National housing and impervious surface scenarios for integrated climate impact assessments

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Understanding the impacts of climate change on people and the environment requires an understanding of the dynamics of both climate and land use/land cover changes. A range of future climate scenarios is available for the conterminous United States that have been developed based on widely used international greenhouse gas emissions storylines. Climate scenarios derived from these emissions storylines have not been matched with logically consistent land use/cover maps for the United States. This gap is a critical barrier to conducting effective integrated assessments. This study develops novel national scenarios of housing density and impervious surface cover that are logically consistent with emissions storylines. Analysis of these scenarios suggests that combinations of climate and land use/cover can be important in determining environmental conditions regulated under the Clean Air and Clean Water Acts. We found significant differences in patterns of habitat loss and the distribution of potentially impaired watersheds among scenarios, indicating that compact development patterns can reduce habitat loss and the number of impaired watersheds. These scenarios are also associated with lower global greenhouse gas emissions and, consequently, the potential to reduce both the drivers of anthropogenic climate change and the impacts of changing conditions. The residential housing and impervious surface datasets provide a substantial first step toward comprehensive national land use/land cover scenarios, which have broad applicability for integrated assessments as these data and tools are publicly available.

urbanization | land planning | water quality

Land-use and land-cover change are recognized to have global consequences (1) and demographic trends drive land development, including residential housing, which define many landscapes (2). However, it remains challenging to develop a deeper understanding of the consequences of these changes because most urban-growth models that can incorporate policy drivers are limited to local and regional scales (e.g., ref. 3, but see ref. 4). This gap limits the effectiveness of integrated assessments of global change impacts, particularly to assess the combined effects of land use and climate change on environmental endpoints. Moreover, in this context it is important for scenarios of growth and development to be consistent with the assumptions used to develop global climate-change scenarios and storylines (5–7).

Land-use change plays a central role in determining the consequences of climate change for people and the environment (8, 9), and has consequences for many environmental endpoints, such as water and air quality (10–12). These complex interactions influence the condition of resources regulated under the Clean Water and Clean Air Acts and are important considerations to include in planning and policy analyses. For example, changes in water quality and effects on aquatic ecosystems have a strong linkage with impervious surface cover associated with development (13). Here we provide initial estimates of the likely effects of national residential land-use change and impervious surface cover on water quality and aquatic ecosystems. Importantly, our models and spatial datasets provide a platform for national-scale assessments of these and other effects and interactions to facilitate more comprehensive analyses of potential impacts and effectiveness of environmental and land-use policies.

Our analyses are based on land-use change scenarios for the conterminous United States forecast decadally from 2000 to 2100. As part of a project called Integrated Climate and Land Use Scenarios (ICLUS), our goal was to create national and consistent land-use change scenarios in a transparent modeling framework that could be integrated with assessments of climate-change effects on environmental endpoints (14). We used standard demographic approaches and a spatial allocation model to create scenarios of housing density changes with national coverage at 1 ha resolution. Each scenario is consistent with the main storylines of the Special Report on Emissions Scenarios (SRES) driving global circulation models and other land-use change modeling efforts (7, 15–18). The SRES describe population, socioeconomic, and technological trajectories for broad regions of the world. The storylines are organized along two major axes: regionalization vs. globalization and environmental vs. economic development. The resulting quadrants can be compared to the base-case (BC) scenario and represent four scenario families: A1, A2, B1, and B2 (7).

We developed a county-level spatial interaction model (i.e., gravity model) to represent domestic migration within the context of a cohort-component population-growth model. The forecasted populations in turn drive the number of housing units required in a county. The Spatially Explicit Regional Growth Model (SERGoM) spatial allocation model (4, 19, 20) then distributes the housing units to 1 ha areas based on past land-use patterns and travel time along roads from urban areas (see *Materials and Methods*). Each scenario used rates of population growth from the US Census Bureau as the baseline that was modified to reflect the four main SRES storylines (Fig. S1 and Table S1). Parameters in SERGoM that influence the growth patterns (i.e., compact vs. dispersed) were also modified to be consistent with the SRES storylines (Table S2).

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Results and Discussion

Forecasted Land-Surface Changes. The population forecast for 2100 for our base-case scenario (based on the US Census midline scenario) is approximately 450 million, but could range from approximately 380 million for the B1 scenario to nearly 690 million for the A2 scenario (Fig. S1). The scenarios show significant spatial and temporal differences in population allocations (Fig. 1 *A–D*). The high population growth rate and business-as-usual dispersed development pattern in scenario A2 result in the largest changes in urban and suburban housing density classes, greater conversion of other land-cover classes, and an increased percentage of impervious surface cover by 2100 (Fig. 2 and Table S3). Under all modeled scenarios by 2100, urban areas (~1/4 acre or less per housing unit) are expected to increase by 74% to 164% and suburban areas (~1/4 acre to 1.68 acres per housing unit) by 59% to 154%. Combined, these land classes are expected to increase the most in the A2 scenario, adding more than 190,000 km^2 of residential development over the next century, or 156% more than 2000 levels (about 122,000 km^2) for a total of over 300,000 km^2 of urban/suburban area by 2100 (Table S2).

Comparisons of scenarios A1 with B1 and BC with B2 show differences in the distribution of housing due to domestic migration and the allocation pattern. By midcentury, the weighting toward compact urban development is evident in B1, as opposed to A1 (Fig. 2). By the year 2100 the differences in the amount of urban and suburban housing are much larger, mainly due to high domestic migration in A1, which drives development in and around cities. The effect of domestic migration is also evident in the greater amount of suburban development in BC compared with B2 (Fig. 2). The combination of different development patterns, dispersed versus compact, and higher domestic migration, favors larger population centers and new housing. Overall, high domestic migration tends to draw population from more rural areas (Fig. S2), which contributes to a slight decrease in exurban densities to 2100 (Table S2). This population shift is already evident at the county level in the near-term (e.g., 2030), where total population is nearly the same across scenarios (Fig. S2). The strength of the spatial interaction model, which draws population to larger urban centers, counterbalances a dispersed, or sprawl-type, development pattern, especially in scenarios A1, A2, and BC. This results in a shift from suburban densities to urban densities as the largest land-use class from 2050 to 2100 in the A-family scenarios (Fig. 2).

As population grows and residential land use expands, other land-cover types will be converted into residential land use. 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 the National Land Cover Dataset's Anderson Level I coding (21). By percent area, wetlands are most affected by new housing development (Fig. 2). These effects may be direct conversions, which would be mitigated elsewhere, or other impacts due to development within the 1 ha area containing a wetland. More accurate wetlands data would allow explicit protection from development in future scenarios. The largest impacts in terms of total area are estimated to be on agricultural (cropland) land cover. Disproportionate impacts also occur on the grassland/shrubland class in scenarios A1, A2, and BC (Fig. 2). The least amount of change occurs in B1, especially from 2050 to 2100, because total population remains nearly constant and domestic migration is low, which reduces the need for new housing. Housing development impacts nearly one-third of wetlands under all scenarios by 2050 and nearly half by 2100 for A2, highlighting the potential vulnerability of this ecosystem type to runoff, sedimentation, and habitat loss if buffers or other policies are not used. The projected conversion of approximately 30% of current agricultural lands in the next 50 years under all scenarios underscores the potential for conflicts between biofuels policies that may increase demand for agricultural production and demographic patterns.

The projected growth in population, and therefore housing, along with the conversion of land-cover types, is anticipated to lead to a variety of impacts on other environmental and health endpoints. These endpoints include changes in water quality, ecosystem condition, air quality, other environmental amenities, heat-related mortality, and disease incidence. These impacts will not be uniformly distributed across the United States because of the interaction of demographic rates, international immigration, housing location preferences, and climate variability. The scenarios developed here provide an important, and previously unavail-

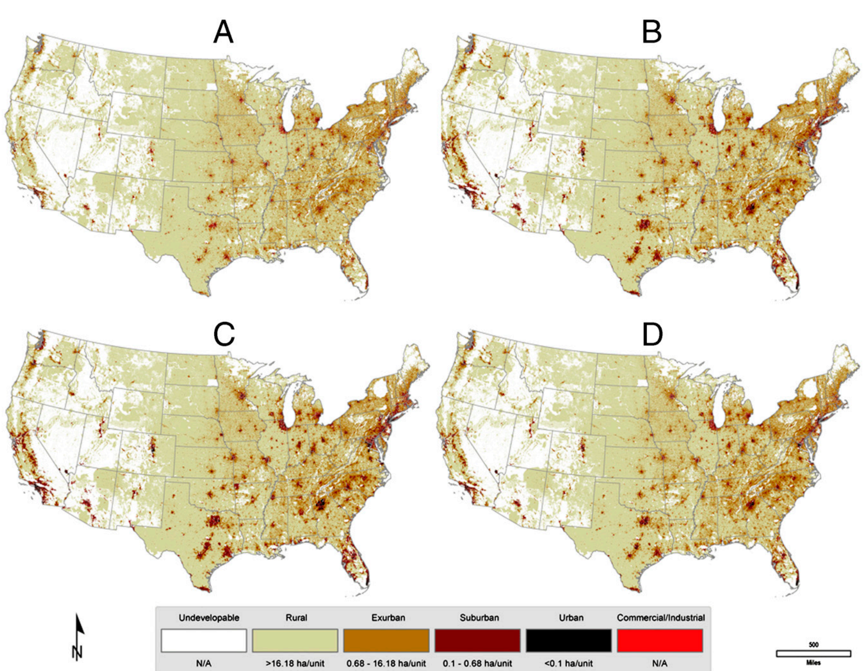

Fig. 1. Housing density for the conterminous United States shown as (*A*) actual housing density in 2000; (*B*) modeled housing density in 2100 for base case; (*C*) for scenario A2; and (*D*) for scenario B1.

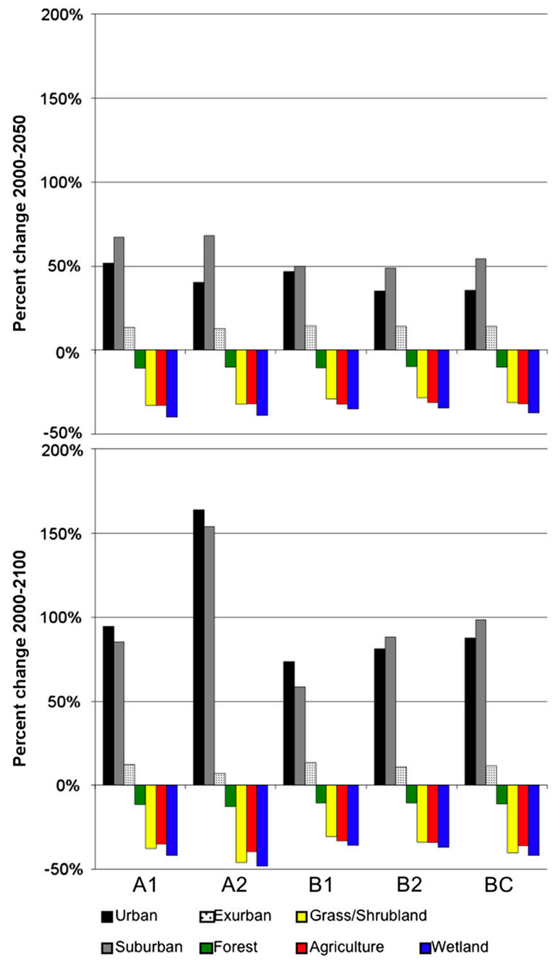

Fig. 2. Percent changes in housing classes and other land cover types by scenario.

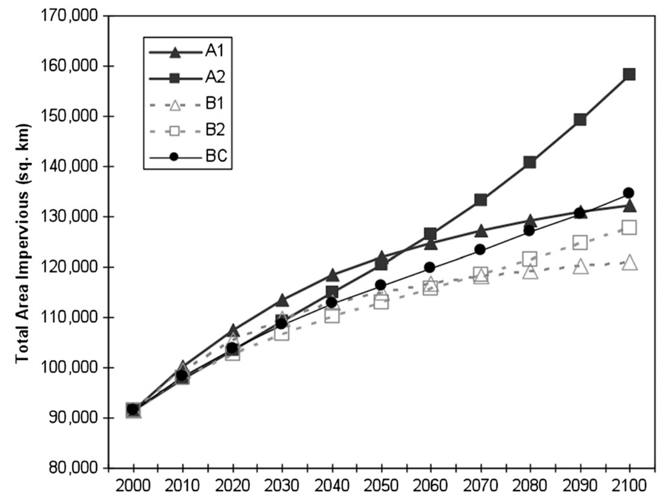

Fig. 3. Area covered by impervious surface over time for all five scenarios.

able, piece of information needed for the integrated assessment of these issues at the national scale.

Projected Changes in Watersheds and Vulnerabilities for Aquatic Ecosystems. Expansion and higher housing densities on the landscape also lead to increases in the amount of impervious surfaces present (Table S3). Impervious surfaces have consequences for stormwater runoff, water penetration, and water quality (13). These hydrologic changes influence the status of water resources in a watershed and can be described in terms of their relative vulnerabilities to droughts and floods, for example. These vulnerabilities may change, both positively and negatively, with changes to the land surface.

In 2000, urban/suburban areas (<1.68 acres per unit) comprised 50% of the total impervious surface, exurban areas (1.6–40 ac per unit) comprised 34%, and rural comprised 16%. We estimated that in 2000 there were 124 (out of a total of 2100) watersheds classified at the 8-digit hydrologic unit code (HUC) scale that were stressed or higher (at least 5% impervious surface) (22) and this will likely increase to between 182 to 199 in 2050 and to between 193 and 274 watersheds in 2100 depending on the scenario (Table S3). In general, there are significant differences between the amount of impervious surface cover that can result from different growth scenarios—from ~5% more (scenario A1) compared to the base case to ~3% less (scenario B2) by 2050. The compact scenarios (B1, B2) result in less impervious surface cover over time (Fig. 3), particularly in conjunction with low domestic migration, which reduces new housing development and favors higher-density housing allocations. Although high domestic and international migration initially increase impervious surfaces in A1, the low fertility rate results in a stabilization in housing development assuming historic patterns of household formation. In contrast, high fertility and high domestic migration results in the continued increase in impervious surface cover through 2100 in scenario A2 (Fig. 3). The differences among scenarios illustrate the potential impacts of policies that limit the amount of impervious surface cover, such as Smart Growth planning principles and Low Impact Development strategies. The results also suggest that the use of pervious surfaces and Low Impact Development strategies could alter the current relationship between housing densities and impervious surface cover and modify the marginal impact of future residential development. Redevelopment activities converting commercial or industrial land uses to residential housing can also alter this relationship and improve water quality and aquatic ecosystem condition in these watersheds.

The potential impacts on watersheds due to impervious surface cover are likely to occur predominantly adjacent to already stressed or impacted watersheds (Fig. 4), because we assume that current development patterns continue into the future. However, the large increase in population and assumption of dispersed development under scenario A2 result in new population centers that cause watersheds in previously unstressed or lightly stressed regions to become stressed or impacted. One potential impact of climate change is an increase in the intensity of individual storm events (23). Because these events are responsible for the majority of impacts to water quality from stormwater runoff, examining the possible extent of impervious surfaces becomes even more important given the anticipated impacts of climate change. The watersheds and regions that are likely to cross the threshold to stressed highlight areas where these potential problems may arise and where efforts to limit water quality impacts through development patterns, stormwater management, improved infiltration, and other best management practices may be particularly effective. Conversely, our results also suggest areas where housing development is less likely to cause additional impacts to aquatic ecosystems, because these watersheds are already impacted or damaged, unless extensive restoration occurs. However, redevelopment in these areas provides opportunities to restore degraded ecosystems and reverse these trends. From this standpoint, watersheds that are already impacted or damaged might represent the highest priority areas to target for use of Smart Growth planning principles and Low Impact Development strategies so that redevelopment can improve water quality and aquatic ecosystem condition.

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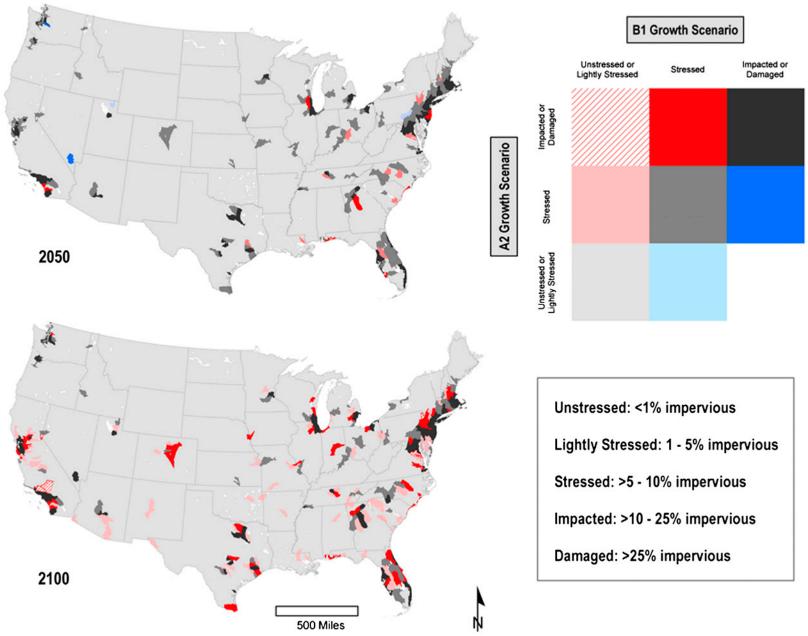

Fig. 4. Comparison of status of HUC-8 watersheds between B1 and A2.

Limitations of Results and Recommended Uses of Data. The resolution, spatial extent, and temporal coverage of our land-use scenario outputs are designed to inform national policy issues relevant to decisions that span decades. Whereas a spatial resolution of 1 ha may tempt potential analyses of smaller spatial extents, we caution against using these outputs at scales below a state or multistate region.

The range of scenarios presented in our outputs can serve as useful benchmarks to compare other scenarios of population growth or emissions. The outputs can also assist with placing more customized land-change scenarios into a broader context that incorporates long-term population growth trends and CO_2 emissions scenarios. These uses underscore the fact that our outputs are scenarios and should not be interpreted as predictions. Our outputs are one interpretation of a set of well-documented social and demographic storylines (i.e., SRES), but many other interpretations and alternative storylines are possible. We have presented five scenarios and illustrated several analytical applications that can inform policies and decision making.

Additional analyses are possible using the land-use scenarios at national scales. These include estimating traffic demands using correlations of vehicle miles traveled with housing density classes; calculating changes in stormwater quality based on impervious surface cover; and analyzing alternative development patterns with respect to Smart Growth or low impact development goals. These results could also provide information on current development trends and trends in habitat loss or conversion to support the watershed approach outlined in the new rule to establish compensatory mitigation requirements for Clean Water Act Section 404 permits (24).

Conclusions

The assessment of climate change impacts on people and the environment requires the development of reasonable scenarios for both future climatic conditions and, critically, future land use and land cover. Interactions between these dynamic processes will ultimately determine impacts and provide the context for environmental management. Our results suggest that some of the plausible land-use futures may alter assumptions used in the development of key environmental policies. For example, integrated consideration of climate and landscape dynamics will be necessary to develop effective long-term policies, such as the restoration and antidegradation goals underlying current water quality regulations or public health goals underlying air quality regulations. Development trajectories more broadly consistent with scenario A2 are likely to make it more challenging to meet these objectives, particularly as these conditions are likely to be associated with more severe climatic change. Residential housing patterns consistent with scenario B1 are likely to be more successful in meeting these objectives.

Although here we compared a basic set of scenarios, these data and models provide the basis to analyze combinations of what best management practices and in what locations may have the fewest impacts on natural land cover, while also reducing impervious surfaces. Also, future research should better incorporate direct linkages and feedbacks between future land use patterns, their effects on land cover, and resulting changes in climatic processes (i.e., albedo, evapotranspiration, etc.). Generating these types of scenarios, along with the integration of climate change effects and feedbacks, can inform both mitigation activities and adaptation planning across a variety of sectors.

Overall, our scenarios suggest that developed lands (exurban density or greater) could expand in the United States between ∼19% to ∼23% by 2100. Conversion of and impacts to wetlands and grassland/shrubland land cover types may be extensive in terms of percentage, whereas agricultural (cropland) lands may suffer the greatest area impacts. Examining housing development in terms of impervious surface cover shows that compact development does reduce the number of watersheds that become stressed over time. However, the large number of watersheds that may become stressed may pose challenges for surface water quality management, including degradation of currently unimpaired waters, particularly in regions where climate-mediated changes to precipitation patterns exacerbates the amount of impervious surface cover.

Materials and Methods

Development of Residential Housing Density Scenarios. We used the socioeconomic storylines in the SRES as the basis for our scenarios (7). 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. The storylines describe linkages between physical changes in climate and socioeconomic factors by linking development pathways with greenhouse gas emissions levels used as inputs to general circulation models (17). The A1 storyline of the SRES reflects a globally integrated economy that leads to social, economic, and demographic convergence by the second half of the century; A2 has a more regional orientation and slower rate of economic growth with more limited flows of people and fertility rates that remain high throughout the world; B1 has a more environmental focus with rapid social development and lower fertility rates as in A1; and B2 reflects moderate economic development with a more regional focus.

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, we wanted to be consistent in qualitative terms with the global SRES storylines. Given the wide range of potential interpretations, we modified the global SRES such that the qualitative trends do not contradict established theory, historical precedent, or current thinking (8). Our US-adapted storylines reflect the following scenarios: A1 represents a world of fast economic growth, low fertility, and high global integration modeled as high immigration. Domestic migration is also modeled as high, because economic development encourages a flexible and mobile workforce. A2 has a more regional focus to economic development and therefore international migration is modeled as low. However, domestic migration is high, because the economic development focus is likely to encourage movement within the United States. Fertility is the highest of the scenarios. B1 represents a globally integrated world similar to A1, but with an emphasis on sustainability. Fertility is low and international migration high, for similar reasons as A1; however, domestic migration is low due to less rural development in light of the environmental focus. B2 has both a regional and a sustainability focus, whereas fertility is medium and both international and domestic migration rates are low due to the local emphasis. We used the medium fertility and immigration scenarios from the US Census as our base case.

We used a cohort-component methodology to represent population growth in the United States. Beginning with 2005 population estimates from the National Center for Health Statistics, we used US Census projections of demographic components of change as the basis for the different scenarios. Fertility rates and international migration rates were provided by the US Census and varied (low, medium, high) by scenario (Table S1). We held mortality rates constant (Census medium). Domestic migration, which was also varied by scenario, was represented using a spatial interaction model (i.e., gravity model) that creates county-to-county migration patterns as a function of county size, distance between counties, and environmental amenities. The model was developed based on historic county-to-county migration data from the US Census' Public Use Microdata Sample files. The amenity factors considered in the final model included January and July temperatures, January sunlight, July relative humidity, and percent water area (8). The final model also included 1980–2000 county population growth rates as a proxy for economic growth.

Spatial allocation is accomplished using SERGoM (4), a hierarchical (national to state to county), deterministic model that calculates the number of additional housing units needed in each county to meet the demand specified by population projections from the demographic model, based on the ratio of housing units to population (downscaled from census tract to block). Housing units are spatially allocated within a county in response to the spatial pattern of land ownership, previous growth patterns, and travel time accessibility. The model is dynamic in that as new urban core areas emerge, the model recalculates travel time from these areas. We refined SERGoM by updating land ownership, transportation, and groundwater well density using 2009 data, and by weighting housing units by NLCD 2001 cover types: developed open space $(21) = 0.085$; developed $(22–24) = 0.55$; transitional $(31–33) = 0.115$; wildland vegetation $(41–44,51,52,71–74) = 0.15$; agricultural $(61,81,82) = 0.05$; and wetlands $(90–94) = 0.05$(8). The resulting outputs, called ICLUS/SERGoM v1.2, are seamless, nationwide maps at 1 ha resolution for each decade to 2100 for each scenario modeled (8).

We modified several SERGoM parameters to reflect different assumptions in the SRES storylines. We modified household size (roughly family size) to adjust for assumed changes in demographic characteristics (Table S1). 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 (25). The changes in household size correspond to changes in fertility rates 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.

We also modified travel times by adjusting weighting values as a function of distance away (travel time) from urban cores (Table S1). This weighting surface is recomputed at each decadal time step. We modified the weights of travel times for the B1 and B2 storylines to model a "compact" growth scenario. Given the environmental orientation of the B1 and B2 storylines, we assumed that growth patterns in these scenarios would place a greater emphasis on promoting denser growth patterns closer to existing urban centers, whereas the other represent business-as-usual growth patterns.

A few key parameters, and the uncertainty of our estimates of them, likely have a strong influence on the behavior of the SERGoM model. As our five scenarios demonstrate, fertility rates have a strong effect on population growth rates, which affects the amount of developed land needed. Although our estimates of current fertility rates are reasonably solid because they are calibrated from comprehensive Census databases, the uncertainty of future rates is high because cultural values and norms can change rapidly. Because our model runs were based on 1990–2000 growth patterns for different types (i.e., urban vs. exurban), they do not incorporate effects of the recent economic recession. The forecasted spatial pattern of development is highly sensitive to land protection activities that typically remove lands from being developed. The spatial pattern of the SERGoM forecasts likely are slightly compact—because we mapped only currently protected land so that housing units might be allocated in forecasted maps at the urban fringe, where future lands are often protected. However, if lands further from the urban fringe are protected, then the reverse could occur—a contracting of the spatial expanse of developed areas. Moreover, there is high uncertainty about the accessibility parameter of SERGoM as major transportation improvements or infrastructure (especially bridges and tunnels) that substantially improve accessibility to undeveloped areas would result in a more dispersed pattern of development.

We benefited from detailed, readily available demographic and environmental data to conduct our national analysis. To extend our modeling approach to other countries, or perhaps even globally, would likely require making simplifying assumptions about growth rates and migration patterns when developing the demographic cohort models, and using coarser (>1–100 km^2) resolution spatial datasets. Also, demographic parameters would need to be temporally (decadally) dynamic to allow for changes in rapidly developing economies.

Analysis of Vulnerabilities to Watersheds and Water Resources. We developed a single, nationwide regression tree model at 1 km resolution that relates housing density estimates in 2000 to estimates from the Percent Urban Impervious from the NLCD 2001 dataset (22). We developed a tree with 66 nodes but did not prune because deviance did not increase with additional nodes during a tenfold cross-validation exercise. We evaluated our estimates by computing a simple linear regression with values from three "ground-truth" datasets generated from high-resolution aerial photography. Comparing our estimates of impervious surface at 1 km^2 cells with a national dataset of 80 points (1 km^2 "chips") placed along a gradient of urban land uses from 13 major urban centers in 2000 (26), we found a good fit ($R^2 = 0.69$, $y = 0.624x + 5.730$), but we underestimated particularly in urban areas with commercial/industrial land use. Compared to conditions in 1989 for 56 watersheds (14-digit Hydrologic Unit Code) in Maryland (we averaged our 1 km^2 cells to watersheds), we had a good fit ($R^2 = 0.69$, $0.658x + 5.873$) but systematically overestimated impervious surface because of the decade time difference. Finally, we found a very good fit ($R^2 = 0.96$, $y = 0.823x\text{-}1.060$) compared to conditions in 1999 for 13 watersheds (12-digit Hydrologic Unit Code) in the Atlanta metro area (27).

Based on our regression tree model, we forecast impervious surface based on future patterns of residential housing density that reflect our SRES growth scenarios (22). 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%) (28, 29). All housing classes were included when estimating the impervious surface of a watershed. Although watersheds are commonly classified by percent impervious surface cover with an aim to general guideline (i.e., biological degradation occurs around 10%), we recognize that this is a coarse surrogate variable. Biological responses to imperviousness are likely to vary widely, and the estimates of impervious are highly dependent on watershed unit size and if upstream units are incorporated (8).

We compared our estimates of impervious surface to the Wadeable Streams Assessment (WSA) as a rough "field check." The WSA has 3,646 sample points across the United States—46% are reference sites, where stream ecosystems are in the highest condition. In 2000, 2.9% of these reference sites were already in watersheds (14-digit Hydrologic Unit Code) with greater than 5% impervious surface cover. By 2050, this number of sites located in a stressed watershed doubles to 5.9%. Part of our overestimation in the cur-

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rent number of reference sites in stressed watersheds likely stems from a slight scale mismatch—reference sites can refer to subwatersheds within our watersheds.

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