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Different patterns of urban development may have widely varying long-term effects on greenhouse gas (GHG) emissions. To investigate such effects, we used UPlan geographic information system–based software to model three 2050 urban-growth scenarios for Yolo County, a predominantly agricultural area near Sacramento, California. Two scenarios correspond to the Intergovernmental Panel on Climate Change's A2 and B1 storylines. We also added a third, infill-only scenario called AB32-Plus that assumes continued strong climate change policy in California and highly compact urban development. Results show dramatically different levels of GHG emissions from transportation and residential-building energy use in the three scenarios, especially when compact urban development is combined with strong assumptions about energy efficiency and population. The preservation of farmland is also an important climate mitigation and adaptation benefit of the compact-development alternative.

Keywords: urban growth; growth management; GHG emissions; climate change mitigation; climate adaptation; agricultural preservation

Introduction

The State of California and many other jurisdictions around the world have adopted the goal of reducing greenhouse gas (GHG) emissions by 80% below 1990 levels by 2050. In addition to other changes throughout the economy, this target is likely to require substantially different urban-development patterns, emphasizing features such as compactness, a greater mixture of land uses, and greater orientation toward pedestrian, bicycle, and public transport (see e.g. Norman, MacLean, and Kennedy 2006; Ewing et al. 2008; Marshall 2008). However, relatively little is yet known about what an 80%-GHG-reduction urbanization strategy might look like, how land use, population, and energy-efficiency strategies might interrelate, and what sorts of co-benefits might occur in terms of farmland and open space preservation.

We address this need by investigating the GHG emissions and land use impacts of dramatically different urbanization storylines[1] for an agricultural county within one of California's rapidly growing metropolitan regions. In contrast to traditional urban-growth modeling, which projects scenarios into the future based on current and past policy, we take a "backcasting" approach that seeks to consider the implications of radically different alternative strategies at a date far in the future. Accordingly, we propose strongly different storylines for 2050, develop modeling parameters based on these

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alternative futures, model the spread of new urban development across the landscape between now and then, and then estimate annual emissions from transportation and residential energy use in 2050 as well as the effects of urban growth on agricultural land. In terms of urbanization, our storylines range from business as usual in the county, with 65% of new households in traditional suburban or exurban densities, to a very-compact-development scenario with only 10% of new households in these categories. Also factored into the scenarios are differential levels of urban rural connectivity such as local food marketing and consumption, which help build interest and support in the climate-related co-benefits of agriculture.

The results are necessarily broad-brush, given that population, economic conditions, and political attitudes cannot be estimated with any degree of precision over such a long period. Still, such an approach can be useful to illustrate dramatically different policy approaches, and indeed can be seen as necessary in order to give policymakers and the public a sense of the level of change required to meet climate change planning goals (Wheeler 2008).

As a foundation for our work, we use the *Special Report on Emissions Scenarios* (SRES) storylines that the Intergovernmental Panel on Climate Change (IPCC) established in 2000. According to the IPCC working group, "Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyze how driving forces may influence future emission outcomes and to assess the associated uncertainties" (IPCC 2000). The IPCC scenarios are based on very broad storylines for alternative global futures, specifying different trajectories for population, globalization, economic growth, and environmental protection. The working group intended them to assist in the modeling of future GHG emissions, and also to assist with understanding of global warming impacts, climate adaptation (i.e. policies to reduce the severity of climate change impacts), and mitigation (i.e. policies to reduce emissions). We chose the A2 and B1 scenarios for higher and lower GHG emissions, respectively, which can be conceptually downscaled to explore how future local land use patterns will respond to climate change (see e.g. Rounsevell et al. 2006; Hallegatte, Przyluski, and Vogt-Schilb 2011). Scenario A2 has higher economic and population growth and less emphasis on sustainability priorities than Scenario B1.

Because IPCC storylines do not include specific action to mitigate GHG emissions, we have added a third alternative, called AB32-Plus, which assumes continued development of State of California climate change policy as set out by a 2006 law, Assembly Bill 32 (AB32), as well as other state legislation and policy. In particular, Senate Bill 375 of 2008 requires each metropolitan area to develop a Sustainable Communities Strategy aimed at coordinating land use and transportation planning so as to reduce GHG emissions from transportation. Although coordinated transportation–land use planning in California certainly predates these pieces of climate change legislation (Barbour and Teitz 2006), the state's metropolitan areas began developing the new Sustainable Communities Strategies in the early 2010s (ARB 2012), potentially establishing a stronger trajectory of urban-growth planning. We sought to design urbanization assumptions within the AB32-Plus storyline so as to meet the state's GHG mitigation goals as well as to achieve other benefits such as farmland preservation, greater provision of ecosystem services at the rural–urban interface, biodiversity conservation, improved rural livelihood options, and business opportunities that build social capital (Gutman 2007). Our overall process then, was to review relevant literature, assemble storylines and scenario assumptions, model urbanization for the county with geographic information system–based software, calculate likely transportation and building emissions from new residential development for each scenario, and assess land use change implications. The analysis concludes with a number of strategies, some already in progress, which could inform a growth-management framework to limit urban development and enhance preservation of agricultural lands.

Background

The approach of downscaling IPCC storylines to analyze local land use scenarios is still relatively new. However, Solecki and Oliveri (2004) used this strategy to examine conversion of agricultural to urban land in the New York City area, employing the SLEUTH urban-growth model to investigate A2 and B2 trend scenarios for 2020 and 2050, with 1960–1990 growth as a base. Modeling parameters primarily concerned the ways urban grid cells propagated in relation to existing development, urban edges, and transportation infrastructure. Solecki and Oliveri's B2 scenario was substantially weaker in managing urban growth than the alternatives we envisioned developing. Although these authors found less urban sprawl with their environmentally oriented alternative, the percentage of land urbanized still more than tripled from 1990 to 2050.

Rounsevell et al. (2006) downscaled four SRES storylines for Europe and modeled land use for 2020, 2050, and 2080 timeframes, though at a much larger spatial scale than ours (10-min data statistically downscaled to a 250-meter grid size, compared to our 50-meter grid). The main drivers for their model were global resource, market, and policy assumptions rather than local land use policy. Not surprisingly, their relatively green B1 and B2 scenarios performed best at preserving agricultural lands. Barredo and Gómez (2006) tested a cellular automata–based model through analysis of urban growth on 10,000 square kilometers around Madrid under three SRES scenarios (A1, A2, and B2) for the 2000–2040 period. Model parameters focused on land accessibility, suitability, zoning status, and neighborhood effects. Their method produced distinctly different spatial clustering and distribution of development for their different storylines. Van Eck and Koomen (2008) applied two scenarios (which they named Individualistic World and Cooperating Region) based on SRES storylines to model urban concentration and land use diversity in the Netherlands, finding that the latter produced significantly more urban sprawl and less concentration of development. None of these researchers, though, sought to further link their models to GHG emissions from the predicted development patterns.

More general analysis of urban growth has long supported the supposition that low-density suburban sprawl increases motor vehicle use, leading to higher GHG emissions compared with non-urban uses on the same land (Norman, MacLean, and Kennedy 2006; Calthorpe 2010) or with similar new populations living in denser urban environments with greater land use diversity (see e.g. Cervero and Kockelman 1997; Kockelman 1997; Liu et al. 2003). In a 2009 review of the literature, the National Research Council concluded that doubling residential density across a metropolitan area, combined with improved land use mix and transit, might lower household vehicle miles traveled (VMT) by 5% to 12%, and perhaps by as much as 25% (NRC 2009). The relationship is complex, however (Badoe and Miller 2000). In an analysis of 80 growth-scenario planning exercises in 50 US regions, Bartholomew (2007) attributed the relatively modest decreases in VMT usually shown within compact-development scenarios to the traditional insensitivity of travel-demand models to land use patterns, as well as the omission of other variables such as land use diversity and pricing. Sheer population and job densities may not be as important as residents' accessibility to destinations and street-network design (Ewing and Cervero 2010). Other factors such as the availability of public transit, bicycle and pedestrian infrastructure, and economic incentives probably play important roles as well.

Research on relationships between urban form and GHG emissions is still in the early stages, and is based primarily on modeled rather than observed data. Andrews (2008) developed an exploratory land use–GHG emissions analysis framework that considers emissions from buildings, transportation, waste management, landscape management, urban heat islands, and electricity transmission and distribution. Applying this framework to typical types of development found in New Jersey towns, he found per capita CO_2 emissions varying by a factor of two, with transportation emissions much lower in dense urban locations than in suburban ones, building emissions somewhat lower, and single-family detached homes producing 33% more GHG (as CO_2 equivalent) from energy use than units in multifamily structures. Carbon sequestration within forests substantially lowered per capita human emissions in exurban locations compared with suburban or urban settings around the periphery of these towns in this East Coast location. This is less likely to be important in arid or primarily agricultural areas of the country, where the amount of woody vegetation is much lower. Waste management, urban heat-island effects, and electric transportation and distribution losses all proved relatively small factors in Andrews's analysis.

Ewing and Rong (2008) investigated the relation between suburban sprawl and residential-building energy consumption, finding 54% higher energy consumption for space heating for single-family detached units when compared with similar households in multifamily structures. However, they also found that urban areas have somewhat increased energy consumption for cooling, due to urban heat-island effects. In a study of relatively low-density vs. high-density neighborhoods in the Toronto area, Norman, MacLean, and Kennedy (2006) found GHG emissions from the former approximately 81% higher for building operations and 365% higher for transportation activities. In a study of 11 metropolitan regions in the Midwestern US, Stone et al. (2009) estimated that an aggressive smart-growth scenario over 50 years could reduce the growth in transportation emissions from business-as-usual development by 34%, and that over business as usual, and that this land use strategy, combined with use of hybrid-electric vehicles, could reduce the growth in emissions by 97%. The relation between transportation emissions and building-related emissions will vary according to climate and geographical region. Randolph (2008) believes that in general sprawl has far greater impacts on transportation emissions than on building emissions. However, Andrews (2008) points out that, in some locations at least, building emissions are greater in quantity.

Although the idea of modeling urban growth with very-low-GHG scenarios has been rare in academia, public agencies are beginning to move toward such backcasting approaches in an effort to meet emissions-reduction targets and related legislation. As mentioned previously, California's 2008 SB 375 legislation begins the process of encouraging such scenarios throughout California. The Sacramento Area Council of Governments (SACOG), within the preparatory work for its 2012 Sustainable Communities Strategy (a regional-growth plan required by SB 375), developed two significantly different future scenarios for the region based on different assumed energy efficiencies (SACOG 2012b). Apparently, neither spatially explicit modeling of urbanization nor the official Sustainable Community Strategy were included, but this nevertheless represents a relatively strong environmentally oriented urban-growth vision given the current politics around land use. In fact, the Sustainable Community Strategy is not highly conducive to a carbon-neutral future, given that more than 25% of the region's new housing in 2035 would continue to be built in the form of large-lot single-family homes outside of existing urbanized areas (SACOG 2012c), adding to the region's large existing stock of such homes. Modeling of the agency's land use scenario, together with revised transportation priorities, reduces transportation-related GHG emissions by 20% by 2020 compared to 2008, but emissions-reduction progress stalls thereafter, producing only an additional 3% improvement by 2035, far short of the trajectory needed for the state's 2050 emission-reduction goal (SACOG 2012b). If land use is to contribute toward meeting long-term GHG-reduction targets, dramatically different scenarios appear necessary.

The setting

Yolo County is generally representative of agricultural counties in California's Central Valley in that it contains a mix of irrigated perennial and row crops on alluvial plains, upland grazed rangelands, and small towns and cities. These agricultural landscapes also contain riparian corridors and other types of wetlands that are important for natural-resource and biodiversity conservation. The Central Valley is one of the most productive agricultural regions in the world, yet is facing some of the most rapid population growth in the state. Urbanization in Yolo County is somewhat slower than in many other areas of the valley, having fallen to approximately 1% annually during the economic slowdown starting in the late 2000s. Total population was 200,709 in 2009; predictions for 2050 range from 320,000 to 394,000 (SACOG 2007; Sanstad et al. 2009). Given the county's geography, urban expansion will almost certainly occur at the expense of farmland and open space if growth is not restricted to infill development within existing urban boundaries.

Yolo County includes 653,452 acres of land (264,555 ha). The incorporated cities of Davis, West Sacramento, Woodland, and Winters account for about 4.6% of the land area (Figure 1). In 1998, Yolo County alone contained about 40% of the prime farmland in the Sacramento region and yielded the highest farm market values out of all the counties (Sokolow and Kuminoff 2000). Thus, the jurisdiction is an important reservoir of productive farmland within an urban region. The county lost about 6500 acres (2631 ha) of agricultural land (including grazing land) to urbanization between 1992 and 2008 (FMMP 1992, 2008). Most of this was prime farmland and farmland of local importance. Compared with other jurisdictions in California, the county has been relatively successful at protecting agricultural land from urbanization through land-preservation programs, incentives for farmers, and land use policies which make it difficult to develop land zoned for agriculture.

Urbanization presents both opportunities and challenges for agriculture. In some regions, it enhances awareness about how food is produced and generates markets for agricultural products such that farmers produce crops more intensively (Lockeretz 1986; Wu, Fisher, and Pascual 2011). But it is more typically accompanied by challenges: the loss of agricultural land due to subdivision and development; vandalism at the urban edge (Lisansky 1986); and conflicts with new suburban residents about the noise, odor, and potential spray-drift associated with farming operations. Where development takes place in a dispersed pattern that fragments agricultural land, farming may become difficult on some remaining agricultural parcels due to such conflicts as well as to difficulties in moving farm machinery from field to field on more congested roads, creating a ripple effect whereby more agricultural land is then converted to urban uses. Also, fragmentation and loss of farmland cause farmers to lose benefits associated with being part of a large farming community, such as sourcing inputs, accessing information, sharing equipment, and supporting processing and shipping operations (Porter 1998). Impacts on agriculture from urbanization will then be disproportionate to the land area covered.

Figure 1. Location of Yolo County in California.

Method

To investigate the effects of urbanization on GHG emissions and agriculture, we developed storylines and scenario parameters for the county, modeled urban growth between 2010 and 2050, calculated transportation-related and residential-building-related GHG emissions from this new development for each scenario, and examined the effects of this modeled growth on farmland.

1. Storylines

Within previous research, we and our colleagues developed a set of storylines reflecting different climate change and urbanization policies for Yolo County in 2050 (Jackson et al. 2009). As in IPCC Scenario A2 (Regional Enterprise), our A2 storyline assumes that population growth will remain high, with an approximate doubling of the current county population, to 394,000 (Sanstad et al. 2009) (Table 1). This storyline assumes that economic growth and technological innovation remain high, that drive-alone motor vehicles remain the main transportation mode, and that current land use policies remain in place. Although much urbanization will be on previously unbuilt land, there will be some focus on infill development, higher densities, and greater land use mix, as indeed is evident within current development and in county and city planning documents.

Table 1. Selected elements of A2, B1, and AB32-Plus storylines for Yolo County in 2050.

Scenario	Regional Enterprise (A2)	Global Sustainability (B1)	Precautionary Change (AB32-Plus)
Population growth	High (rising from 180,000 to 394,000)	Midrange (335,000)	Low (235,000)
Economic growth	High; emphasis on production for global markets	Moderate; shift to smaller industries and value-added production	Low to moderate; more emphasis on production for local markets
Agriculture	Changed crop mix for hotter climate	Changed crop mix; practices to increase C sequestration and reduce N_2O and CH_4 emissions	Previous changes plus agrobiodiversity-based practices
Land use	Current trends	More compact growth, higher densities, intensified infill, and better land use mix	All new development within existing urban footprints
Water	Diminished Sierra snowpack; increased use of groundwater; increased crop and residential needs	Same, but shift to drip irrigation and high-value crops	Even greater water efficiency; development of artificial groundwater-recharge areas
Technology	Moderate improvements in energy efficiency of vehicles and buildings	Large improvements in efficiencies	Even greater efficiencies
Agricultural land conversion	Continued pressure to urbanize farmland	Increased use of agricultural easements and incentives to preserve farmland	Additional policies such as urban-growth boundaries
Transportation	VMT/capita stabilized at 2008 levels through changes in pricing, land use, and alternative travel modes	VMT/capita reduced substantially (~30% below 2008 levels)	VMT/capita reduced dramatically (60+% below 2008 levels)
Electricity source	Renewable share increases from 12% to 25%	Higher renewable share (50%)	No fossil fuels
Energy pricing	Substantial increases in fossil fuel prices	Even greater increases in prices	Greatest increase in prices

In terms of suburban sprawl, therefore, the A2 storyline is by no means a worst-case scenario. Rather, it is a continuation of practices in the 1990–2010 period. If this storyline had been based on prevailing development patterns from 1950–1990, suburban densities would have been in the range of 4–6 units per acre instead of 8 (10–15 units per hectare instead of 20), less development would have occurred in medium- and high-density forms, and a higher percentage of larger (1–10 acre, 0.4–4 ha) ranchettes would have been created (Wheeler and Beebe 2011). Suburban sprawl would then have covered a much larger percentage of the county, taking far more agricultural land out of production.

In the IPCC's B1 (Global Sustainability) storyline, societies become more conscious of environmental problems and resource limits, and adapt policy accordingly. Under our Yolo County B1 storyline, population growth slows, reaching a midrange population size of 335,000 by 2050 (Sanstad et al. 2009). Economic development is moderate, with a shift from the production of goods to a more service-based economy that is connected to the larger global economy. Technological innovation remains high, with an emphasis on small-scale, green technologies. More compact urbanization occurs through higher densities, increased infill, and a focus on small, locally owned retail stores rather than big box commercial developments. Current transportation and emission policies become more stringent, and the use of high-efficiency vehicles and alternative transport modes increases. In terms of agricultural landscapes, strategies such as conservation easements and tax incentives expand to help maintain land in farming. Farmers also place more emphasis on increasing carbon sequestration, reducing GHG emissions from fossil fuels and fertilizers, and relying on ecologically based practices that reduce dependence on non-renewable inputs (Haden et al. 2013).

To the two IPCC-based storylines, we added a third with more explicit GHG-emissions regulation and sustainability policies. Under our AB32-Plus (Precautionary Change) storyline, Yolo County experiences slower population growth, reaching only 235,000 in 2050 through policies or voluntary actions that affect family planning and migration (Lee 2011). Moderate economic growth focuses on value-added agricultural production enhancing the economic viability of the rural sector, and closer alignment between the rural and urban sectors supports both farmland preservation and protection of ecosystem services (Gutman 2007). A less resource-intensive lifestyle gains acceptance. Urbanization remains at the current extent through strict land use planning policies and development emphasizing efficient use of land, mixed use, intensive infill, increased densities, and growth in urban and neighborhood centers. Public policy emphasizes alternative modes of transportation and far cleaner vehicles. In order to both mitigate and adapt to the changing climate, agricultural producers make major changes in management practices, focusing on ecological intensification and diversification of cropping systems rather than non-renewable inputs and monocultures. Markets for agricultural products become more locally based, and thanks to both more compact physical form of communities and changing economics, travel distances decrease.

2. Modeling

In order to understand the type, extent, and likely locations of urbanization in the county, we modeled these three urbanization storylines using UPlan geographic information system–based software, a rule-based land use allocation model developed by the Information Center for the Environment at the University of California, Davis (Walker, Gao, and Johnston 2007). UPlan is an open-source, relatively simple model that can be run on a subcounty area, a county, or a group of counties. It is suitable for fast, broad-brush urbanization modeling of large land areas using multiple development scenarios, and more than 20 counties in California have used it for urban-growth projections, including a group of rural counties in the San Joaquin Valley which employed it to develop an urban-growth blueprint (Johnston, Roth, and Bjorkman 2009). It has also been employed to assess the impacts of urbanization policies and growth on natural resources (Beardsley et al. 2009), to understand the risk of wildfires in rural woodlands from urban growth (Byrd, Rissman, and Merenlander 2009), and to evaluate the effect of land use policies on natural land conversion (Merenlender, Hilty, and Lidicker 2006).

UPlan relies on a number of demographic inputs (current and future population, household size, employees per household, proportion of population by land use type, density of residential land use types, and floor area per employee) to create scenarios reflecting possible locations and forms of new urban development (ESP 2007). The software divides households into four residential land use types (High, Medium, Low, Very Low) based on density parameters, while assigning employees to nonresidential land use types (Commercial High, Commercial Low, Industrial), also by density. Researchers designate “attractors” (features that would tend to attract urban growth) and “discouragements” (features that would tend to discourage urban growth), and assign weights to each within each scenario. Accessibility and neighborhood attractor parameters can be added in this way, which also allows for detailed local knowledge of development history and policy to be incorporated. For example, within our A2 scenario we assigned relatively strong attraction values to freeway interchanges for commercial development and somewhat less strong attraction values for residential development, because without specific land-protection policies, highly accessible freeway locations tend to attract such development. Within our B1 and AB32-Plus scenarios we assigned increasingly strong attraction values to town and neighborhood centers, as well as to existing commercial strips and rail station areas, because over a 40-year period these are likely to be a focus of infill development policy. Finally, UPlan uses “masks” to prohibit growth in certain locations because of logistical or ownership considerations. For example, we masked existing parks and wetlands in this way. However, we assigned discouragement values (not masks) to floodplains, because despite environmental concerns, development continues to occur in Sacramento Valley floodplains.

For the purposes of this project, we modified UPlan in several ways when compared to previous uses. Because our time frame is longer, and given that land use politics and regulation can change greatly over 40 years, we no longer required that the model place new urban development in areas conforming to the current county General Plan (Yolo Co 2012). We also modified UPlan to allow development within existing urban areas; the tool had been used previously mainly to consider growth on unbuilt county lands outside of existing cities and towns. To predict infill development more accurately, we added additional attractors such as existing commercial strips, shopping centers, freeway retail zones, neighborhood centers, and rail transit station areas, all of which can potentially be redeveloped with higher densities. Partly as a result of these changes, our urbanization assumptions for both the B1 and AB32-Plus scenarios are considerably stronger than used by other researchers. For example, even the strongest growth-management scenario considered by Neimeier, Bai, and Handy (2011) in a study of urbanization scenarios for the nearby San Joaquin Valley still allows substantial suburban sprawl. This approach may accurately reflect current political realities for that region (it was based on input from an advisory board of regional officials), but it involves very different assumptions from our backcasting approach, which aimed at investigating potentially very-low-GHG scenarios in 2050.

Table 2 shows the primary modeling assumptions we used in UPlan. The software divides new development by land use type (e.g. different densities of residential, commercial, and industrial development), and then, drawing upon these inputs, allocates it across the landscape into the geographic cells with the highest combined attraction weights and the user-defined land use order. The model uses 50 m $\times$ 50 m cells, roughly half an acre. This is a fine-grained grid conducive to handling small increments of development such as often occur at infill and urban-edge locations. The final output is a map displaying the location by land use type of future urbanization, as well as associated tables.

Throughout the scenario-development process, we sought to keep our assumptions relatively simple and transparent. In their study of the New York metropolitan area, Solecki and Oliveri (2004) added a layer of new roads for their A2 scenario. For Yolo County, there is no political demand for new roads under current conditions, and the location of

Table 2. A2, B1, and AB32-Plus modeling parameters for Yolo County 2050 growth.

	Regional Enterprise (A2)	Global Sustainability (B1)	Precautionary Change (AB32-Plus)
Census blocks with recent growth	Attract further development	Less influence	Less influence
Town centers	Low influence	Attract higher-density growth	Strongly attract higher-density growth
Neighborhood centers	Low influence	Attract higher-density growth	Strongly attract higher-density growth
Commercial strips and shopping centers	Low influence	Attract higher-density growth	Strongly attract higher-density growth
Freeway exits	Attract further development	Less influence	Precluded from development
Freeway retail	Attract further commercial growth	Attract residential infill	Strongly attract mixed-use redevelopment
Industrial areas	Attract further industry	Attract mixed-use infill	Strongly attract mixed-use infill
Other existing commercial and industrial zoning	Low influence	Attract mixed-use infill	Strongly attract mixed-use infill
Existing residential areas	Very little additional development (in large part due to political obstacles)	Little additional development (in large part due to political obstacles)	Modest additional development (e.g. second units)
Arterial streets	Attract commercial and higher-density residential development	Strongly attract commercial and higher-density residential development	Strongly attract commercial and higher-density residential development
Rail stations	Low influence	Attract high-density mixed-use development	Strongly attract such development
Municipal spheres of influence (outside cities)	Attract development	Attract development	Growth restricted to existing urban areas
Floodplains	Available for development	Development discouraged	Development prohibited
Vernal pools, wetlands, and natural-diversity priority areas	Available for development	Development prohibited	Development prohibited

such routes if added would be highly conjectural. Likewise, the concatenation of new residential clusters outside of existing urban areas was not modeled, because access to roads and proximity to past rural development are probably strong enough to approximate this relatively weak clustering tendency. Lastly, we did not need to consider land slope in our modeling, because the vast majority of the county is quite flat, and the western hills are far removed from existing population centers.

Among the specific assumptions within our three scenarios, the most controversial is that our AB32-Plus scenario assumes that all new development takes place within existing urban areas. We did this to develop the strongest possible backcasting scenario for reducing GHG emissions. New development in Yolo County's largest city, Davis, is in fact currently almost entirely infill, because voters passed ballot measures in 2000 and 2010 preventing any development on open space or agricultural lands without a majority vote of city residents. Statewide, infill development has greatly increased in recent years due to scarcities of unbuilt land in places like the central Bay Area and the Los Angeles Basin and is likely to increase further due to overbuilding of lower-density housing and strong needs for denser forms of housing (Nelson 2011). Redevelopment of existing urban lands is a main goal of the Sacramento region's 2004 Preferred Blueprint Scenario (SACOG 2005) and Sustainable Communities Strategy (SACOG 2012a), as well as state legislation such as SB 375. While many practical constraints pertain to infill (see e.g. Landis and Hood 2005), within a strongly environmental vision of the future there is no physical or procedural reason why 100% infill could not be achieved if the political obstacles could be overcome, for example through an escalation in the urgency of the climate challenge.

For all scenarios, we established density levels that are fairly close to the density levels of recent development in the more urban portions of the state. Our categories were Very Low Density Residential, with an average lot size of one acre; Low Density Residential, with an average density of 8 units per acre (20 units per ha); Medium Density Residential, with an average density of 20 units per acre (49 units per ha); and High Density Residential, with an average of 50 units per acre (123 units per ha) (SCANH n.d.). In terms of building types, the Medium Density category might consist of two-to-three-story apartment or condominium buildings with significant green space around them, while the High Density category might include three-to-five-story multifamily buildings in a more urban format as well as some townhouses. It is important to emphasize that none of these categories requires high-rise apartment living, although this development type is not forbidden, and might in fact be desirable for limited locations within the county during the study period. We apportioned development differently between these residential types for each scenario. The A2 vision focuses primarily on Low Density Residential development, while the B1 scenario is relatively evenly split between Low, Medium, and High Density types, and AB32-Plus favors Medium and High densities.

In addition to modeling these three scenarios, we examined additional versions of A2 and AB32-Plus in which we held population constant at the B1 level, and in which we held population, energy efficiency for both homes and vehicles, and utility-portfolio assumptions constant. This step provides a more analogous comparison of the land use influence within the three scenarios.

3. Emissions Calculations

After modeling urban-growth footprints for the A2, B1, and AB32-Plus scenarios, we calculated two main categories of GHG emissions for the new urbanization produced by each scenario. These calculations help provide a ballpark sense of the magnitude of emissions variations that can result from different policy approaches. For the sake of simplicity, we focused on emissions from the operation of motor vehicles and residential structures, not their lifecycle emissions from construction and materials, because operating emissions are likely to be a large majority of the total in both cases (Kendall and Price 2012, Ochsendorf et al. 2011) and thus estimate the emissions tradeoffs of different urbanization trajectories.

Within the transportation category of GHG emissions, many factors potentially affect individual travel decisions within a given type of urban location, including: land use mix and densities in the surrounding area; the availability, attractiveness, and price of alternative travel modes; the nature of the travel route network, including available route choices and congestion; social pressures, influences, and incentives; and self-selection of residents living in that type of urban location. An extensive field of travel modeling has attempted to take many of these variables into account (see e.g. Oppenheim 1995), usually projecting travel in the future based on changes to current conditions. But given that travel, like many other behavior choices, is highly multi-determined, the process is problematic. Even within timeframes of 20 years or less, travel forecasts are often highly inaccurate (Flyvbjerg et al. 2006), and have had particular difficulties in incorporating variables related to land development and urban design. For a longer timeframe such as 2050, social factors, economic conditions, and behavioral changes are likely to play a larger role, changing travel demand in unpredictable ways and making modeling even more problematic. Accordingly, we have chosen here to keep our calculations to a very basic level, simply extrapolating travel based on the existing range of travel differences between residents in areas of different densities. Household travel surveys done by SACOG show that household vehicle miles travelled (VMT) vary by a factor of 6 between households in low-density (<4 dwelling units per acre) and high-density (>40 dwelling units per acre) locations (SACOG 2007). Some of this difference may be due to household size, composition, and demographics, but much is probably due to accessibility factors (Kockelman 1997), including proximity to jobs, shopping, and schools, and alternative transportation modes. All of these environmental variables can be assumed to vary in unison: the B1 and AB32-Plus storylines assume improved balance of jobs, housing, and shopping within communities; improved bicycle, pedestrian, and public-transit options; rising gas prices and/or carbon taxes; and other economic incentives such as higher parking and road-use charges. Likewise, we can assume that these multiple changes tend to influence resident behavior in synergistic ways; for example, individuals drive less in a dense urban environment because people discover alternatives and are influenced by their peers. Thus, the assumption of a strong difference in driving between low- and high-density environments in 2050 for purposes of backcasting scenarios seems reasonable.

Transportation emissions also depend on the fuel efficiency of motor vehicles. The average fuel efficiency of American vehicles remained more or less unchanged from the mid-1980s through the early 2010s, and so for purposes of illustration we assumed only modest further improvements in the A2 scenario until 2050. In the B1 scenario, we assumed additional efficiency increases of 2% a year (for an average of 61 mpg in 2050), which would plausibly be brought about through improvements in the US national CAFE (Corporate Average Fuel Economy) standards. For the AB32-Plus scenario, we assumed improvements of 4% a year (for an average of 136 mpg in 2050, or more likely a largely electric vehicle fleet yielding indirect emissions equivalent to such an efficiency level). These assumptions are reasonable given recent efficiency improvements such as the spread of hybrid vehicle technologies. The private motor-vehicle transportation emissions of new households for each dwelling type were calculated as:

> [(number of households of each dwelling type × VMT per household for that type) / average miles per gallon] × GHG (CO_2 equivalent) per gallon.

The second category of calculated GHG emissions was from household energy use. In Yolo County, domestic energy comes almost entirely from electricity and natural gas; oil heating is rare in California, and use of wood stoves is also low (and increasingly discouraged due to local air pollution concerns). Substantial differences in GHG emissions between infill urbanization and new residential development on agricultural land are to be expected, due to larger unit sizes and a much higher percentage of stand-alone single-family homes in the latter case.

To calculate household energy use for the three scenarios, we used data from the 2009 California Residential Appliance Saturation Study (CEC 2010), a collaboration of the state's five largest utility companies that surveyed the detailed consumption habits of nearly 26,000 households. This source has the advantage of being measured, not modeled, data, and the disadvantage of including existing structures of varying ages. However, California homes have been relatively energy efficient since the advent of Title 24 standards in the early 1980s, a large percentage of the state's homes has been built during this period, and increases in efficiency in recent years have been partly offset by the growing size of units (Wilson and Boehland 2008). These issues diminish the age factor. The study breaks households down by climate zone, and compares energy consumption for single-family homes, townhomes, small multifamily buildings, large multifamily buildings, and mobile homes by California Energy Commission climate zone. Single-family homes used about twice as much natural gas as townhomes and multifamily buildings, probably in large part because average unit sizes for these latter types are smaller and shared-wall construction tends to be more energy efficient than stand-alone construction. Single-family homes also used almost twice as much electricity as townhouses and units in large multifamily buildings. Surprisingly, units in small multifamily buildings used 30% less electricity per unit than the other types; the reason for this reduction is unclear. Mobile homes were profligate with natural gas, probably due to poor insulation, but moderately efficient with electricity.

After converting UPlan density categories into relative percentages of unit types across our three scenarios, we calculated approximate energy use for the new households in each scenario. We adjusted for assumed trends in household energy use and efficiency within each scenario, using the 1985–2005 statewide reduction of approximately 15% per household (Harper, Sheppard, and Chamberlin 2011) as a baseline. We assumed that the A2 scenario over twice that time (40 years compared to 20) would produce a 30% reduction, that the B1 scenario would produce double that, or 60%, and that the AB32-Plus scenario would produce 90% improvements in energy use, with net-zero-energy development being required at some point during the 40-year period. (The county's first net-zero-energy neighborhood, UC Davis West Village, opened in 2011.) This is an ambitious efficiency-improvement assumption, granted, but it is probably necessary for reducing overall state emissions to 80% below 1990 levels in 2050, as mandated by Executive Order S-3-05.

The household energy-related emissions for each dwelling type in each scenario can then be represented as:

> total GHG emissions (CO_2 equivalent) = number of households × average energy consumption for that type of household × assumed 2050 efficiency improvement × GHG emissions per unit of energy

To clarify the relative contributions of land use change, energy-efficiency assumptions, and population assumptions to reduced GHG emissions, we ran calculations for each scenario additional times, holding population and energy-efficiency assumptions constant at the B1 (midrange) level. These different runs are shown in Tables 3 and 4.

Table 3. Summary of new development by land use type under each storyline. All values in acres. (Values in parentheses indicate results if population is held constant at B1 levels.)

Land use type	2050 development		
	A2	B1	AB32-Plus
Industrial	554 (386)	55	14 (54)
Commercial High	172 (120)	200	68 (259)
Residential High	288 (201)	402	188 (717)
Commercial Low	2,687 (1872)	100	0 (0)
Residential Medium	541 (377)	614	377 (1,435)
Residential Low	9,081 (6,328)	4,576	377 (1,435)
Residential Very Low	1,441 (1,004)	558	0 (0)
TOTAL	14,764 (10,288)	6,505	1,024 (3,900)

4. Agricultural impact calculations

To determine the impacts of the three urbanization scenarios on the county's agriculture, we overlaid the UPlan results with a detailed map of cropland in Yolo County for 2008 (Richter 2009) as well as maps of land form, soil quality (Storie 1978), and habitat types (derived from the California Natural Diversity Database and state Department of Conservation data-sets). Cropping patterns do change somewhat from year to year, but this comparison allowed us to draw general conclusions on the types of agricultural land likely to be lost to urbanization.

Results

In all three scenarios, new development accounts for a very large percentage of county housing by 2050: 49% of units by 2050 in the A2 scenario, 46% in B1, and 40% in AB32-Plus. The high-emissions A2 scenario shows a substantial amount of sprawl development, though absolute quantities are limited by the county's relatively small population size and its history of growth management. Had this scenario been run for the more populous, pro-growth counties in the Highway 99 corridor within the Central Valley, the amount of suburban sprawl and its effects on agriculture and ecosystems would have been much more dramatic (Beardsley et al. 2009; Neimeier, Bai, and Handy 2011). New development covers more than 14,000 acres (5668 ha), with substantial fragmentation of farmland between the county's two largest cities, Davis and Woodland (Figure 2; Table 3). Under the B1 scenario, growth is more concentrated around the urban spheres of influence; new development takes up more than 6000 acres (2429 ha). Under AB32-Plus, due to the storyline's strict infill planning policy, all new development occurs within existing city boundaries.

It is striking just how little land is required to house future populations at higher densities in the more environmentally oriented storylines. The B1 and AB32-Plus scenarios require 44% and 7% of the newly urbanized land of the A2 scenario, respectively. Even holding population increase constant, these scenarios use 63% and 38%, respectively, of the land of the A2 scenario, most or all of it within existing urban areas. Under the A2 scenario, low-density land uses take up nearly 90% of all new land developed, while in the other alternatives most land is allocated to the higher-density categories of development.

Table 4. Greenhouse gas emissions (million tons CO_2 equivalent) from new 2010–2050 residential development and transportation under A2, B1, and AB32-Plus storylines based on various urbanization, energy-efficiency, and population-growth scenarios.

Scenarios	**A2**			**B1**			**AB32-Plus**		
	Transportation	Residential	Total	Transportation	Residential	Total	Transportation	Residential	Total
Urbanization only*	331,031	187,724	518,755	254,243	144,932	399,175	155,396	101,181	256,577
Urbanization + energy efficiency**	671,047	310,361	981,408	254,243	144,932	399,175	90,128	29,709	119,837
Urbanization + energy efficiency + lower pop. growth	789,229	328,518	1,117,747	254,243	144,932	399,175	63,244	26,795	90,039

*Energy efficiency and population held constant at the B1 level.
**Population held constant at the B1 level.

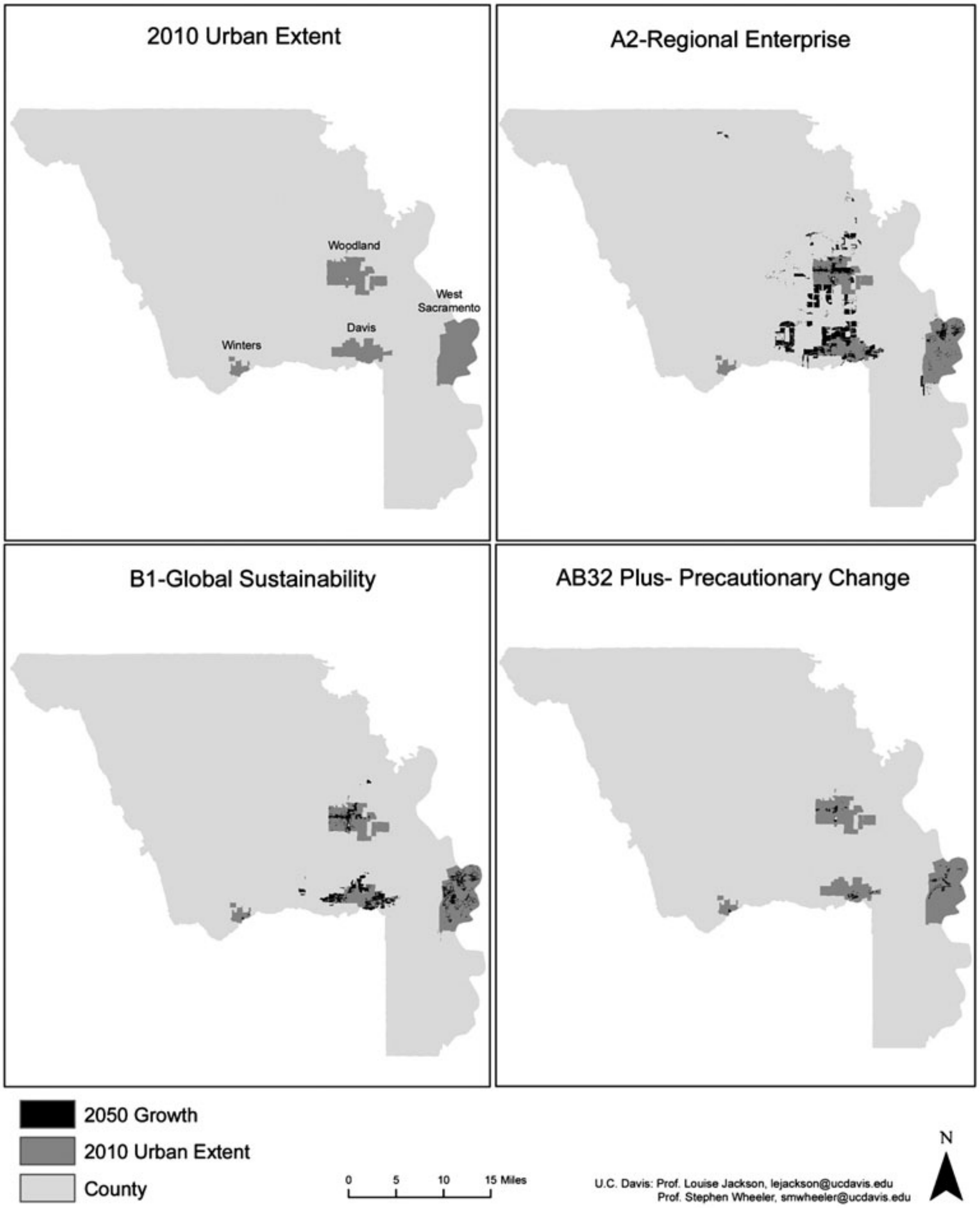

Figure 2. Urban growth in Yolo County, 2010–2050, by scenario.

Not surprisingly, transportation-related GHG emissions from new development vary greatly across the three scenarios (Table 4). Land use changes alone decrease emissions by about 23% in the B1 scenario and 53% in the AB32-Plus alternative. (Figures are for private motor vehicles only; we did not consider emissions from public transit.) Adding other storyline assumptions about population and energy efficiency produces a 12-fold difference in transportation-related emissions; our greenest scenario represents about a 92% reduction compared with the A2 alternative. The story is similar with GHG emissions from residential energy use. Land use changes alone lower residential

Table 5. Agricultural area lost to urbanization by 2050, by crop type, under each storyline. All values in acres.

Crop type	A2	B1	AB32-Plus
Alfalfa	2,329	621	2
Almond and pistachio	81	2	–
Barren	28	3	–
Corn	505	167	–
Cucurbits	13	–	–
Dry beans	85	54	1
Fallow	170	25	–
Forest	–	–	–
Grain	1,422	471	–
Grassland	67	48	1
Onions and garlic	68	2	–
Other deciduous trees	107	83	–
Other field crops	1,358	366	–
Other subtropical crops	2	–	–
Other truck crops	23	3	–
Pasture	1,629	514	15
Processing tomato	1,958	704	4
Rice	–	–	–
Safflower	515	258	–
Vine	203	40	–
TOTAL	**10,562**	**3,363**	**23**

energy-related emissions by about 46% in the infill-only scenario. When other storyline assumptions are added, differences in emissions are again about 12-fold. Overall, development in AB32-Plus produces approximately 8% (compared to A2) of the emissions from transportation and residential-housing operations, or about 14% with population held constant.

Other portions of our larger project (Jackson et al. 2009; Jackson et al. 2012) focused on the impact of climate change and urbanization on agricultural landscapes. Overall land losses, even in the A2 scenario, are modest in relation to the size of the county: about 3% of irrigated farmland, which is a testament to the county's relatively good track record of protecting agricultural land. The acreages of crops lost to development range from 10,562 in A2 (4274 ha) to 3363 in B1 (1373 ha), to 23 in AB32-Plus (9.31 ha) (Table 5). (Even though the AB32-Plus storyline calls for all development to occur within existing urban areas, current municipal boundaries include some farmland.) Alfalfa, processing tomatoes, and pasture lands had the highest acreage loss under the A2 storyline. Under the B1 storyline, impacts were higher on processing tomatoes than on alfalfa, a lower-value crop. This analysis is based on observed planting patterns as of about 2008. At this time, agricultural production is dominated by a few crops that can be easily stored and transported, because only 2% is consumed locally (Jackson et al. 2012). But the climate and soils in the region support a diverse set of other fresh-market crops, and loss of this agricultural land near towns and cities would make a future locally based food system more difficult to achieve.

The relatively dispersed pattern of urban growth in A2 could make agriculture more difficult by making it harder to move equipment between fields, by undermining agricultural supply and processing industries, and by creating public opposition to aerial spraying, noise, odor, and other typical agricultural occurrences. In these ways, this scenario could amplify farmers' operational or economic hardships due to climate change. Other types of land use change are also related to urban sprawl. UPlan modeling showed, for example, that the loss of floodplain land was 1226 acres (496 ha) in the A2 scenario, versus 20 and 9 acres (8.1 and 3.6 ha) in B2 and AB32-Plus, respectively. By fragmenting the landscape and consuming more land area in wetlands, vernal pools, and natural-diversity areas, urbanization in the A2 scenario could also work against the provision of ecosystem services, biodiversity conservation, and open space and its aesthetic and recreational value.

Conclusion

These results show that the compact urban AB 32-Plus development storyline in an agricultural county as shown in our AB 32-Plus storyline is likely to be able to reduce GHG emissions from transportation and residential building operations from new development by more than 50% in 2050 compared with business-as-usual development (our A2 scenario, which is by no means a worst-case-sprawl future). Adding assumptions about increased energy efficiency of vehicles and buildings as well as dramatic improvements in the utility-portfolio mix produces an 88% emissions reduction. And adding slower population growth would produce more than 92% lower 2050 GHG emissions from new development compared with the trend scenario. If builders were to add photovoltaic panels or other alternative energy technologies to structures, presumably most new development could then be carbon-neutral, and could perhaps even produce enough surplus electricity to offset vehicle usage (assuming vehicles were electric). Thus, in terms of new development at least, our AB32-Plus storyline does seem to point the way toward urban-growth patterns that meet the state's strong GHG-reduction goals.

Despite this significant achievement, it is important to be realistic about the overall prospects for meeting the state's goal of bringing GHG levels to 80% below 1990 levels by 2050. New development does not directly help in meeting this goal unless it is undertaken to replace existing units (not our assumption here). If built to house additional population, new development simply adds to total emissions, unless it generates enough energy itself to offset building and occupant usage. If done in such a way as to improve the market for public transit, promote local businesses, and better balance jobs, housing, and other land uses, such development is likely to lower the VMT by residents of existing housing units as well. However, such influences go beyond the analysis presented here. Overall, we can conclude that development in highly compact forms has great potential to bring about a nearly carbon-neutral future, and offers striking contrasts with conventional forms of development. But many other policies related to existing buildings, industry, agriculture, transportation, and lifestyle will be required, as well, to reduce overall GHG emissions 80% by 2050.

The county's Climate Action Plan is designed to address only GHG reductions for 2020 and 2030 (Yolo County 2011), so it is difficult to determine the relative share of reductions that land use strategies might account for within a 2050 policy package. Again, this will depend in large part on what policies are undertaken to improve existing urban development, as well as the forms that new development takes. To compensate for increased population and related emissions (e.g. personal consumption, diet, air travel, and the emissions inherent in new-building construction), it is quite likely that both new and existing development would need to have even lower operating emissions than the 80% target would indicate. Changes in personal consumption and lifestyle (e.g. the demand for travel) are likely to be essential. A broad storyline encompassing many different changes such as these appears necessary to charting a path towards effective climate action.

In terms of form, new urbanization under our AB32-Plus scenario could take the form of mixed three-to-five-story multifamily buildings and townhouses of types already widely constructed in the more urban regions of California (and of course traditional within older cities such as San Francisco). This building format, widely promoted in New Urbanist typologies (e.g. Zone T5 in the SmartCode developed by DPZ & Company [2012]) and within SACOG's own regional planning materials (e.g. SACOG, n.d.), can yield net densities of 50 dwelling units per acre or more. In terms of farmland protection – one important climate-adaptation goal, given likely local and global needs for food supplies in a changed world – the AB32-Plus scenario is highly useful, although diversification and changes to farming practices will be necessary for climate adaptation and orientation toward local food production (Jackson et al. 2011). A co-benefit is that farmland produces approximately 1/70th the GHG emissions per acre, compared to urban land in the county (Haden et al. 2013). Differences in farmland protection between the AB32-Plus and the A2 paths would be even greater were the county's baseline land use policy of the pro-growth nature common to most other jurisdictions in the Central Valley. A strong growth-management framework (as under our AB32-Plus scenario) would most likely combine a number of the following strategies, many already contained within the county's General Plan, municipal General Plans within Yolo County, and the Sacramento Region's Blueprint, and also modeled by jurisdictions elsewhere in California:

- Strong agricultural zoning – for example, requiring 80-acre or 160-acre minimum parcel sizes in much of the county (the current status)
- Farmland-protection measures such as mitigation-fee requirements on developers, purchase of development rights, transfer of development rights along with conservation easements, and funding of California's Williamson Act, which preserves agricultural and open space lands by discouraging conversion to urban uses
- Urban growth boundaries, urban service boundaries, or similar policies establishing sharp edges between urban and agricultural lands and locking in farmland protection more securely than through zoning
- Acquisition of conservation easements on agricultural lands by local agencies or nonprofit organizations, especially on farmland in likely-to-develop locations such as near freeway interchanges
- Adoption of municipal policies to facilitate and encourage infill development near town and neighborhood centers, major employers, and transit-accessible locations
- Adoption of municipal policies for urban greening – that is, to increase urban tree canopy, create coordinated greenspace networks, decrease hardscapes, and reduce runoff, thus enhancing a range of environmental benefits for both urban residents and nearby farmers
- Expanded county and regional planning to coordinate infrastructure with these strategies, and to develop large-scale land use plans identifying, for example, desirable habitat-conservation corridors through both urban and agricultural lands, and strategies to promote long-term agricultural viability and improved farm-to-table connections within the region

Overall, this study has outlined one method by which global climate change storylines such as those developed by the IPCC might be downscaled to the local level and applied to urban-growth modeling using a backcasting approach. We acknowledge that such modeling is broad-brush and involves policy assumptions far removed from current reality in land use planning and other fields. However, we believe such efforts are important to help the public and decision-makers understand the need for dramatic long-term changes in patterns of urbanization, and for policymakers to begin developing multidimensional agendas for sustainability that take into account urbanization, energy systems, population, agriculture, lifestyles, and ecosystems.

Note

1. A note on terminology. "Storyline", as used by the Intergovernmental Panel on Climate Change, refers to a generalized set of expectations about the future that form an internally consistent trajectory. A "scenario" adds more specific parameters to that storyline such as can be used for modeling.

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