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Does infill outperform climate-adaptive growth policies in meeting sustainable urbanization goals? A scenario-based study in California, USA

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HIGHLIGHTS

- Demonstrates integration of climate impacts and urban growth for a large area.
- Informs strategic regional planning for new urban growth.
- Responds to calls in the literature to advance beyond general impact projections to strategy-informing research.

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ABSTRACT

Land allocation for urban growth is central to sustainable development strategy because urban growth can impact space available for food production, ecosystem services and biodiversity conservation. Urbanization is a growing stressor due the 2.5 billion additional people projected to live in urban areas by 2050. Potential climate change impacts to natural systems increase the need for sustainable urbanization, which should integrate land use needs for urban growth with climate adaptation objectives such as maintaining biodiversity, food production and ecosystem services. Here we compare climate-neutral and climate-adaptive urbanization scenarios to see which produces the most sustainable urbanization, defined as being the most effective at meeting development, conservation, and two climate adaptation objectives. We modeled five urban growth scenarios portraying an increase of 25.8 million people by 2050 for California, USA comprising three climate-neutral scenarios: business-as-usual, compact-new-growth and infill (redevelopment); and two climate-adaptive scenarios: preservation of agricultural climate refugia or future plant dispersal corridors. Infill was the least impacting for the multiple objectives tested; preserving 46–57% more land for other uses. Each climate-adaptive scenario reduced land consumption for its respective target, but increased impacts to the opposite climate-adaptive scenario target. Infill has the potential to contribute towards sustainable urbanization, particularly if combined with other climate adaptation targets.

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1. Introduction

Urbanization is an important factor in achieving sustainable development (Wu, 2014) because over 54% of the global population is in cities and urban environments. Since 2008 most humans experience urban environments as the new normal and cities are expanding at a rapid rate, with an additional 2.5 billion peo-

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ple projected to live in them by 2050 (United Nations, 2014). A major challenge to make urbanization sustainable is to understand the trade-off between allocating land for future urban areas and the opportunity costs of such land consumption on existing ecosystems. Urban growth impacts land available for agriculture (Lambin & Meyfroidt, 2011), livestock production (Satterthwaite, McGranahan, & Tacoli, 2010), timber (Nowak & Walton, 2005), biodiversity (Grimm, Faeth et al., 2008; Grimm, Foster et al., 2008; Newbold et al., 2015; Seto, Gunerlap, & Hutyra, 2012), and ecosystem services such as water delivery and carbon sequestration (Grimm et al., 2008a,b; Hutyra, Yoon, & Alberti, 2011; Theobald, Hobbs, Bearly, Zack, Shenk, & Riebsame, 2000). However, land allocation for urban growth should also consider the stress that climate change may impose on regional ecosystems and the services they provide. Climate change may fundamentally alter the spatial patterns of land needed for a variety of objectives. For example, climatically suitable environments for native species may shift from one area to another (Brooker, Travis, Clark, & Dytham, 2007), food production areas may be more or less vulnerable to climate change (Schmidhuber & Tubiello, 2007), and risks from fire and other disturbances may become more pronounced (Moritz et al., 2012). Therefore, we expect that the careful coupling of climate change effects in surrounding ecosystems with projected urban growth models can yield more sustainable urbanization opportunities, i.e. future urbanization that minimizes consumption of existing and potential future ecosystem lands at regional scales.

To determine whether climate-adaptive urban growth scenarios outperform climate-neutral, or conventional, urban growth scenarios to achieve sustainable urbanization, we used UPlan, a high-resolution, spatially explicit gridded urban growth model (Johnston, Shabazian, & Gao, 2003) whose input parameters can be manipulated to represent different policy scenarios (Thorne, Santos, & Bjorkman, 2013). We modeled five policy scenarios: three are conventional urban development approaches that do not consider climate impacts (Business-as-Usual, Compact-New-Growth, Infill); and two others target climate adaptation by preventing new urban development on agricultural land projected to be least impacted from climate change, or on lands identified as the most critical climate corridors required for 2235 plant species native to California to reach future climate-suitable locations (Thorne, Bjorkman, & Roth, 2012; Hannah, Shaw, Roehrdanz, Ikegami, Soong, & Thorne, 2012). Climate projections were used to identify the most important aggregate pathways for plant dispersal to future climatically suitable areas (Hannah et al., 2012; Phillips, Williams, Midgely, & Archer, 2008). For the Agricultural Adaptation scenario, we ranked agricultural lands from most to least climatically exposed, and assigned a range of urban growth attractor and detractor values to move new urban growth towards agricultural lands expected to be most impacted by climate change, and minimize new growth on the least climatically impacted agricultural lands. For the Biodiversity Adaptation scenario, we similarly discouraged new growth from occurring in corridors needed by the most plant species for dispersal to future climatically suitable locations, and attracted new urban growth elsewhere.

We used California, USA as a model system. California covers 410,000 km^2, and is expected to grow to 50–60 million inhabitants by 2049 from 33.5 million in 2000, the base year for our urban growth modeling (Sanstad, Johnson, Goldstein, & Franco, 2009; State of California, 2012). In 2000, the state had 21,230 km^2 in urban extent containing 81.3% of the state's population (State of California, 2012). By 2010 the urban area has increased by 1.4% (United States Census, 2010). The projected 50-year time frame represents the outer horizon for which state and county planning typically occurs in California. We used the higher population growth projection and the more impacting of two climate projections tested in order to have a clear picture over the potentially conflicting land-use needs. We used a population growth projection of $\sim 25.8 \times 10^6$ by 2050 (Sanstad et al., 2009), and two climate projections representing annual minimum temperature warming of 1.1–1.8 °C and changes in annual precipitation of +8- −5% by 2050, from base statewide mean climate values of 6.9 °C and 587.1 mm during 1981–2010 (Thorne et al., 2012; Flint, Flint, Thorne, & Boynton, 2012; Thorne, Boynton, Flint, & Flint, 2015). Climate data at 270 m grid scale were used to rank California's agricultural areas (Hollander, 2010) from least to most aggregate climate exposure. We sought the scenario that accommodates new population growth with the least impact on the area of existing natural vegetation, future native plant climate corridors, and agricultural climate refugia as the best (and most sustainable) urbanization solution.

2. Methods

We developed five urban growth scenarios for the projected 25.8 million new California residents by 2050 (Sanstad et al., 2009), and ran projections of the spatial location of the needed urban growth using UPlan (Johnston et al., 2003; Beardsley, Thorne, Roth, & McCoy, 2009; Thorne et al., 2013), an urban growth model with high spatial resolution. Three scenarios are urban growth policy–only and do not incorporate climate adaptation, because we wanted to test whether by such policies alone we could meet goals for both development and climate adaptation, or if additional action would be required for climate adaptation:

1 Business-As-Usual (BAU) that simulates legally permissible urban sprawl;
2 Compact-New-Growth (CNG) that increases the density of new growth and situates it closer to existing urban centers;
3 Infill (IF) a redevelopment scenario that places a proportion of new growth inside existing urban boundaries (Thorne et al., 2012, 2013).

We created two new climate adaptation scenarios that incorporate climate risk:

1 Biodiversity Adaptation (BA) that minimizes new urban expansion on lands projected as needed for large numbers of plant species to disperse from current ranges to new ranges;
2 Agricultural Adaptation (AA) that minimizes impacts to existing agricultural lands that are expected to be those least impacted by changing climate.

Each scenario was run from 2000 to 2050 on a per-county basis for the 58 counties in California, and the results aggregated to statewide scale (Thorne et al., 2012).

2.1. Urban growth model – UPlan

UPlan is a rule-based, spatially explicit model that assigns new urban growth based on a combination of population projections, existing infrastructure, and a series of spatial attractors and discouragement factors. The UPlan model can be used to project and compare future development patterns from different land use policies, and is typically run for individual counties. The UPlan model requires relatively few parameters, and is therefore useful for scenario visualization (Beardsley et al., 2009; Huber, Thorne, Roth, & McCoy, 2011; Roth, Thorne, Johnston, & McCoy, 2012; Byrd, Rissman, & Merenlender, 2009). Actual patterns of development are affected by many things outside of policy. The goal of this tool is not to replicate exact patterns of development, but to estimate the magnitude and spatial pattern of urban growth under various policies to support planning and decision making about future development.

In UPlan, the amount of new urban growth depends on the expected population growth for a region, the proportion of new growth expected within distinct land use classes, the average lot size of each residential class, the average space needed per employee for each commercial and industrial class, and the number of persons and employees per household. By using starting and projected ending population numbers, as well as the average persons-per-household, the model calculates the number of new households needed per year.

In this study, the base population for each county was the population in the year 2000, according to the United States Census (2010). Then we chose future projections that represented the higher projected population numbers and the most impacting of two climate scenarios. This was done so that we could identify strong potential impacts as compared to the impacts from more moderate projections, therefore permitting a clearer assessment of the potentially conflicting land-use needs. We used human population growth projections on a county-by-county basis from Sanstad et al. (2009), in conjunction with county general development plans that delineate each county's lands into lands on which specific land uses can be developed (Appendix A in Supplementary information; Thorne et al., 2012). Note that subsequent projections of California's population growth by 2050 have declined from ~25.8×10^6 people (Sanstad et al., 2009) to 16.5×10^6 people (United States Census, 2010), but we retained the higher projections in this study.

The projected population numbers are partitioned into new units of residential, commercial and industrial buildings, which UPlan allocates sequentially by unit onto a raster grid of the study area, according to the most attractive locations. The user provides the percentage of new growth that should be allocated for each land use class, as well as the average lot size of each land use class. The model then partitions the new units into the different residential size classes. A similar process is used by UPlan to determine the location and area of land consumed for industrial and commercial land use classes, in which the number of workers per household, percent of workers in each employment class, and average area per worker are inputs used to assess the area and number of units constructed (Johnston et al., 2003; Appendices A, B and C in Supplementary information).

The UPlan model was run using a base grid of 50 × 50 m cells. Each grid cell is weighted by its attractiveness to each type of growth (Johnston et al., 2003). The attractiveness of each grid cell is determined through a set of user-defined attractor and detractor weightings that can be combined in different ways to simulate different policies (Beardsley et al., 2009; Byrd et al., 2009; Huber et al., 2011; Roth et al., 2012; Thorne et al., 2012). Examples of attractors include proximity to transportation and infrastructure, detractors can include sensitive habitats and floodplains, and some cells can be masked to prevent development such as for lakes or protected areas. These layers are then combined to create a single version of the landscape with varying overall levels of attractiveness, onto which the new urban units are sequentially assigned. The UPlan spatial output of new development is also guided by city and county general plans, through attractors and detractors that reflect the long-term development plans put forth in map form by the local governments (for example, the locations and proportions of new residential, industrial and commercial development zones).

For this study, the following attractors were used, depending on the scenario and land use class: highways, major roads, minor roads and ramps, city boundaries, Census blocks with positive growth between 1990 and 2000, Amtrak Railroad Stations, rail lines, transit stops and existing urban areas (Appendix D in Supplementary information). Some attractors, such as minor roads, will not likely be considered universally desirable to all new growth, and therefore are only included for certain land use classes, such as residential and commercial. Also, some attractors, such as Amtrak stations and transit stops, were only used for some policy scenarios, such as Infill. The areas considered to deter growth, called discouragement factors, included wetlands, threatened and endangered species and their habitat, vernal pools and the locations of 100-year floodplains for all of the scenarios used for this study. Additional discouragers for the BP and AP scenarios include the layers created using future climate models, detailed below. The areas that were masked completely, prohibiting new growth, include lakes and rivers and public open space; and the existing urban areas were masked for BAU, CNG, AA and BA (Appendix D in Supplementary information). Full parameters for the policy-only models are in Thorne et al. (2012).

Rules for the policy-only model scenarios:

(1) "Business-As-Usual" (BAU): the percentage of people placed in each residential density class is similar to the current residential density patterns (United States Census, 2010), and assigns a higher percentage of the new population to lower-density residential classes that require more area than the next two scenarios. This scenario represents no change in current policy.
(2) "Compact-New-Growth" (CNG): more of the new population is placed in new, high-density living space. Urban growth in this scenario is concentrated around the edges of existing towns and cities. The CNG changes the percentage of new population in each residential class from the BAU allocation to a new amount such that the higher-density classes have a higher percentage of new households and the low-density classes will have fewer new households. However, the CNG does nothing in the way of redevelopment or infill, so all new growth continues to consume exurban open space.
(3) "Infill" (IN): the predicted new population is entirely placed inside existing urban areas, resulting in some urban areas becoming denser. People and buildings displaced by the infill are then placed, in a second run of the model, using the CNG rules (Thorne et al., 2012). This has the overall effect of simulating a proportion of the new population within existing urban areas that varies by county from 42.7 – 89.6%, excepting a few counties that did not have enough urban in the starting conditions for infill to occur (Appendix E in Supplementary information). In this case new urban growth was placed elsewhere using CNG rules.

For the climate-adaptive scenarios we used two Global Climate Models (GCMs) described below under an emission scenario that has greenhouse gas concentrations that are relatively close to actual measured conditions. We then reduced the projected impacts to a single value per grid cell that is conservative, in that it ranks the climate inputs and selects the highest impact potential to agriculture and to biodiversity movement. These values became inputs to the two urban growth scenarios that simulate climate adaptation strategies (Fig. 1):

(1) "Agricultural Adaptation" (AA): new urban growth is directed through model discouragements, away from agricultural lands expected to be less impacted by future climate change, while agricultural lands expected to be more adversely climatically impacted if they remain in agriculture are made relatively more attractive to new urban growth. The overall effect of this scenario is to reduce land consumption for the most climate resilient agricultural lands. Some agricultural lands are still converted to urban, in places where the attractions are stronger

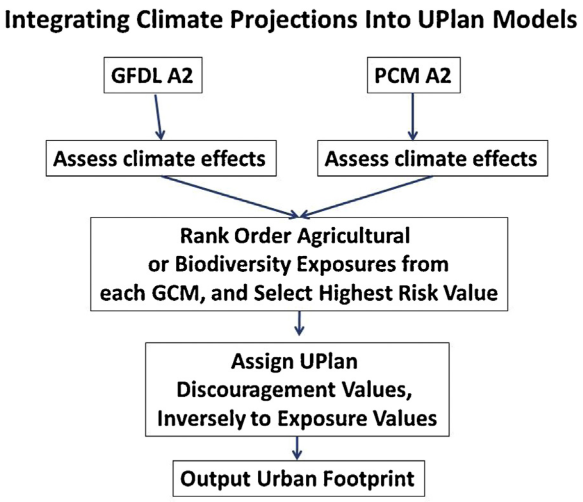

Fig. 1. Schema showing how climate data are integrated on a per-pixel basis to inform urban growth models.

than the discouragements (Appendix G in Supplementary information).

(2) "Biodiversity Adaptation" (BA): new urban growth is progressively discouraged from lands ranked increasingly important for plant connectivity of 2225 native plant species under climate change. This scenario prioritizes enabling native taxa to meet the predicted range shifts under climate change, by discouraging urban growth in areas projected to be needed for plant populations to move through over 50 years to reach newly climatically suitable areas (Appendix G in Supplementary information).

We used two GCMs that portray a hot and dry future, and a warmer and slightly wetter future for California (A2 scenario, Parallel Climate Model [PCM] and Geophysical Fluid Dynamics Laboratory [GFDL]), for the time period 2040–2069 to compare with the current (1981–2010) climate (Cayan, Mauer, Dettinger, Tyree, & Hayhoe, 2008). These future and current climates were previously statistically downscaled to 270 m grids (Flint et al., 2012; Thorne et al., 2012, 2015). Other GCMs and emission scenarios have been developed for this region, but to limit the complexity of the subsequent modeling only two were used. We used the level of climate change from each GCM in each grid cell to identify the highest level of risk from changing climate in that grid cell. Every grid cell was then resampled to the 50 m grids of the UPlan models, rank-ordered for climate risk (also called 'climate exposure'), and this value was used to assign the level of attraction each grid cell had for the two climate adaptive urban growth scenarios (Fig. 1).

For the "Agricultural Adaptation" scenario, a map portraying the extent of California's agricultural lands (39,861 km^2; Hollander, 2010) was used to assess current and future climatic conditions for existing agriculture. Mean annual minimum temperature (Tmin) and annual precipitation (PPT) were calculated by grid cell, and their average for a recent 30-year time period (1981–2010) were developed, as well as the associated one and two standard deviation values. To measure the level of change at each grid cell, the mean annual values of Tmin and PPT under each of the two future climate scenarios for the 2040–2069 period were calculated, and the difference from current conditions was taken. Grid cells were then ranked, with a value of one if the future PPT declined by ≤ 1 standard deviation of the current precipitation value, and a value of 2 if changes in PPT were >1 standard deviation. For Tmin, a value of one was given to crop areas that were ≤ 1 standard deviations of the current Tmin value. Crop areas that had values beyond this range were given a value of two. The four reclassified precipitation and minimum temperature values, two from each GCM used, were then summed for each cell. The higher the resulting value, the more risk to existing agriculture was assumed. Scores from four to eight were assigned decreasing levels of discouragement from 60 to 0 for use in the UPlan model run (Fig. 2a). Grid cells with higher discourager weights represent a policy attempt to preserve them from future development, because the climate risk at those locations is lower. Conversely, agricultural lands that appear highly exposed to climate change received lower discouragement values, which would permit urban growth on these lands if they were generally more attractive than other locations. Areas with lower increases in Tmin and either increasing or less loss of PPT were considered the priority for preservation.

The "Biodiversity Adaptation" scenario seeks to preserve priority areas for the conservation of native California plant species under future climate change. Hannah et al. (2012) adapted the Network Flow Analysis (NFA), originally described by Phillips et al. (2008), to identify connectivity chains, which are areas of suitable habitat linked through time. This approach uses the modeled range of a single species through time as a directed network, identifying nodes in succeeding time steps that are within a defined dispersal range. The network and nodes form a temporal connectivity chain, or a continuous path through which a species could potentially disperse from currently suitable habitat through decadal future time steps to future suitable habitat. The Hannah et al. (2012) study included 2235 native California plant species, which were modeled under the same two climate model outputs (GFDL and PCM A2), for two time periods (2000–2050 and 2000–2080), using two minimum conservation target areas (100 and 1000 square kilometers), and three dispersal assumptions (no dispersal, limited dispersal per time period of 1.54 km grid cells, and intermediate dispersal per time period of 2.5 grid cells; Fig. 2). For inclusion in the UPlan BA Scenario, only the 2000–2050 time period and intermediate dispersal outputs were used. UPlan discouragement weights were highest for grid cells that Hannah et al. (2012) prioritized for multiple plant species connectivity chain dispersal under both GCMs and both the 100 and 1000 km^2 conservation target analyses. The two climate model outputs and two conservation targets were combined to provide a range of discouragement weights (Appendix B in Supplementary information). The highest discouragement weight was given to areas that were prioritized under both climate scenarios and both dispersal target areas, with decreasing weights for cells that were prioritized under only one climate scenario or one target area (Fig. 2b). Decreasing values of discouragement were assigned to grid cells that emerged as conservation priorities under only one GCM or only one spatial analysis.

Except for additional weightings provided as per the climate modeling, the climate-adaptive scenarios follow the Business-As-Usual parameters. We did not apply the climate adaptation rules to CNG, BAU and IN because we wanted to isolate the effects of the climate-adaptive scenarios. We ranked all grid cells in the state in terms of areas most climatically likely to remain productive in agriculture, because the climate conditions changed least at those locations; and the areas most likely to be used by large numbers of native plant species as they are forced to migrate to keep up shifting climatically suitable habitats. We used these rankings to develop each of the two climate-adaptive policy scenarios.

There are a number of simplifying assumptions in UPlan. One assumption has to do with the parcel size of residential density classes, which can vary in reality, while the model requires the lot size of each residential density class be a single value. Thus, the area consumed as represented by the model may differ from the actual area used. Another assumption is that the attractors and detractors used are the primary drivers of where new urban growth would go. While this is likely the case, there may be places with attrac-

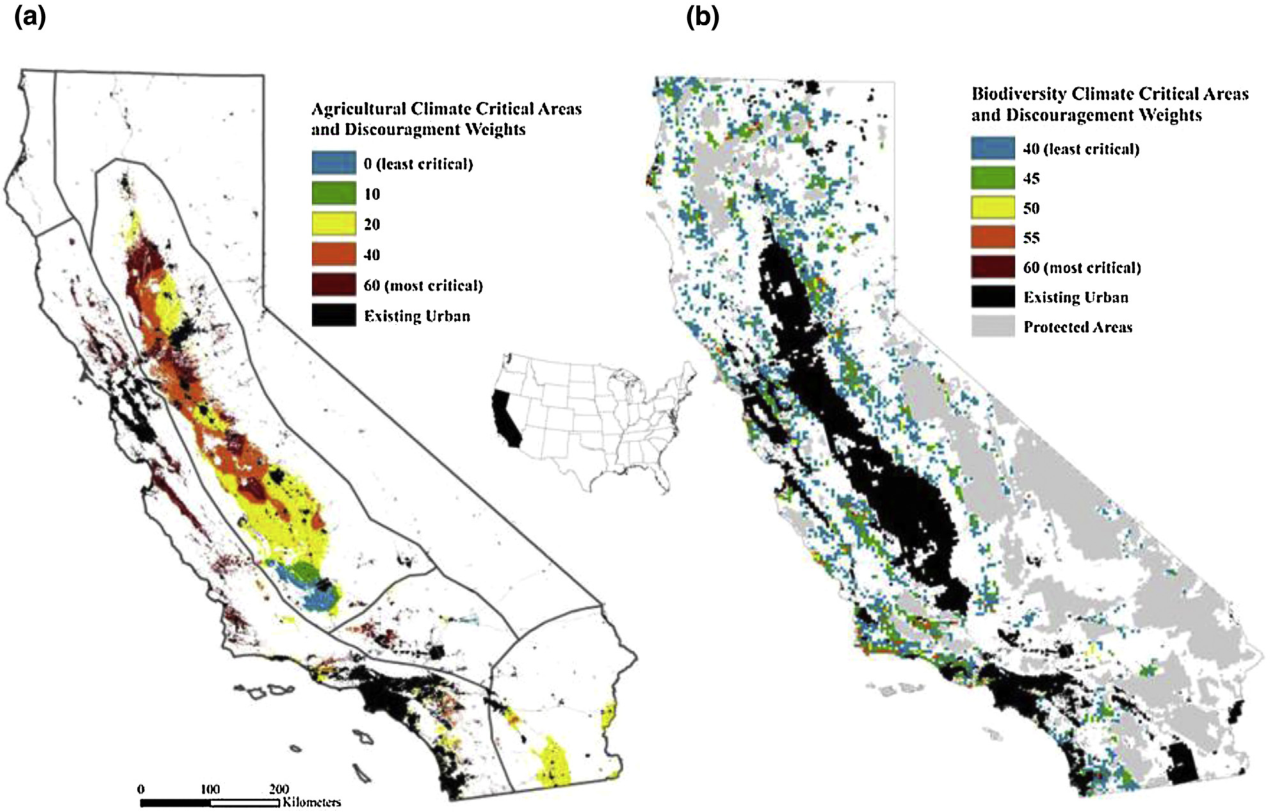

Fig. 2. Spatial discouragement weighting used in the climate-adaptive urban growth policy models: (a) Agricultural Adaption (AA), (b) Biodiversity Adaptation (BA). For the AA scenario, a map of California's agricultural lands (39,861 km^2; Hollander 2010) was used to assess current climatic conditions and future climate exposure for existing agriculture. This allowed integration of a climate-related data into the urban growth model. For the BA scenario, maps of important linkages from the Network Flow Analysis (Hannah et al., 2012) with an assumption of intermediate dispersal capacity were used. The higher importance values from the two GCM NFAs was used to weight levels discouragement for new urban growth.

tions or detractions that UPlan does not readily capture. In addition, the model scenarios are assumed to be uninterrupted for 50 years. In reality things may change on a decade-by-decade basis, but we feel it is informative to visualize the projected influence of a policy across a longer time period.

3. Results

The most efficient scenario for minimizing impacts to current and future natural vegetation is Infill. Over all the scenarios, the projected land consumed varied from 8289 km^2 (Infill) to 19,022 km^2 (Business-as-Usual). Across all scenarios, the most new urban land was allocated to residential land use (mostly low density residential areas, or in the case of Infill intermediate density residential areas; Table 1). Among the conventional scenarios, Business-as-Usual predicted the greatest extent of new development (Fig. 3), including 14,537 km^2 (76.4%) of new residential, 521 km^2 industrial and 3964 km^2 commercial (Table 1). The Compact New Growth and Infill scenarios used 15,495 km^2 and 8289 km^2, respectively (Table 1; Fig. 3). Residential growth was the largest land consumer,

Table 1
The extent of land required for residential, commercial and industrial uses under five urban growth scenarios: BAU – Business-as-Usual, CNG – Compact New Growth, IN – Infill, BA – Biodiversity Adaptation, and AA – Agricultural Adaptation. Residential urban uses include seven house densities (in residential units per 0.4 ha; Thorne et al., 2013). Commercial urban uses include two categories, high and low; industrial urban use is defined in a single category.

Urban (km^2)	2050				
	BAU	CNG	IN	BA	AA
Total Urban	19 022	15 495	8 289	19 018	19 018
Residential	14 537	10 985	5 665	14 534	14 534
Commercial	3 964	3 987	2 338	3 963	3 963
Industrial	521	523	286	521	521
Number of Residential Units per 0.4 ha					
Residential 50	0	49	303	0	0
Residential 20	598	697	918	598	598
Residential 10	0	463	1 741	0	0
Residential 5	4 583	2 822	532	4 582	4 582
Residential 1	2 740	2 635	270	2 740	2 740
Residential 0.5	0	276	535	0	0
Residential 0.1	6 615	4 044	1 366	6 614	6 613
Commercial H	423	416	439	423	423
Commercial L	3 541	3 571	1 899	3 540	3 540
Industrial	521	523	286	521	521

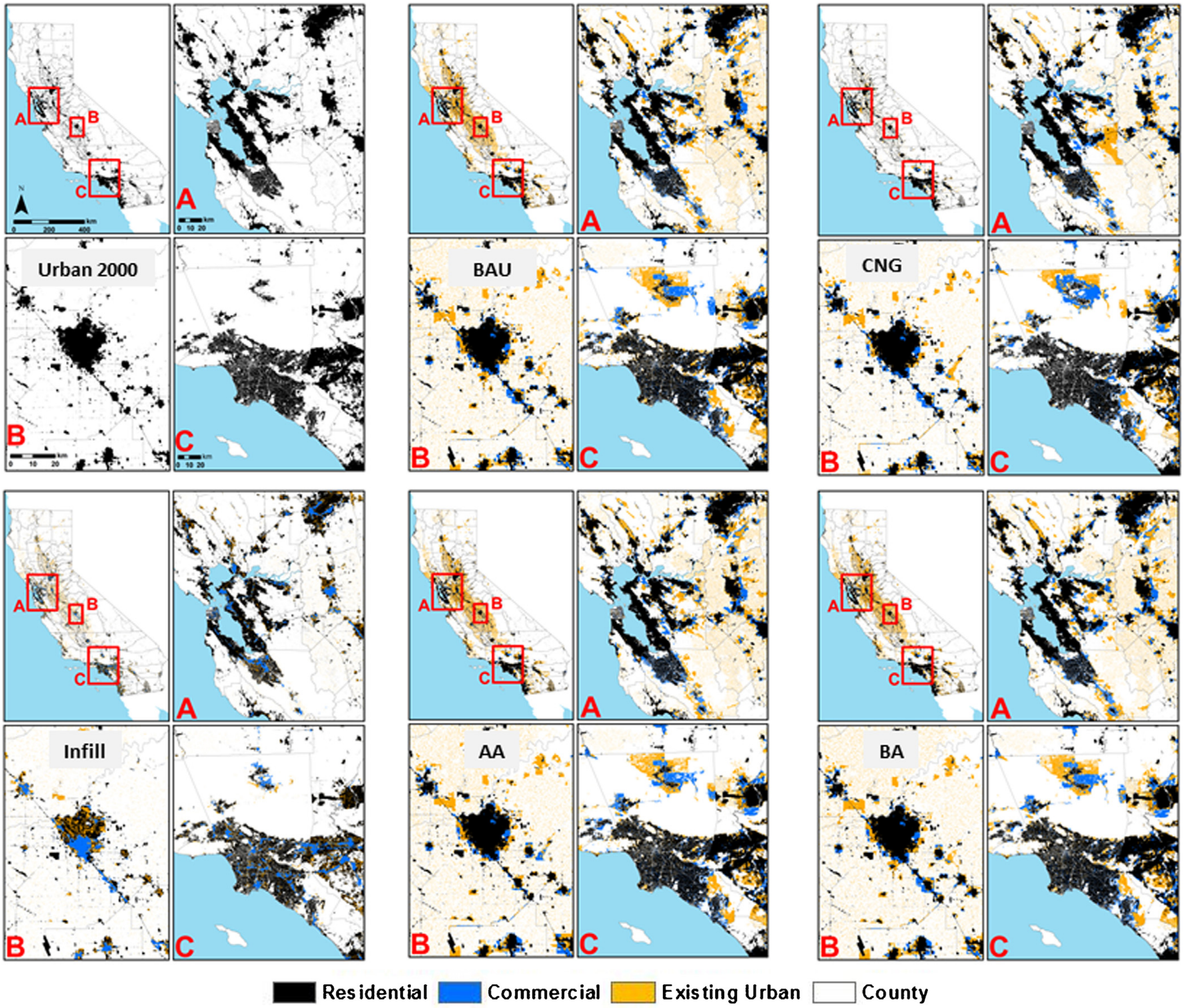

Fig. 3. Starting and predicted urban growth for California under five growth scenarios. From left to right top row: Urban in 2000, Business-as-Usual, and Compact New Growth; second row from left: Infill, Agricultural Adaptation, and Biodiversity Adaptation.

with 68.3% of land used under Infill, 70.9% under Compact New Growth. Both climate-smart scenarios consume nearly identical amounts of land to the Business-as-Usual scenario reflecting the fact that these adaptive scenarios used the BAU rules (Table 1; Fig. 3).

Impacts to natural vegetation were lowest with the Infill scenario (588 km^2), and greatest for the Agriculture Adaptation scenario (11,334 km^2), as new urban growth was diverted from agricultural areas to natural areas. The BAU scenario required 10,493 km^2 of current vegetation, with grasslands, oak woodlands, and desert vegetation dominated by Joshua trees being the most impacted. Compact new growth required 8480 km^2 of California's natural vegetation, and Infill consumed 588 km^2 (Table 2; Fig. 4) while the BA scenario required 10,431 km^2 of current natural vegetation.

Consumption of climate-adaptive agriculture and plant connectivity lands was lowest for the Infill scenario (Fig. 4, Table 3). The policies targeting particular climate-adaptations did respectively reduce land conversion in agricultural refugia and plant connectivity areas as intended. The AA scenario consumed a similar amount of agricultural land as the CNG scenario, but reduced impacts to agriculture lands projected to be less climatically vulnerable. Similarly, the BA scenario reduced impacts to dispersal corridors, slightly more efficiently than the CNG.

4. Discussion

As land use and climate continue to transform the environment (Newbold et al., 2015), it is ever more important to examine the policies and practices that govern where and how growing urban populations can be placed to minimize environmental impacts and maximize sustainability. In particular, it is important to assess what land use policies offer regional solutions that meet both development and multiple other spatial land use needs for resilience to climate change such as biodiversity, ecosystem services and agriculture. While the scientific community is already aware of the need to preserve natural attributes and ecosystem services (Zank et al., 2016; Lambin & Meyfroidt, 2011), on the one hand, and the impacts of urban growth and climate change on the other (Haddad et al., 2015); this study integrated these considerations to explore

Table 2
Extent of California's natural vegetation types in 2010 and projected conversions to urban uses under five urban growth scenarios: BAU – Business-as-usual, CNG – Compact New Growth, IN – Infill, BA – Biodiversity Adaptation, and AA – Agricultural Adaptation, in km^2.

Natural Vegetation Types	Area 2010 (km^2)	BAU	CNG	IN	BA	AA
Annual Grassland	41612	3290	2564	22	3194	3705
Barren	10374	45	38	12	41	49
Brush and Timber	6195	1270	1008	72	1239	1354
Coastal Scrub	6795	749	669	44	719	786
Eucalyptus	49	9	8	0	8	10
Joshua Tree	94424	2165	1905	174	2274	2274
Native Vegetation	199	28	23	9	28	30
Pinyon-Juniper	20287	188	146	19	196	193
Redwood	5221	70	66	12	73	72
Sagebrush	17891	126	100	19	123	132
Subalpine Conifer	8500	3	2	3	3	3
Valley Oak Woodland	37607	1951	1477	35	1914	2095
Water	5981	42	37	16	44	49
Wet Meadow	2948	118	98	53	114	132
White Fir	51662	441	341	98	461	451
Total area (km^2)	309745	10493	8480	588	10431	11334

Table 3
Projected extent of urban growth on agriculture lands ranked by climate exposure and on biodiversity lands ranked by climate exposure in California by 2050, under five urban growth scenarios: BAU – Business-As-Usual, CNG – Compact New Growth, IN – Infill, AA – Agricultural Adaptation, and BA – Biodiversity Adaptation. The higher the discouragement class the more suitable areas are as agricultural refugia or biodiversity corridors, and therefore less attractive to urban growth.

Urban Growth Discouragement Class	Climate-resilient Agricultural Land (km^2)					Climate-Resilient Biodiversity Connectivity (km^2)				
	BAU	CNG	IF	AA	BA	BAU	CNG	IF	AA	BA
1 (Lowest)	70	63	6	99	77	2272	1858	500	2363	1544
2	61	55	5	39	65	611	465	180	629	442
3	2306	1839	307	2048	2323	125	111	29	136	71
4	1875	1456	229	1510	1906	158	133	38	164	88
5 (Highest)	1508	1234	180	968	1527	37	32	8	39	9
Total	5819	4646	727	4663	5898	3204	2598	755	3330	2155

how different public policies may impact current and future agricultural and biodiversity spatial needs.

Our results illustrate that patterns of climate-adaptive urban growth scenarios can potentially impact ecosystems to the same extent as the least constrained conventional urban growth policies, when prioritizing either urban or agricultural land-uses comes at the expense of natural vegetation types, a trade-off that is often associated with land use decisions (Guerry et al., 2015; Hamin & Gurran, 2009). We found that modification of the patterns of new urban growth through infill has the potential to greatly reduce impacts to natural vegetation, a similar conclusion to (Byrd et al., 2015), and that such alterations could be a useful strategy for sustainable urban development in the face of climate change.

While the two climate-adaptive scenarios we examined each conserved lands for their adaptation targets, each had large impacts on the lands needed for the opposite climate-adaptive scenario, because each diverts new urban growth to areas outside its own objectives; when agriculture is prioritized, urban growth was diverted towards natural vegetation, and vice-versa. While not specifically tested here, we conclude from these findings that an Infill policy, which preserves the most land for all alternate purposes, combined with policies that discourage new urban growth in areas needed for regional climate-adaptation of natural resources, would provide the most effective spatial patterns of urban development and regional climate resilience. Such an approach would be responsive to recent calls to explicitly link natural capital and ecosystem services to planning and decision making related to adaptation and mitigation of climate change impacts (Guerry et al., 2015; Schaefer, Goldman, Bartuska, Sutton-Grier, & Lubchenco, 2015).

The benefits of the Infill scenario emerged when all three impact criteria were considered. Infill required the least area and it was the scenario that least conflicted with climatically-stable existing agricultural lands and the most likely plant biodiversity corridors. Further, Infill is a conventional policy scenario which can provide for a variety of needs (development, biodiversity and ecosystem services) simultaneously and is familiar to many planners and governments. Recognizing the benefits of Infill for climate adaptation can also permit local governments to meet the targeted levels of land protection and emissions limits and the potential benefits of urban renewal. It is likely that a combination of Infill and climate-adaptive urban growth will be the most effective strategy for sustainable urban development. Given the rapid expansion of urban areas globally, this framework offers a forward-looking approach to regional sustainability planning.

For California, steps to improve on our modeled outcomes include developing better maps of the locations of existing housing units. Particularly for rural areas, the specific locations of structures are not currently well mapped. Developing robust maps of this information would allow much better assessment of how future development will impact and interact with a variety of California's natural resources. Planners could also use the numbers of structures identified by various scenarios to project energy consumption, potentially urban water consumption, and other outcomes under current and future conditions. While our study used relatively simple spatial metrics to portray regional alternative policy futures, we recognize that more spatially and normatively complex modeling approaches for alternative futures analyses (e.g. Hoversten 2013; Mahmoud et al., 2009; Rastandeh 2015) may also be useful in the next generation of policy models for California. Further, the level of spatial precision of our model, while operating at a 50 m resolution, is dependent on regional-scale GIS inputs, and we recommend that planners considering individual urban areas or even district (county)-level exercises consider the implications of

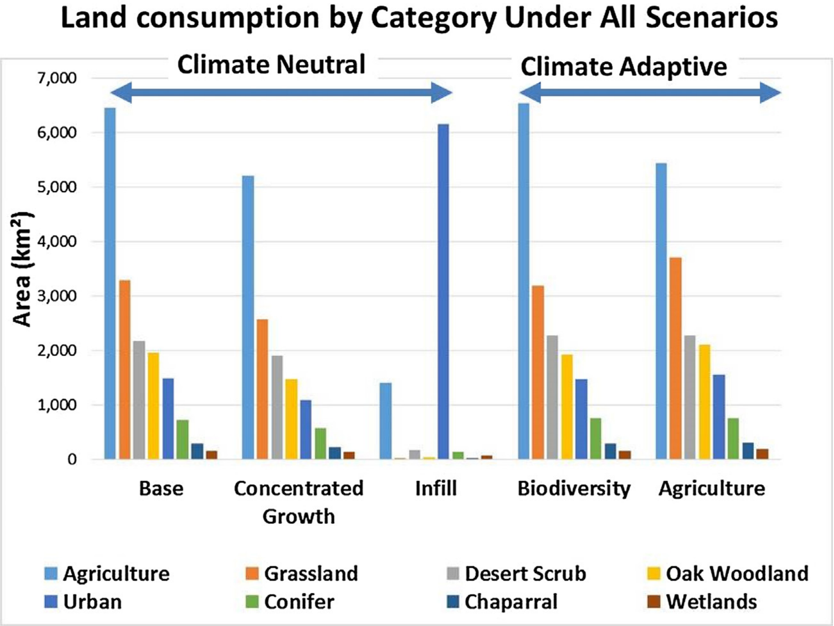

Fig. 4. Predicted land area needed by land cover type for five urban growth scenarios. Some vegetation types have been combined to more general categories for ease of visualization.

our results, rather than using the exact spatial footprints we modeled to represent the most likely areas for development for their particular area of focus. Another approach to improving the spatial accuracy of our model outputs would be to apply one of a variety of validation approaches (Pontius, Huffaker, & Denman, 2004) such as to run 10-year increments of growth over historical times, and use historical patterns of growth to calibrate the model.

As land use and climate effects continue (Newbold et al., 2015), it will become more critical to examine the policies and practices that govern where and how urban populations will spread. In particular, it is important to assess what land use policies offer solutions that integrate urban development and other land use needs; particularly the areas needed for regional resilience to climate change for biodiversity, ecosystem services, and agriculture. There is a need for global and regional models that address regional resource needs and risks to sustainability (Ordonez, Martinuzzi, Radeloff, & Williams, 2014). While the scientific community is already aware of the need to preserve natural attributes (Lambin & Meyfroidt, 2011; Ordonez et al., 2014), and also of the impacts of urban growth and climate change, this study modeled both types of stressors. It explored what optimum public policy could look like at a scale that can help provide actionable information to support spatial urban growth strategies and decisions.

Expanding the modeling effort for the Infill policy could provide valuable information for urban planners at all levels of California government. Specifically, developing a response curve that quantifies how much open space may be preserved for a variety of other functions when placing varying proportions of the new population urban into existing urban areas would be a way to inform planning efforts without constraining local planning about where the infill would have to be placed, and what lands should be maintained for other purposes. For example, in Alameda County we placed ~60% of new-and displaced-population (612,463 people) within the existing urban footprint, which required the infill/redevelopment of 16% or 124 km^2 of the existing urban (Appendix E in Supplementary information). This lowered the land use beyond the existing urban areas from 284 km^2 under the BAU scenario to 46 km^2. The Infill policy scenario is consistent with the goal of denser urban growth also identified by regional planners in Alameda County. However, it would be informative for their efforts if other levels of infill and land consumption could be identified, such as how much land would be preserved under 50% or 70% of new population being placed in existing urban areas? Such an approach would recognize that planners and local governments are constrained by a variety of factors not accounted for in the modeling, and also must guide and make decisions about urban development proposals on a project by project basis. Under such pressures, it may be more effective to inform these groups of the proportions of open space that could be retained for long-term sustainability goals at different levels of infill, rather than specifying what areas should be retained as non-urban.

Finally, it would be useful to develop urban growth scenario models that combine Infill or Compact New Growth with climate-adaptive models in a future study. This could answer questions on trade-offs and benefits between climate-neutral policies and climate-incorporating ones. This study examined the policy categories separately to distinguish their individual characteristics, and found the Infill policy provided the most flexibility for conservation and climate adaptation. Given that, we expect the combination of the two would not save much more open space, but it might further identify the areas that should be saved for open space, and thereby provide better guidance for local and regional planners.

5. Conclusions

This study provides several insights for planners. First, a supra-regional perspective is needed to understand how local urban growth policies can impact regional resources, and can by design potentially mitigate those impacts across broader landscapes. This can address regional sustainability goals concurrently with identifying suitable locations for new urban growth. The regional consequences of policies that increase urban land consumption may not be readily apparent when considering a single urban area, but when all future urban areas of California were examined in aggregate; their cumulative spatial impacts could be quantified, and compared across policy scenarios. Second, the most efficient policy at preserving open space for a variety of seen and unforeseen future conditions was urban infill. This policy also promotes lower carbon footprints for transportation, and is at the forefront of current design thinking, wherein walkable cities and improved urban settings are an objective. Third, it is possible to develop climate-incorporating regional urban growth scenarios, and these can preserve more open space for the target criteria such as agriculture or biodiversity. However, they did so at the expense of impacts to other resources, and multiple criteria should be considered concurrently, to minimize unintended impacts. The spatial analysis in this study presents a way to help set regional land use efficiency goals and patterns (Lambin & Meyfroidt 2011) that incorporate risk factors such as climate change and urban expansion.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2016.08.013.

References

Beardsley, K., Thorne, J. H., Roth, N. E., & McCoy, M. (2009). Impact of rapid human population growth on biological resources in the San Joaquin Valley of California. *Landscape and Urban Planning*, *9*, 172–183. http://dx.doi.org/10.1016/j.landurbplan.2009.07.003

Brooker, R. W., Travis, J. M. J., Clark, E. J., & Dytham, C. (2007). Modelling species' range shifts in a changing climate: The impacts of biotic interactions, dispersal distance and the rate of climate change. *Journal of Theoretical Biology*, *245*, 59–65. http://dx.doi.org/10.1016/j.jtbi.2006.09.033

Byrd, K. B., Rissman, A. R., & Merenlender, A. M. (2009). Impacts of conservation easements for threat abatement and fire management in a rural oak woodland landscape. *Landscape and Urban Planning*, *92*, 106–116. http://dx.doi.org/10.1016/j.landurbplan.2009.03.003

Byrd, K. B., Flint, L. E., Alvarez, P., Casey, C. F., Sleeter, B. M., Soulard, C. E., et al. (2015). Integrated climate and land use change scenarios for California rangeland ecosystem services: Wildlife habitat, soil carbon, and water supply. *Landscape Ecology*, *30*, 729–750. http://dx.doi.org/10.1007/s10980-015-0159-7

Cayan, D. R., Mauer, E. P., Dettinger, M. D., Tyree, M., & Hayhoe, K. (2008). Climate change scenarios for the California region. *Climactic Change*, *87*, S21–S42. http://dx.doi.org/10.1007/s10584-007-9377-6

Flint, L. E., Flint, A. L., Thorne, J. H., & Boynton, R. (2012). Fine-scale hydrologic modeling for regional landscape applications: The California Basin Characterization Model development and performance. *Ecological Processes*, *2*, 25. http://dx.doi.org/10.1186/2192-1709-2-25

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., et al. (2008). Global change and the ecology of cities. *Science*, *319*, 756–760. http://dx.doi.org/10.1126/science.1150195

Grimm, N. B., Foster, D., Groffman, P., Grove, J. M., Hopkinson, C. S., Nadelhoffer, K. J., et al. (2008). The changing landscape: Ecosystem responses to urbanization and pollution across climatic and societal gradients. *Frontiers in Ecology and the Environment*, *6*, 264–272. http://dx.doi.org/10.1890/070147

Guerry, A., et al. (2015). Natural capital and ecosystem services informing decisions: From promise to practice. *Proceedings of the National Academy of Sciences*, *112*, 7348–7355. http://dx.doi.org/10.1073/pnas.1503751112

Haddad, N., et al. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, *1*, 1–9.

Hamin, E. M., & Gurran, N. (2009). Urban form and climate change: Balancing adaptation and mitigation in the U.S. and Australia. *Habitat International*, *33*, 238–245.

Hannah, L., Shaw, M. R., Ikegami, M., Roehrdanz, P. R., Soong, O., & Thorne, J. H. (2012). *Consequences of climate change for native plants and conservation.* California Energy Commission. Publication number: CEC-500-2012-024.

Hollander, A. D. (2010). *California augmented multisource landcover map (CAML).* Davis, California: Information Center for the Environment, University of California.

Hoversten, M. E. (2013). *Decision-making, values and discursive moments in alternative futures landscape planning (Doctoral dissertation, Lincoln University).*

Huber, R. P., Thorne, J. H., Roth, N. E., & McCoy, M. (2011). Assessing the ecological condition and vulnerability of a potential conservation network in a working landscape. *Natural Areas Journal*, *31*, 234–245. http://dx.doi.org/10.3375/043.031.0306

Hutyra, L. R., Yoon, B., & Alberti, M. (2011). Terrestrial carbon stocks across a gradient of urbanization: A study of the Seattle, WA region. *Global Change Biology*, *2*, 783–797. http://dx.doi.org/10.1111/j.1365-2486.2010.02238.x

Johnston, R. A., Shabazian, D. R., & Gao, S. (2003). UPlan: A versatile urban growth model for transportation planning. *Transportation Research Record*, *1831*, 202–209. http://dx.doi.org/10.3141/1831-23

Lambin, E., & Meyfroidt, P. (2011). Global land use change, economic globalization and the looming of land scarcity. *Proceedings of the National Academy of Sciences*, *108*, 3465–3472. http://dx.doi.org/10.1073/pnas.1100480108

Mahmoud, M., Liu, Y., Hartmann, H., Stewart, S., Wagener, T., Semmens, D., et al. (2009). A formal framework for scenario development in support of environmental decision-making. *Environmental Modelling & Software*, *24*(7), 798–808.

Moritz, M. A., Parisien, M. A., Batllori, E., Krawchuk, M. A., Van Dorn, J., Ganz, D. J., et al. (2012). Climate change and disruptions to global fire activity. *Ecosphere*, *3*(6), 49. http://dx.doi.org/10.1890/es11-00345.1

Newbold, T., et al. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, *520*, 45–50. http://dx.doi.org/10.1038/nature14324

Nowak, D. J., & Walton, J. T. (2005). Projected urban growth (2000–2050) and its estimated impact on the US Forest Resource. *Journal of Forestry*, *103*, 383–389. http://www.ingentaconnect.com/content/saf/jof/2005/00000103/00000008/art00004

Ordonez, A., Martinuzzi, S., Radeloff, V. C., & Williams, J. W. (2014). Combined speeds of climate and land-use change of the conterminous US until 2050. *Nature Climate Change*, *4*, 811–816. http://dx.doi.org/10.1038/nclimate2337

Phillips, S. J., Williams, P., Midgley, G., & Archer, A. (2008). Optimizing dispersal corridors for the cape Proteaceae using network flow. *Ecological Applications*, *18*, 1200–1211. http://dx.doi.org/10.1890/07-0507.1

Pontius, R. G., Huffaker, D., & Denman, D. (2004). Useful techniques of validation for spatially explicit land-change models. *Ecological Modelling*, *179*, 445–461.

Rastandeh, A. (2015). Challenges and potentials in using alternative landscape futures during climate change: A literature review and survey study. *Urbani Izziv*, *26*(2), 83. http://dx.doi.org/10.1023/A:1008165311026

Roth, R., Thorne, J. H., Johnston, R., & McCoy, M. (2012). Financial costs to agriculture and municipal governments of urban growth in an agricultural valley. *Journal of Agriculture, Food Systems, and Community Development*, online:. http://www.agdevjournal.com/volume-2-issue-4/278-modeling-impacts-to-ag-revenue.html?catid=111%3Aopen-call-papers

Sanstad, A. H., Johnson, H., Goldstein, N., & Franco, G. (2009). *Long-run socioeconomic and demographic scenarios for California.* California Energy Commission, Public Interest Energy Research (PIER). CEC-500-2009-013-D.

Satterthwaite, D., McGranahan, G., & Tacoli, C. (2010). Urbanization and its implications for food and farming. *Philosophical Transactions Royal Society B-Biological Sciences*, *365*, 2809–2820. http://dx.doi.org/10.1098/rstb.2010.0136

Schaefer, M., Goldman, E., Bartuska, A. M., Sutton-Grier, A., & Lubchenco, J. (2015). Nature as capital: Advancing and incorporating ecosystem services in United States federal policies and programs. *Proceedings of the National Academy of Sciences*, *112*, 7383–7389. http://dx.doi.org/10.1073/pnas.1420500112

Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences*, *104*, 19703–19708.

Seto, K. C., Gunerlap, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*, 16083–16088. http://dx.doi.org/10.1073/pnas.1211658109

State of California (2012) E-4 Population Estimates for Cities, Counties, and the State, 2001–2010, with 2000 & 2010 Census Counts. Sacramento, California.

Theobald, D. N., Hobbs, T., Bearly, T., Zack, J. A., Shenk, T., & Riebsame, W. E. (2000). Incorporating biological information in local land-use decision making: Designing a system for conservation planning. *Landscape Ecology*, *15*, 35–45. http://dx.doi.org/10.1023/A:1008165311026

Thorne, J., Bjorkman, J., & Roth, N. (2012). *Urban Growth in California: Projecting growth in California (2000–2050) under six alternative policy scenarios and assessing impacts to future dispersal corridors, fire threats and climate-sensitive agriculture.* California Energy Commission. CEC-500-2012-009.

Thorne, J. H., Santos, M. J., & Bjorkman, J. (2013). Regional Assessment of urban impacts on landcover and open space finds a smart urban growth policy performs little better than business as usual. *PLoS ONE*, http://dx.doi.org/10.1371/journal.pone.0065258

Thorne, J. H., Boynton, R. M., Flint, L. E., & Flint, A. L. (2015). The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. *Ecosphere*, *6* http://dx.doi.org/10.1890/es14-00300.1

United Nations (2014) World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352). United Nations, Department of Economic and Social Affairs, Population Division.

(2010). *United States census*. http://www.census.gov/2010census/

Wu, J. (2014). Urban ecology and sustainability: The state-of-the-art and future directions. *Landscape and Urban Planning*, *125*, 209–221. http://dx.doi.org/10.1016/j.landurbplan.2014.01.018

Zank, B., Bagstad, K. J., Voight, B., & Villa, F. (2016). Modeling the effects of urban expansion on natural capital stocks and ecosystem service flows: A case study in the Puget Sound, Washington, USA. *Landscape and Urban Planning*, *149*, 31–42. http://dx.doi.org/10.1016/j.landurbplan.2016.01.004

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