Land Use Policy 41 (2014) 438–452

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Modeling residential development in California from 2000 to 2050: Integrating wildfire risk, wildland and agricultural encroachment

Michael L. Mann[a,b,*], Peter Berck[b], Max A. Moritz[c], Enric Batllori[c], James G. Baldwin[d], Conor K. Gately[d], D. Richard Cameron[e]

[a] The George Washington University, Geography Department, Washington, District of Columbia, United States
[b] UC Berkeley, Agricultural & Resource Economics, Berkeley, CA, United States
[c] UC Berkeley, Environmental Science, Policy, and Management, Berkeley, CA, United States
[d] Boston University, Earth & Environment, Boston, MA, United States
[e] The Nature Conservancy, San Francisco, CA, United States

ARTICLE INFO

Article history:
Received 29 October 2013
Received in revised form 13 March 2014
Accepted 25 June 2014

Keywords:
Housing
Spatial econometrics
Conservation
Wildfire
California
Wildland Urban Interface

ABSTRACT

Between 1940 and 2000, nearly 10 million housing units were constructed throughout California. This increased interaction between human and natural communities creates a number of significant socio-ecological challenges. Here we present a novel spatially explicit model that allows better characterization of the extent and intensity of future housing settlements using three development scenarios between 2000 and 2050. We estimate that California's exurban land classes will replace nearly 12 million acres of wild and agricultural lands. This will increase threats to ecosystems and those presented by wildfire, as the number of houses in 'very high' wildfire severity zones increases by nearly 1 million.

Introduction

Between 1940 and 2000 nearly 10 million housing units were constructed throughout California (US Census Bureau, 1990, 2000a,b). Although urban growth is pronounced in most of California's urban centers, its impact is far outweighed by the acreage disturbed by low-density exurban and rural development. Almost 80% of the acreage used in recent development over the US has been outside of urban areas (Heimlich and Anderson, 2001; Newburn and Berck, 2006), as individuals seek low cost housing and more rural living amenities (Crump, 2003). These low density settlements affect increasingly large swaths of land, with nearly 57% of recent development occurring on lots of 10 acres or larger (Heimlich and Anderson, 2001; Newburn and Berck, 2006). We estimate the loss of sparsely settled and agricultural land through the expansion of exurban and rural communities between 2000 and 2050. These future exurban and rural developments will be encumbered by the complex and consequential interactions among settlements, climates, and the ecosystems. Here we examine the interaction between the these developments and the fire driven ecology where they are located.

The interaction of human and natural communities creates a number of significant environmental challenges. These challenges include climate change, loss of wildlife habitat and ecosystem fragmentation, introduction of invasive species, threats to endangered and sensitive species, as well as water and air pollution issues (Alavalapati et al., 2005; Hammer et al., 2004; Radeloff et al., 2005). All this, which is further exacerbated by the appeal of development in areas with high ecological value (McGranahan, 1999), can have significant consequences for ecosystems services. Therefore, the persistence and growth of exurban settlements creates complex patterns under which species and habitats, depending on their capacity for adaptation and resilience, ebb and flow with the course of human development (Hansen et al., 2005). Along with threats to the natural environment, the increasing proximity to wildlands (i.e., the expansion of Wildland–Urban Interface, WUI) brings risks to human communities as well. Low housing densities and increased exposure to natural lands can make exurban communities both more likely to experience natural disasters and makes many of their effects more costly (Calkin et al., 2005; Gebert et al., 2007a,b; Gude et al., 2008a,b; Liang et al., 2008).

After a respite induced by the December 2007 to June 2009 credit crunch and recession, housing development in California

* Corresponding author at: The George Washington University, Geography Department, Washington, District of Columbia, United States. Tel.: +1 202 994 4567.
E-mail address: mmann1123@gwu.edu (M.L. Mann).

http://dx.doi.org/10.1016/j.landusepol.2014.06.020
0264-8377/

has resumed along with its complex mix of economic, social and ecological impacts. In 2013, housing starts in the state expanded to 2.3 times their 2009 levels, nearly 70% of the 1990 to 2012 average (CBIA, 2013a, 2013b). The expansion of human settlements is of primary concern as it shapes a series of irreversible spatial and temporal patterns on the landscape. These patterns determine both the direct and indirect costs and benefits associated with development.

The development of new housing is primarily a response to the demographic pressures of population, economic growth, and other incentive structures that underpin the process of household formation (Heimlich and Anderson, 2001). The specific location of new housing, however, is driven by more complex factors including autoregressive factors, spatial spillovers, terrain, climate, access to employment and services, transportation costs, aesthetics, weather and cultural and environmental amenities, amongst others. Researchers have made efforts to forecast housing development using a variety of methods.

Cellular automata are capable of replicating the complex yet highly structured spatial patterns based on a set of deterministic or probabilistic rules that determine the state of a cell based on the states of its neighbors. Models like SLEUTH have been successfully employed to model land-use change and urban growth for discrete land-use or urban development classes (see Dietzel and Clarke, 2007; Irwin and Geoghegan, 2001). Although their usefulness is widely acknowledged, these models have been criticized for the complex and arbitrary nature of calibration, and the inability to attribute simulated patterns to particular drivers such as changes in population, employment etc. (Dietzel and Clarke, 2007; Irwin and Geoghegan, 2001; Jantz et al., 2010). Another set of models, dynamic simulations, model the interactions between the drivers of a land-use system. This is accomplished by creating a set of differential equations that portrays *a priori* a simplified representation of the complex states and interactions between system components (Lambin et al., 2004).

Empirical or statistical models of land-use and land-use change focused on modeling deforestation (Mann et al., 2010, 2014; Nelson et al., 2004; Pfaff, 1999) have also been applied to urban land-uses type and housing density (Landis and Zhang, 1998; Newburn and Berck, 2006). Broadly, this class of model determines the likelihood of conversion based on exogenous information on initial land-use, site characteristics, accessibility, community characteristics, and policy factors. The majority of these models are implemented as discrete choice models where land-use is classified as residential, commercial, or industrial, or they classify density in broad or narrow density categories. Many of these applications have endogeniety problems. The problems are caused by inclusion of accessibility measures based on transportation networks that are jointly determined with land-use choices, especially over longer time periods (Chomitz and Gray, 1996; Irwin and Geoghegan, 2001; Jacoby, 2000). Due to the complexity of implementation, these models are also typically limited to local or semi-regional case studies (Theobald, 2005). Additionally, spatially explicit discrete-choice regression models face difficulties in estimation due to the complex likelihood functions and other numerical challenges (Holloway et al., 2007). However recent advances in Bayesian techniques have rendered these models more computationally tractable (Holloway et al., 2007).

Hybrid models use a handful methodologies allowing each to interact or drive the behavior of another module (Berry et al., 1996; Pijanowski et al., 2002; Veldkamp and Fresco, 1996; Walker et al., 2007). Due to the flexibility and modular nature of these models, they are often adapted to represent complex interactions between systems, such as policy tools, socio-economic drivers, or impacts on biodiversity, and real estate values. The Spatially Explicit Regional Growth Model (SERGoM) utilizes two core modules to forecast housing density classes (Theobald, 2005). The first module estimates the demand for new housing based on county-level population and a county specific housing to population ratio. The second module allocates housing based on a set of weights developed from the local growth rates over two periods and a measure of travel time to the nearest urban core. Weights are then adjusted to improve accuracy for the observed density classes in 1990 and 2000. This approach has been adopted by the EPA for the Integrated Climate and Land-Use Scenarios (ICLUS) model (EPA, 2010).

Here we present a novel spatially explicit model that allows us to better characterize the extent and intensity of housing settlements for California up to 2050. Our spatial panel econometric approach stands out from existing models due to the ease of implementation and attribution, estimation over a long historic record, the lack of reliance on transportation networks and other endogenous variables as a basis for land-use change, implementation of spatial spillovers, and explicit consideration of housing density.

Materials and methods

The following section lays out the methodology used to predict housing densities for the state of California from the year 2000 to 2050. A spatial panel regression, with robust standard errors, is used to estimate the effect of spatial and temporal lags as well as exogenous variables such as climate on the spatial distribution of housing density in each period. County-level demographic forecasts drive the total supply of housing for future periods. To provide a range of estimates depicting potential patterns of housing development and therefore of associated interactions with climate and ecosystems, three development scenarios are used: business as usual, greater urban development, and further rural development.

Response variable

Our model estimates housing density measured as housing units per acre. Historical housing density from 1940 to 2000 is derived from the Census Bureau's split census block group data (US Census U.S. C. Bureau, 2000a,b). Block groups represent the aggregation of a cluster of census blocks. Block groups typically represent between 600 and 3000 people with a target size of 1500 people (US Census U.S.C. Bureau, 2012b). Split block groups (SBG) add additional accuracy by breaking groups by the boundary of other tabulation entities including Native American areas, voting districts, or urban boundaries. SBGs therefore provide a much more accurate representation of the housing stock. After the removal of undevelopable land (see below) all SBGs have a median size of 115 acres, with a first and third quartile of 58.8 and 280.1, respectively. Urban and rural classified SBGs have a median size of 96.2 and 524 acres, respectively, whereas in very sparsely populated or unpopulated areas SBGs can be as large as 593,000 acres.

Retrospective estimates of housing counts are provided by data from the census long form, which includes tabulations of 'year housing structure built' (US Census U.C. Bureau, 2007). A housing unit may include houses, apartments, mobile homes either occupied or vacant (Radeloff et al., 2005), and year housing structure built "refer[s] to when the building was first constructed, not when it was remodeled, added to, or converted" (US Census U.C. Bureau, 2012a). This data provides the retrospective data on housing counts at the SBG level. Following the approach of Hammer et al. (2007), the houses built in each successive decade are added to create an estimate of the number of houses present in each decade from 1940 to the year 2000, where year 2000 SBG level estimates match actual housing counts.

Although census data is currently available for 2010, this part of the census was reassigned to collection under the American Community Survey which samples only 1 in 40 households versus 1