surface, realizing that it is a conservative estimate, and that future efforts should better represent urban/industrial land use growth as a function of population/housing density growth.

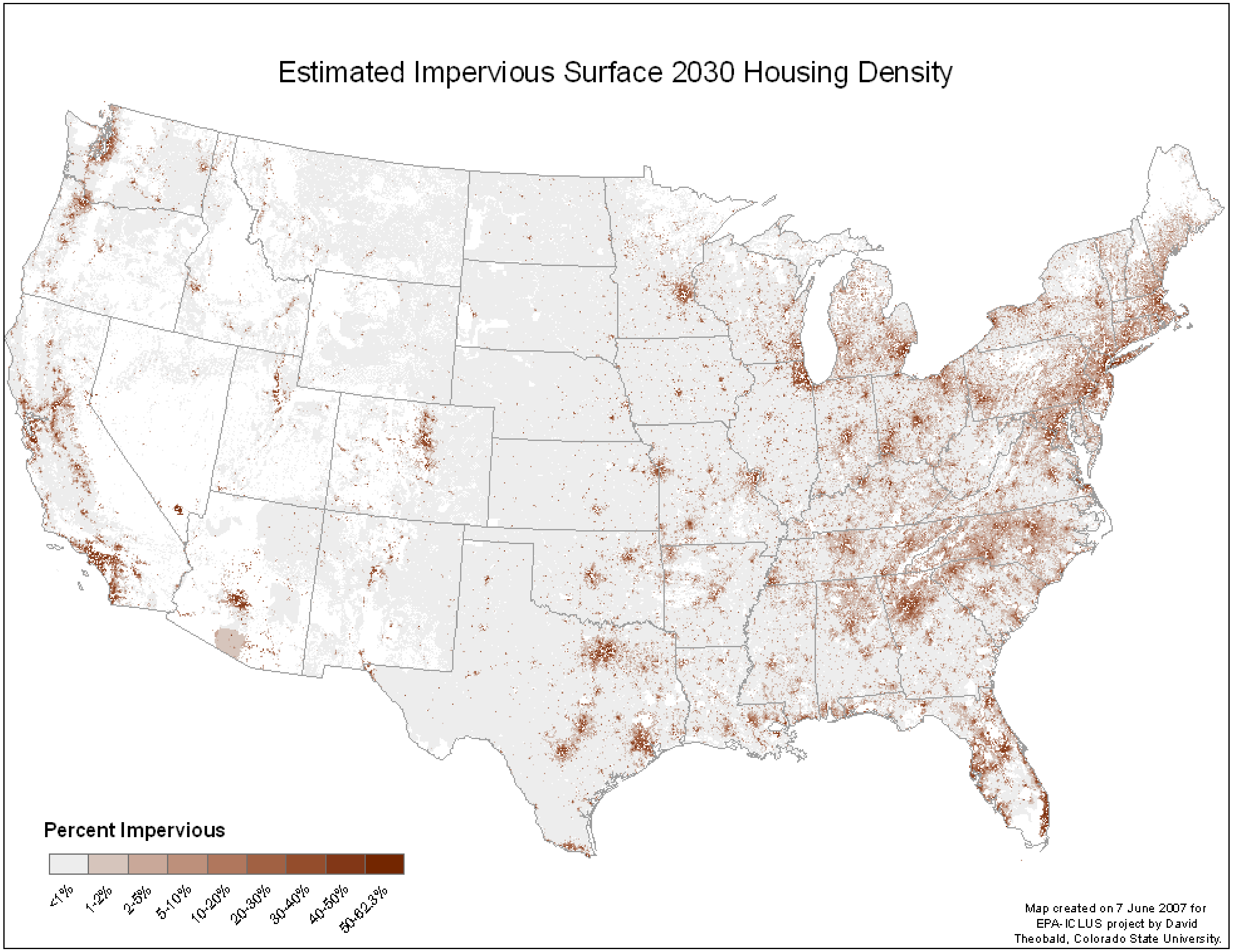

Figure C-9: Estimated Impervious Surface, 2030

Appendix D - REGIONAL POPULATION GROWTH RATES AND PROJECTIONS BASED ON U.S. EPA REGIONS

Table D-1 below provides a list of the EPA regions that were used for the analysis of regional differences in population growth. Table D-2 provides the projected populations for each of the regions and each of the modeled storylines for 2005, 2030, 2060, and 2090.

Table D-1: EPA Regions

Region		States
Region 1	Northeast	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont
Region 2	Mid-Atlantic	New Jersey, New York*
Region 3	Mid-east	Delaware, District of Columbia, Maryland, Pennsylvania, Virginia, West Virginia
Region 4	Southeast	Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee
Region 5	Mid-west	Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin
Region 6	Southwest	Arkansas, Louisiana, New Mexico, Oklahoma, Texas,
Region 7	Cornbelt	Iowa, Kansas, Missouri, Nebraska
Region 8	Mountain-west	Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming
Region 9	Pacific-south	Arizona, California, Nevada**
Region 10	Northwest	Idaho, Oregon, Washington***

*Puerto Rico and the U.S. Virgin Islands were not included in Region 2 for this analysis

**Hawaii, American Samoa, Guam, Northern Mariana Islands, and Trust Territories were not included in Region 9 for this analysis.

***Alaska was not included in Region 10 for this analysis.

1 **Table D-2: Projected Population and Growth Rate by Scenario and EPA Region**

	Population				Growth Rate		
EPA Region	2005	2030	2060	2090	2005-2030	2030-2060	2060-2090
Base Case							
1	14,255,073	15,519,657	15,902,916	16,887,110	9%	2%	6%
2	28,018,871	35,109,989	41,602,295	49,258,590	25%	18%	18%
3	28,797,147	31,978,301	34,424,923	38,637,662	11%	8%	12%
4	57,405,312	70,474,771	82,641,728	97,900,593	23%	17%	18%
5	51,257,348	55,592,269	57,423,505	60,486,700	8%	3%	5%
6	35,680,974	45,708,352	55,363,006	65,879,226	28%	21%	19%
7	13,269,562	14,224,959	14,504,537	15,010,238	7%	2%	3%
8	10,006,652	12,930,609	15,592,590	18,402,596	29%	21%	18%
9	44,519,456	56,426,295	67,555,641	79,977,083	27%	20%	18%
10	11,360,137	13,024,245	14,030,327	15,397,072	15%	8%	10%
Storyline A1							
1	14,255,073	15,141,889	14,141,988	12,659,207	6%	-7%	-10%
2	28,018,871	39,117,688	46,902,172	51,792,819	40%	20%	10%
3	28,797,147	32,682,229	34,693,103	36,115,978	13%	6%	4%
4	57,405,312	73,800,430	85,111,046	92,041,933	29%	15%	8%
5	51,257,348	54,146,181	51,539,278	47,200,686	6%	-5%	-8%
6	35,680,974	47,647,066	55,559,004	59,071,696	34%	17%	6%
7	13,269,562	13,780,804	12,800,038	11,445,472	4%	-7%	-11%
8	10,006,652	13,473,510	15,807,016	16,909,652	35%	17%	7%
9	44,519,456	56,021,194	61,616,885	62,219,659	26%	10%	1%
10	11,360,137	13,654,349	14,511,247	14,785,715	26%	10%	1%
Storyline A2							
1	14,255,073	15,987,287	18,051,181	22,566,774	12%	13%	25%
2	28,018,871	35,917,932	45,986,762	61,228,288	28%	28%	33%
3	28,797,147	32,999,574	40,088,688	54,511,203	15%	21%	36%
4	57,405,312	74,318,414	97,906,372	138,195,518	29%	32%	41%
5	51,257,348	56,019,601	63,041,628	77,561,440	9%	13%	23%
6	35,680,974	47,833,571	64,361,337	90,250,013	34%	35%	40%
7	13,269,562	14,369,471	15,919,641	19,525,569	8%	11%	23%
8	10,006,652	13,630,155	18,236,722	25,157,767	36%	34%	38%
9	44,519,456	58,911,077	78,044,717	108,283,362	32%	32%	39%
10	11,360,137	13,137,594	15,229,105	19,198,490	16%	16%	26%
Storyline B1							
1	14,255,073	15,141,889	14,141,988	12,659,207	6%	-7%	-10%
2	28,018,871	39,117,688	46,902,172	51,792,819	40%	20%	10%
3	28,797,147	32,682,229	34,693,103	36,115,978	13%	6%	4%
4	57,405,312	73,800,430	85,111,046	92,041,933	29%	15%	8%
5	51,257,348	54,146,181	51,539,278	47,200,686	6%	-5%	-8%
6	35,680,974	47,647,066	55,559,004	59,071,696	34%	17%	6%
7	13,269,562	13,780,804	12,800,038	11,445,472	4%	-7%	-11%
8	10,006,652	13,473,510	15,807,016	16,909,652	35%	17%	7%
9	44,519,456	56,021,194	61,616,885	62,219,659	26%	10%	1%

	Population				Growth Rate		
EPA Region	2005	2030	2060	2090	2005-2030	2030-2060	2060-2090
10	11,360,137	13,654,349	14,511,247	14,785,715	20%	6%	2%
Storyline B2							
1	14,255,073	15,543,670	15,997,050	17,077,923	9%	3%	7%
2	28,018,871	35,422,606	42,541,498	51,216,096	26%	20%	20%
3	28,797,147	32,086,103	34,216,490	37,647,265	11%	7%	10%
4	57,405,312	69,018,096	79,590,169	92,831,550	20%	15%	17%
5	51,257,348	57,089,003	60,336,151	64,684,730	11%	6%	7%
6	35,680,974	45,225,069	54,516,450	64,720,598	27%	21%	19%
7	13,269,562	14,552,312	15,227,145	16,041,584	10%	5%	5%
8	10,006,652	12,703,387	15,085,697	17,639,212	27%	19%	17%
9	44,519,456	55,960,255	66,985,991	79,576,422	26%	20%	19%
10	11,360,137	13,326,862	14,723,525	16,493,287	17%	10%	12%

Appendix E – COMPONENT AND COHORT MODEL DATA

Through provide data used to calculate demographics for the component and cohort model. The following tables provide summary values for the entire population; actual rates used in the model vary by age, sex, and race/ethnicity.

Table E-1: Fertility Rates (Births per 1000 Women)

Year	Low	Mid	High
1999	2,036	2,048	2,059
2000	2,032	2,055	2,080
2001	2,026	2,063	2,100
2002	2,021	2,070	2,120
2003	2,015	2,077	2,140
2004	2,009	2,083	2,161
2005	2,002	2,090	2,181
2006	1,996	2,097	2,201
2007	1,990	2,103	2,221
2008	1,984	2,110	2,241
2009	1,978	2,117	2,261
2010	1,971	2,123	2,280
2011	1,964	2,129	2,299
2012	1,958	2,135	2,318
2013	1,951	2,140	2,337
2014	1,944	2,146	2,355
2015	1,937	2,152	2,374
2016	1,931	2,157	2,392
2017	1,924	2,163	2,411
2018	1,917	2,169	2,430
2019	1,910	2,175	2,448
2020	1,903	2,180	2,467
2021	1,896	2,186	2,485
2022	1,888	2,191	2,503
2023	1,881	2,197	2,522
2024	1,873	2,202	2,540
2025	1,866	2,207	2,558
2026	1,864	2,208	2,563
2027	1,862	2,210	2,567
2028	1,860	2,211	2,572
2029	1,857	2,212	2,576
2030	1,855	2,213	2,580
2031	1,852	2,213	2,584
2032	1,849	2,213	2,588
2033	1,846	2,214	2,591
2034	1,843	2,214	2,594

2035	1,840	2,214	2,597
2036	1,837	2,214	2,601
2037	1,834	2,214	2,604
2038	1,832	2,214	2,607
2039	1,829	2,214	2,610
2040	1,826	2,215	2,613
2041	1,823	2,215	2,617
2042	1,820	2,215	2,620
2043	1,818	2,216	2,624
2044	1,815	2,216	2,627
2045	1,813	2,217	2,631
2046	1,810	2,217	2,634
2047	1,807	2,218	2,637
2048	1,805	2,218	2,641
2049	1,802	2,219	2,644
2050	1,800	2,219	2,647
2051	1,797	2,219	2,650
2052	1,794	2,219	2,652
2053	1,791	2,219	2,655
2054	1,789	2,219	2,658
2055	1,786	2,219	2,660
2056	1,783	2,219	2,662
2057	1,780	2,218	2,665
2058	1,776	2,218	2,667
2059	1,773	2,217	2,669
2060	1,770	2,217	2,671
2061	1,767	2,216	2,673
2062	1,764	2,216	2,675
2063	1,760	2,215	2,677
2064	1,757	2,215	2,679
2065	1,754	2,214	2,682
2066	1,751	2,214	2,684
2067	1,747	2,213	2,686
2068	1,744	2,213	2,688
2069	1,741	2,212	2,690
2070	1,738	2,212	2,692
2071	1,734	2,212	2,695
2072	1,731	2,211	2,697
2073	1,728	2,211	2,699
2074	1,725	2,210	2,701
2075	1,721	2,209	2,703
2076	1,718	2,209	2,705
2077	1,715	2,208	2,706
2078	1,711	2,207	2,708
2079	1,708	2,206	2,710
2080	1,705	2,206	2,711

2081	1,701	2,205	2,713
2082	1,698	2,204	2,714
2083	1,694	2,203	2,716
2084	1,690	2,202	2,717
2085	1,687	2,201	2,719
2086	1,683	2,199	2,720
2087	1,680	2,198	2,721
2088	1,676	2,197	2,723
2089	1,672	2,196	2,724
2090	1,669	2,195	2,725
2091	1,665	2,194	2,726
2092	1,661	2,193	2,728
2093	1,658	2,191	2,729
2094	1,654	2,190	2,730
2095	1,651	2,189	2,731
2096	1,647	2,188	2,733
2097	1,643	2,187	2,734
2098	1,640	2,185	2,735
2099	1,636	2,184	2,736
2100	1,632	2,183	2,737

Table E-2: Mortality Rates (Lifespan-Equivalent)

Year	Low	Mid	High
1999	79.74	79.74	79.68
2000	80.01	79.9	79.95
2001	80.16	80.05	80.10
2002	80.32	80.2	80.25
2003	80.47	80.36	80.40
2004	80.62	80.51	80.54
2005	80.78	80.67	80.69
2006	80.94	80.82	80.85
2007	81.09	80.97	80.99
2008	81.24	81.13	81.14
2009	81.39	81.28	81.29
2010	81.66	81.43	81.54
2015	82.41	82.19	82.26
2020	83.26	82.93	83.07
2025	83.88	83.56	83.65
2030	84.60	84.17	84.33
2035	85.20	84.78	84.88
2040	85.90	85.4	85.53
2045	86.51	86.01	86.08
2050	87.21	86.62	86.71
2055	87.80	87.22	87.22
2060	88.47	87.81	87.82
2065	89.05	88.4	88.30
2070	89.70	88.97	88.85
2075	90.24	89.53	89.28
2080	90.86	90.09	89.80
2085	91.39	90.64	90.21
2090	92.00	91.18	90.69
2095	92.51	91.71	91.06
2100	93.00	92.24	91.42

Table E-3: Projected International Migration

Year	Low	Mid	High
2000	670,138	1,020,435	1,432,695
2001	593,255	1,030,425	1,570,973
2002	531,919	1,030,293	1,671,881
2003	462,200	995,679	1,704,589
2004	404,294	961,750	1,722,833
2005	355,173	928,453	1,729,993
2006	312,734	895,833	1,728,678
2007	275,252	863,540	1,720,305
2008	241,908	831,875	1,706,158
2009	211,938	800,663	1,687,319
2010	184,668	769,797	1,664,477
2011	179,040	774,125	1,699,910
2012	174,268	778,360	1,733,468
2013	170,255	782,327	1,765,441
2014	166,833	786,288	1,795,997
2015	163,809	790,010	1,825,332
2016	161,032	793,650	1,853,500
2017	158,577	797,129	1,880,682
2018	156,347	800,507	1,907,047
2019	154,457	803,815	1,932,527
2020	152,592	806,979	1,957,368
2021	166,085	840,341	2,041,510
2022	179,067	873,156	2,125,426
2023	191,267	905,230	2,208,839
2024	202,980	936,857	2,292,232
2025	214,147	967,891	2,375,342
2026	224,882	998,465	2,458,340
2027	235,272	1,028,622	2,541,223
2028	245,307	1,058,406	2,624,090
2029	255,086	1,087,913	2,706,829
2030	264,891	1,117,043	2,789,455
2031	257,533	1,110,301	2,797,150
2032	250,901	1,104,092	2,804,858
2033	244,888	1,098,310	2,812,504
2034	239,382	1,092,915	2,820,177
2035	234,661	1,088,005	2,827,787
2036	230,311	1,083,384	2,835,422
2037	226,341	1,079,014	2,842,719
2038	222,757	1,074,903	2,850,066
2039	219,520	1,071,081	2,857,333
2040	216,643	1,067,573	2,864,468
2041	213,996	1,064,300	2,871,496

Year	Low	Mid	High
2042	211,696	1,061,065	2,878,370
2043	209,507	1,058,054	2,885,342
2044	207,356	1,055,215	2,892,083
2045	205,448	1,052,456	2,898,727
2046	203,620	1,049,922	2,905,317
2047	201,922	1,047,331	2,911,896
2048	200,347	1,044,964	2,918,282
2049	198,712	1,042,694	2,924,605
2050	197,203	1,040,387	2,930,848
2051	195,780	1,038,197	2,936,971
2052	194,554	1,036,208	2,942,987
2053	193,265	1,034,270	2,949,104
2054	192,017	1,032,477	2,955,004
2055	190,931	1,030,777	2,960,927
2056	189,843	1,029,070	2,966,785
2057	188,619	1,027,388	2,972,462
2058	187,498	1,025,691	2,978,058
2059	186,448	1,024,149	2,983,567
2060	185,302	1,022,613	2,989,148
2061	184,102	1,021,041	2,994,495
2062	183,076	1,019,540	2,999,780
2063	181,927	1,018,071	3,004,997
2064	180,848	1,016,574	3,010,217
2065	179,608	1,015,188	3,015,235
2066	178,444	1,013,731	3,020,298
2067	177,282	1,012,362	3,025,208
2068	176,119	1,011,015	3,030,105
2069	174,912	1,009,672	3,034,978
2070	173,632	1,008,378	3,039,655
2071	172,478	1,007,139	3,044,480
2072	171,308	1,005,888	3,049,252
2073	170,122	1,004,724	3,053,972
2074	169,012	1,003,494	3,058,708
2075	167,811	1,002,407	3,063,253
2076	166,788	1,001,342	3,067,923
2077	165,628	1,000,147	3,072,497
2078	164,501	999,100	3,076,939
2079	163,329	998,085	3,081,488
2080	162,359	997,098	3,085,910
2081	161,216	996,136	3,090,373
2082	160,066	995,099	3,094,759
2083	159,026	994,178	3,099,047
2084	158,066	993,261	3,103,452
2085	156,995	992,333	3,107,792
2086	155,981	991,460	3,112,064

Year	Low	Mid	High
2087	154,984	990,630	3,116,245
2088	154,078	989,894	3,120,601
2089	153,015	989,122	3,124,829
2090	152,160	988,353	3,129,030
2091	151,203	987,576	3,133,229
2092	150,290	986,934	3,137,378
2093	149,360	986,237	3,141,620
2094	148,521	985,542	3,145,634
2095	147,543	984,815	3,149,846
2096	146,699	984,223	3,153,959
2097	145,840	983,650	3,158,109
2098	145,004	983,071	3,162,141
2099	144,195	982,546	3,166,233
2100	143,407	982,038	3,170,286