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# Natural amenities and low-density residential development: Magnitude and spatial scale of influences

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ABSTRACT

Low-density residential development in rural areas is an important land use trend in many parts of the world, and has disproportionate ecological impacts due to its large footprint relative to population. It is widely suggested that this type of land use change is driven in part by natural amenities, raising the concern that locations of high natural value are most rapid to develop. We examine the contribution of natural amenities to the probability of low-density development controlling for more traditional drivers of land use change. We do so considering the influence of natural amenities at two scales, individual plots, and the larger communities in the immediate vicinity. We use a unique primary dataset based on photo interpretation of high resolution imagery to capture residential development at the scale of a single house between 1990 and 2010. We combine these data with spatially-referenced census and other secondary data to estimate a multilevel regression model of the probability of residential land conversion. Our results demonstrate that communities near National Parks, other public lands and ski resorts experienced significantly higher rates of residential land conversion than those further from these amenities. Within communities, undeveloped plots that were 10 min closer than average to public land had a 67 % higher probability of conversion to residential use holding other characteristics constant, plots that were 75 min closer than average to a large lake had a 139 % higher probability of conversion, and plots with 1 standard deviation more forest/non-forest variation had a 44 % higher probability of conversion. Our findings regarding community and plot level influences of natural amenities on rural development are unique in the land use literature, and are important for identifying which communities and individual parcels have the highest probability of development. This can inform policy makers' and conservationists' efforts to protect places facing the highest threats, and help both regional and local land-use planners manage tradeoffs between environmental protection and economic growth.

## 1. Introduction

Expansion of low-density residential development beyond the urban fringe is an important trend in many parts of the world, including northern and southern Europe (Salvati et al., 2013; Ward and Brown, 2009), the United States (Brown et al., 2005), Argentina (Matteucci and Morello, 2009), and some parts of China (Xi et al., 2012). Due to its large footprint, this type of development poses considerable threats to biodiversity through habitat alteration, disturbance to ecological and biotic processes, and direct disturbance by humans (DeFries et al., 2010; Hansen et al., 2005; Pejchar et al., 2015). Of particular concern is that rates of residential development are highest in areas of significant ecological value (Leu et al., 2008; Matteucci and Morello, 2009; Poudyal et al., 2016). It therefore poses a particular threat within relatively pristine and ecologically important places (Eichenwald et al., 2019).

Existing studies suggest that natural amenities influence people's choices in ways that are likely to affect land use. Migration patterns in many countries over recent decades have been towards areas with

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abundant natural amenities (Deller et al., 2001; McGranahan, 2008; Partridge, 2010; Rappaport, 2009). For example, regions with warm, dry climates have experienced population growth in the US (Cragg and Kahn, 1997; Egan and Mullin, 2016; Rappaport, 2009) and Europe (Cheshire and Magrini, 2006). Other natural amenities associated with population growth include environmentally-based recreation opportunities, and landscape qualities characterized by open land, forests, water, and topographic variation (Chi and Marcouiller, 2013; Deller et al., 2001; McGranahan, 2008; Stephens and Partridge, 2015; Tong and Qiu, 2020; Ulrich-Schad, 2015). Empirical research has also demonstrated the importance of natural amenities for the value of residential land. For example, open space influences rural land values (Fernandez et al., 2018; Geoghegan, 2002; Hardie et al., 2007; Jones and Reed, 2018), as do attractive scenery, protected natural areas, recreational opportunities and wildlife (Bastian et al., 2002; Bin and Polasky, 2005; Izón et al., 2016; Kovacs et al., 2017; Liu et al., 2020; Schmidt and Courant, 2003; Wu and Lin, 2010).

While the evidence on the relationship between natural amenities and population or land values suggests that places with abundant natural amenities are likely to face greater development pressures, direct evidence on the relationship between natural amenities and conversion of land to residential use is more limited. Studies using aggregate data have found that growth of housing density on private lands that surround protected areas has occurred at faster rates than national averages (Davis and Hansen, 2011; Radeloff et al., 2018; Wade and Theobald, 2010). More broadly, expansion of low-density exurban development has been concentrated in amenity-rich regions, such as regions with forests, mountains or large inland lakes in the United States (Brown et al., 2005; Radeloff et al., 2005), or coastal and mountains regions in Australia and New Zealand (Argent et al., 2010; Collins and Kearns, 2010). Previous analyses of parcel-scale residential land use change have found that preferences for open space are a significant driver of fragmented land use change patterns in exurban areas (Brambilla and Ronchi, 2016; Cheshire and Magrini, 2006; Irwin and Bockstael, 2007; Wu et al., 2004; Zipp et al., 2017). Additionally, a preference for living in low density areas nonetheless accessible to the urban infrastructure and services associated with existing development has been shown to be an important determinant of rural residential development (Carrion-Flores and Irwin, 2004).

The evidence using data on patterns of population growth, land values and regional land-use change shows that people have preferences for places that are high in natural amenities. These studies help inform which regions are likely to experience greater development pressures, but not where development is likely to occur within the regional landscape. Previous parcel-scale analysis has been limited to small geographic areas, such as single counties, which have relatively homogenous landscapes. These studies have therefore focused on the role of open space in driving land fragmentation rather than a wider range of natural amenities. Fine-scale analysis is needed to understand which particular natural amenities have the strongest association with residential development; the geographic scale at which specific natural amenities are related to land conversion; and how important natural amenities are as influences on low-density residential development relative to other factors such as access to urban areas or demographic structure. This study contributes to the literature by quantifying patterns of low-density residential development at a high spatial resolution over a large heterogeneous geographic area to answer these questions. This provides information on threats to the ecological integrity of natural lands at the scale necessary for land-use planning and conservation prioritization.

Empirical understanding of the factors that determine where low-density residential development occurs has been limited by challenges in measuring it (Bierwagen et al., 2010; Brady and Irwin, 2011; Theobald, 2004). We use a new primary dataset that quantifies low-density residential development using photo-interpretation of high-resolution (~1 m) imagery over all or parts of seven states in the US Mountain West (Powell et al., 2020). Unlike previous studies, this allows us to quantify the relationship between natural amenities and land use change both within and across communities using multilevel regression models. Modeling the influences on land conversion at multiple scales is important because in theory the decision to convert land for residential use is the outcome of a hierarchical process: at the scale of the individual parcel, the conversion decision depends on the returns to development relative to the returns from using the land in its undeveloped form, for example for agriculture. These relative returns depend on the biophysical and locational characteristics of the plot, including natural amenities (Carrion-Flores and Irwin, 2004), and also on regional demand for housing which is influenced by natural amenities at a broader scale through effects on population mobility (Tong and Qiu, 2020).

Quantification of the influence of natural amenities on patterns of residential land conversion has important application in our study region, an area of approximately 1 million km$^2$ in the Northwestern United States. The region is centered on iconic National Parks such as Yellowstone, and contains among the largest areas of wildlands (i.e. land not used for resource extraction or more intensive uses) in the contiguous 48 states. As such it supports ecosystem services that are valuable not only to those who live within it, but to the nation as a whole. Low-density housing development, both for primary residences and for second homes, threatens these services. Our analysis of the spatial patterns of land conversion has direct application in informing planning decisions made by city and state governments within this region, which are facing challenges of how to balance population growth with protection of ecological assets (Power and Barrett, 2001).

Another application of our analysis relates to prioritization of conservation efforts. Conservation programs targeting private land are expanding, in recognition of the ecological value of such lands and their importance for maintaining connectivity between public protected areas (Davis and Hansen, 2011; Knight, 1999; Norton, 2000). In a context of limited budgets, identifying both which regions face the highest threats and which parcels within those regions have the greatest probability of conversion is necessary to maximize the effectiveness of conservation expenditures (Carwardine et al., 2012; Margules and Sarkar, 2007; Withey et al., 2012). We distinguish the influences on aggregate development patterns identified in regional models of land-use change from the localized determinants of conversion of individual parcels. Therefore, we can provide fine-scale yet broad scope information on the distribution of land conversion probabilities within our study region. Recent high resolution maps of land values show that the scale of the analysis affects the targeting of conservation policy (Nolte, 2020). Our work therefore informs the broader evidence base on patterns of land use change in high natural amenity regions and illustrates methods for locally-specific analyses that can be applied in other settings.

Natural amenities can influence residential land conversion both by attracting population to a community or region, which raises overall demand for housing and returns to land development, or by increasing the returns to development of an individual plot relative to others within the same community or region. In this study, we answer the following questions:

1) Which natural amenities are most strongly related to the location of low-density residential development within a community?
2) Which natural amenities are associated with differences in low-density residential development between communities?
3) How important are natural amenities compared with other influences on low-density residential land conversion such as access to urban centers and socio-demographic characteristics?

## 2. Theoretical framework

Theoretical models developed by economists show that whether rural land is developed for residential use is a function of its value ($V$) if developed relative to its value in an undeveloped use such as agriculture, forestry or wildland. The landowner is assumed to choose between alternative land uses to maximize the discounted value of expected net returns from the land over an infinite time horizon:

$$V_{Residential} > V_{Alternative}$$

The optimal land use for each parcel, and the associated development probabilities, will depend on factors that influence the returns to land in each use, and the costs of conversion. Classic location models such as those of von Thünen and Ricardo suggest that proximity and transport links to urban centers ($L_p$) and biophysical parcel characteristics such as slope ($B_p$) are important determinants of the likelihood of development at the parcel level. The empirical literature discussed in the previous section also shows that natural amenities ($A_p$) influence preferences for individual parcels:

$$\Pr(Development) = f(L_p, B_p, A_p; D_c)$$

The influences of the location, biophysical and natural amenity characteristics of a given parcel on the probability of residential development are predicted to be conditional on the regional or community-level development pressures ($D_c$). These depend primarily on population and income growth, although demand for tourist accommodation or second homes may also be important (Haarsma and Qiu, 2017; Skog and Steinnes, 2016). The Roback (1982) model of migration posits location choice to be a function of individual or household utility as determined by real wages and quality of life in a given location. Real wages are influenced by the location of the community with respect to other urban centers and transportation infrastructure ($L_c$), and quality of life depends on the presence of natural amenities in the local area ($A_c$). The socio-economic and demographic characteristics of the community ($S_c$) affect both real wages and quality of life. Therefore we hypothesize that these characteristics will influence community level demand for residential land:

$$D_c = g(L_c, A_c, S_c)$$

At equilibrium in the Roback (1982) model, real wages adjust via changes in labor and housing supply to compensate for differences in location specific natural amenities so that utility is equalized across locations. In this framework, changes in population occur when preferences for location-specific natural amenities change. If we assume that location-specific natural amenities are normal or superior goods then rising incomes would lead to an increase in demand and population growth (Graves and Linneman, 1979). Falling transportation costs; structural shifts towards service industries rather than location-dependent resource extraction or manufacturing industries; and developments in information and communication technology can also affect rural population growth through changes in the ability of firms and households to locate away from major urban centers (Glaeser and Kohlhase, 2004; Johnson, 2001; Kilkenny, 1998).

Based on the theoretical models of regional population and land use change outlined above, we hypothesize that proximity to natural amenities, and other variables such as location and demographics, are important both as characteristics of a given parcel that influence its probability of development, and as determinants of overall housing demand. Our empirical model will therefore include natural amenities and other influences on residential land conversion at the community and plot levels to account for both processes.

## 3. Methods

### 3.1. Study region

Our study region, in the Northwestern United States, is defined based on ecological boundaries (Fig. 1). It consists of the Northern Rocky, Cascade and Coastal Mountain Ranges, covering all of the states of Washington, Oregon and Idaho, and parts of Montana, Wyoming, Utah and Colorado. The region covers approximately 1 million km$^2$, of which about 60 % is public land. Over the period of study (1990–2010), counties in the region have experienced population growth of 37 % on average, compared with the national average of 18 % (US Census Bureau, 2010a, 1990). This population growth, along with expansion of tourism and construction of second homes, has been associated with an estimated 32,500 km$^2$ increase in low-density development (Powell et al., 2020). As much of the region is remote with inhospitable mountain topography, population density and land development have historically been relatively low, which enhanced its ecological value.

Recent population growth, and associated development, particularly

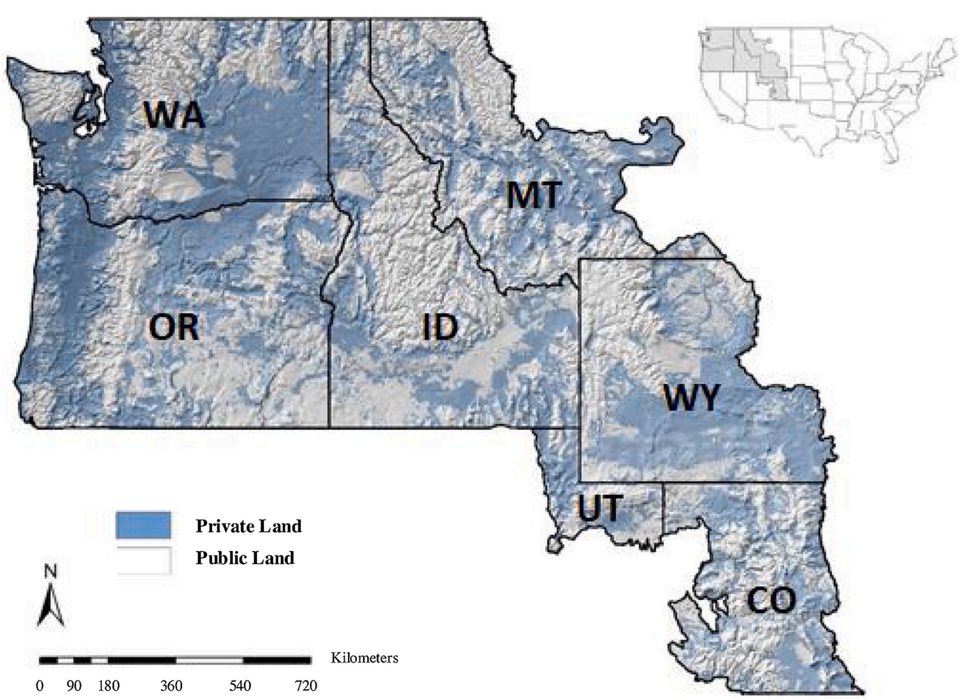


**Fig. 1.** Study region.

on the private lands that surround National Parks and other protected areas (Davis and Hansen, 2011; Gude et al., 2006; Radeloff et al., 2005), threaten the integrity of nationally significant wilderness areas through pollution, increased recreational use, and land conversion. With these protected areas providing crucial support for regional biodiversity, sprawling rural development poses a serious risk of ecological isolation and habitat loss.

### *3.2. Quantifying residential land conversion*

We use data generated from manual interpretation of Google Earth satellite imagery of a stratified random sample of 618 approximately 1-km$^2$ Global Grid cells (Theobald, 2016) located on private lands, each containing five 100-meter radius plots. The stratification process was implemented with the goals of 1) achieving sufficient variation in explanatory variables and 2) ensuring a sufficient number of observations that transitioned from undeveloped to developed between 1990 and 2010 through oversampling where low-density residential development was likely to occur. It was based on county-scale climate, urban/rural designation and socio-demographic characteristics; and plot-scale surrounding development density and natural amenities (Fig. 2).

Within each plot, trained photo interpreters assigned a primary land use for 1990, 2000, and 2010 based on the presence of land use indicators within the 100-meter radius as well as an additional 227-meter radius buffer zone around each plot (Fig. 2). Indicators included commercial, residential or industrial buildings; parking lots or driveways; crops; grazing land; irrigation; logging or mining. Out of eight land use categories (see Table 1), the 3090 plots were further classified as either being developed or undeveloped, yielding the primary unit of analysis: whether an undeveloped plot became developed over the time period of 1990 – 2010. This enables analysis of the relationship between predicted drivers of land use change and the likelihood of development at a fine scale across a large geographic area.

Table 1 shows the number of plots with each land use type in each time period. Overall, transition of any given plot of land from undeveloped to developed is highly unlikely. The majority of plots are undeveloped in all periods, and primarily contain only natural vegetation. 261 plots were already developed by 1990 and a further 108 transitioned from undeveloped to developed by 2010.

**Table 1**
Land use transitions over time.

| Land Use | 1990 | 2000 | 2010 |
|---|---|---|---|
| *Undeveloped* | | | |
| Ag. Cultivated Cropland | 690 | 654 | 639 |
| Ag. Grazing/Other | 642 | 639 | 644 |
| Natural Resource Extraction | 308 | 222 | 234 |
| Natural Cover/Vegetation | 1189 | 1238 | 1205 |
| **Total Undeveloped Plots** | 2829 | 2753 | 2722 |
| *Developed* | | | |
| Urban | 79 | 100 | 108 |
| Suburban | 58 | 77 | 87 |
| Developed Ag. | 49 | 63 | 65 |
| Rural Residential Development | 75 | 97 | 108 |
| **Total Developed Plots** | **261** | **337** | **368** |
| Total | 3090 | 3090 | 3090 |

### *3.3. Linking plots with communities*

We link each plot to the nearest Incorporated Place or Census Designated Place, as defined by the US Census Bureau, to explicitly model the relationship between the process of fine scale development surrounding a community and community level characteristics such as the provision of social, cultural, and economic services. A population threshold of 10,000 in 1990 is used to ensure that each census place is large enough and the distances to linked plots are small enough for community characteristics to impact land use change. Each community has multiple plots linked to it.

In linking each plot to the nearest community, we account for complex terrain of our study region. While two locations may be in close proximity as defined by Euclidean distance, the actual travel time between the two points depends on the existence and quality of infrastructure, particularly in the rural, mountainous landscapes that characterize much of the area. We therefore use cost distance calculated as travel time measured in minutes, as opposed to Euclidean distances to link plots to communities. This travel time is calculated as a function of the location of roads, highways, and interstates, speed limits on those roads, and the terrain of the path between two points of interest (Theobald et al., 2010).

| Scale | Criteria | Categories | Subplot Count | Source |
|---|---|---|---|---|
| County | Climate | Mild | 1,030 | Egan and Mullin (2016) |
| | | Moderate | 1,035 | |
| | | Harsh | 1,025 | |
| County | Rural/ Urban | Rural | 1,835 | US Census |
| | | Urban | 1,255 | |
| County | New West/ Old West | New West | 1,825 | US Census |
| | | Old West | 1,265 | |
| Plot | Natural Amenity Index | High NA's | 2,040 | This Study |
| | | Low NA's | 1,050 | |
| Plot | Prior development density | Rural | 525 | DMSP/ OLS |
| | | Rural Transitional | 1,350 | |
| | | Transitional | 1,085 | |
| | | Urban | 130 | |

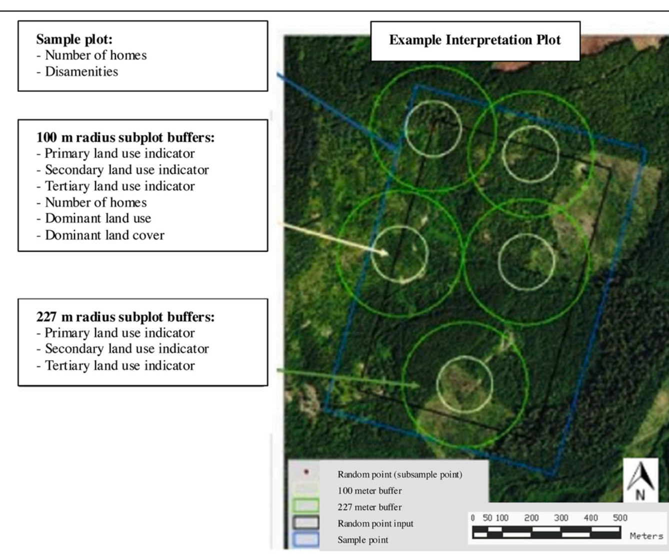


**Fig. 2.** Sampling strategy.

### 3.4. Predicted drivers of residential land conversion

Table 2 contains descriptions and data sources of the plot and community explanatory variables included in the analysis. For each of the 'Travel time to:' variables, we calculate cost distances (travel time in minutes), as described in the previous paragraph. We use data from as close as possible to 1990 for all our explanatory variables to reflect baseline conditions within our 1990–2010 study period.

The natural amenity variables include cost distances to the nearest National Park; other public land (US Fish and Wildlife Service, US Forest Service, Bureau of Land Management, or State land); water body larger than 1 km$^2$; large river; and ski resort. Table 4 lists descriptive statistics for the untransformed plot and census place level explanatory variables included in the analysis. In the regression models, cost distance variables were transformed using the Inverse Hyperbolic Sine (IHS) transformation in order to reduce skewness. This transformation, which is commonly used by applied econometricians to approximate the natural log of a variable, allows estimation of a nonlinear relationship (Bellemare and Wichman, 2020). Since only some of the communities in our study area are in locations where access to skiing would be a relevant amenity, we translate the cost distance estimate to a binary variable for whether there is a ski resort within two hours travel time rather than a continuous travel time variable.

**Table 2**
Definitions and sources of explanatory variables.

| Variable | Description | Data Source |
|---|---|---|
| Distance to National Park | Travel time to nearest National Park (minutes) | US Geological Survey Protected Areas Database (USGS Gap Analysis Project (GAP), 2017) |
| Distance to Public Land | Travel time to nearest US Fish and Wildlife Service, US Forest Service, Bureau of Land Management, or State Land (minutes) | |
| Distance to Large River | Travel time to nearest river > 8 m wide (minutes) | National Hydrography Dataset (US Geological Survey, 2017) |
| Distance to Waterbody > 1 km$^2$ | Travel time to nearest waterbody > 1 km$^2$ in area (minutes) | |
| Distance to Ski Resort | Travel time to nearest Ski Resort (minutes) | NOAA National Operational Hydrologic Remote Sensing Center (2007) |
| Forest Pattern | Moving average of the standard deviation of forest/non-forest variation | National Land Cover Database (US Geological Survey, 2016) |
| Topographic Complexity | Moving average of the standard deviation of elevation | |
| Distance to Census Place | Travel time to nearest census place with population >10,000 (minutes) | - TIGER Shapefiles: Roads (US Census Bureau, 2010b) |
| Distance to Highway | Travel time to nearest highway (minutes) | |
| Distance to Interstate | Travel time to nearest interstate (minutes) | |
| Surrounding development | Nighttime light intensity categories: Urban = urban density; Transitional = suburban density; Rural-transitional = within 20 km of suburban density; Rural = more than 20 km of suburban density. | Defense Meteorological Satellite Program – Operational Line Scanner (DMSP-OLS) (1992) |
| Market Remoteness Index | Remoteness index calculated using factor analysis of travel time to urban centers and transportation infrastructure | - TIGER Shapefiles: Places (US Census Bureau, 2010b) - National Transportation Atlas Database (Bureau of Transportation Statistics, 2016) |
| New West Index | Sociodemographic index calculated using factor analysis of demographic and socio-economic variables selected following Winkler et al. (2007) | US Census Bureau (2010a, 1990) |
| Climate Index (100 km Buffer) | Climate index calculated using factor analysis of temperature and precipitation variables. | Representative Concentration Pathways (RCP) Database 8.5 (Riahi et al., 2007) |
| 1990 Population | Census Place 1990 population | US Census Bureau (1990) |

Other natural amenities include forest pattern and topographical complexity. Using data from the 1992 National Land Cover Database as the baseline, forest pattern is calculated as the standard deviation of forest/non-forest variation of a center cell from the average of all cells within a moving radius of 5.6 km. This is based on previous findings that mixed landscapes including areas with and without forests are more highly valued than landscapes with solely forest or non-forest (McGranahan, 2008). The forest pattern variable will be higher for a more mixed landscape relative to a more uniform landscape. Topographic complexity is calculated as the standard deviation of elevation of a center cell from the average of all cells within a moving radius of 5.6 km. Forest and topographic complexity values are then averaged within the boundary of each plot and within a 100-km radius buffer of each census place.

We include the cost distance (with IHS transformation) from each plot to the nearest highway and interstate, and to the nearest census place with population >10,000, as individual plot level explanatory variables to control for remoteness of plots. We also capture surrounding development density using nighttime light intensity data from the Defense Meteorological Satellite Program – Operational Line Scanner in 1992. We create a categorical variable in which the urban category has high development density; transitional plots are surrounded by areas of moderate suburban density; rural-transitional plots are within 20 km of suburban densities; and rural plots are more than 20 km from suburban densities.

To reduce data dimensions and multicollinearity, we use factor analysis to create indices of remoteness, socio-demographic character, and climate at the community level. Table 3 shows the variables, factor loadings and eigenvalues for each of the indices. All indices were generated using the full population of census places >10,000 people in the study region. The market remoteness index is based on access to transportation infrastructure and distance to population centers of varying sizes. High values indicate remote communities and low or negative values indicate communities with good access to infrastructure and urban areas. The 'New West' index uses the variables selected by Winkler et al. (2007) in their characterization of the New West as places that have attracted migrants from other parts of the country with high levels of education, seeking quality of life based initially around natural amenities, but increasingly also cultural activities and in some cases jobs in technology, manufacturing or tourism (Power and Barrett, 2001). Archetypal examples with high values for the New West index include Boulder, CO or Bend, OR. The climate index includes minimum and maximum temperatures and rainfall. Negative values are associated with drier, more extreme climates and positive values with wetter, more moderate climates. Each of the indices has eigenvalues of around 2 or higher, indicating strong relationships among the component variables.

The population of the census place is measured using 1990 census data and transformed using IHS.

### 3.5. Statistical analyses

In our analysis, the multiple lower level plots tied to the same upper level communities are more likely to be similar to each other due to unobserved factors pertaining to developability, government policies, and historical migration patterns, as well as the fact that existing development influences the likelihood of neighboring development (Carrion-Flores and Irwin, 2004). We model this hierarchical relationship using a multilevel model of the probability that an undeveloped land plot transitions to residential use over a 20-year period, 1990–2010.

By explicitly specifying that plots are linked to communities, multilevel models help control for spatial dependence in which the

**Table 3**
Inputs for community-level indices of Market Remoteness, New West Character and Climate.

| | Mean | Standard deviation | Min | Max | Factor Loading | Scoring Coefficient |
|---|---|---|---|---|---|---|
| **Market remoteness**[1] | | | | | | |
| Distance to Airport (minutes) | 16.80 | 21.69 | 3.81 | 256.30 | 0.733 | 0.170 |
| Distance to Highway (minutes) | 3.13 | 7.27 | 0.23 | 80.20 | 0.878 | 0.426 |
| Distance to Interstate (minutes) | 36.16 | 81.30 | 1.23 | 556.46 | 0.597 | 0.163 |
| Distance to Rail (minutes) | 2976.66 | 5224.81 | 142.37 | 50981.51 | 0.295 | 0.060 |
| Distance to Pop. > 50k (minutes) | 13.45 | 25.80 | 2.95 | 299.05 | 0.788 | 0.222 |
| Distance to Pop. > 250k (minutes) | 254.86 | 971.86 | 6.76 | 12319.42 | 0.609 | 0.141 |
| | | | | | Eigenvalue: 2.74 | |
| **New West Character** | | | | | | |
| % bachelor's degree or more | 21.75 | 10.51 | 9.04 | 63.71 | 0.724 | 0.277 |
| %. born out of state | 50.94 | 9.16 | 26.15 | 90.38 | 0.219 | 0.0438 |
| % housing of value > $200,000 | 6.43 | 12.51 | 0 | 83.88 | 0.774 | 0.357 |
| % employed in finance, insurance and real estate | 5.86 | 2.36 | 1.96 | 13.77 | 0.748 | 0.312 |
| % employed in extractive ind. | 4.22 | 4.23 | 0.36 | 25.21 | −0.485 | −0.138 |
| % employed in tourism | 1.32 | 0.49 | 0.16 | 3.25 | 0.0784 | 0.0367 |
| % seasonal housing | 8.58 | 8.79 | 0 | 55.11 | −0.0517 | −0.027 |
| | | | | | Eigenvalue: 1.97 | |
| **Climate** | | | | | | |
| Average min. January temp. (K) | 269.47 | 4.02 | 258.85 | 274.6 | 0.836 | −0.020 |
| Average max. July temp. (K) | 298.48 | 2.76 | 295 | 304.6 | −0.857 | 0.034 |
| Average annual precipitation | 118.5 | 57.02 | 20.71 | 202.13 | 0.991 | 1.038 |
| | | | | | Eigenvalue: 2.42 | |

[1] All distances in the Market remoteness index are transformed using the Inverse Hyperbolic Sine transformation to account for non-linearity in the effect of distance.

**Table 4**
Descriptive statistics for plot and community variables.

| | Plot | | | | Community | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Standard deviation | Min | Max | Mean | Standard deviation | Min | Max |
| Distance to Public Land (mins) | 46.59 | 58.00 | 0.00 | 512.65 | 26.24 | 18.30 | 4.92 | 93.20 |
| Distance to National Parks (mins) | 293.41 | 169.23 | 0.00 | 1147.00 | 236.46 | 130.24 | 13.94 | 621.74 |
| Ski resort within 2 h travel time | | | | | 0.066 | 0.004 | 0 | 1 |
| Forest Pattern | 31.21 | 16.06 | 0.00 | 49.00 | 31.17 | 11.30 | 4.95 | 45.20 |
| Topographic Complexity | 75.91 | 48.52 | 2.22 | 274.30 | 83.74 | 26.42 | 33.42 | 176.55 |
| Distance to Large River (mins) | 182.38 | 186.12 | 0.00 | 1499.74 | 18.67 | 27.35 | 2.94 | 150.86 |
| Distance to Waterbody > 1 $km^2$ (mins) | 281.33 | 246.57 | 0.00 | 1659.14 | 108.88 | 115.89 | 3.35 | 588.34 |
| Distance to Census Place (mins) | 248.15 | 205.44 | 6.69 | 1128.33 | | | | |
| Distance to Highway (mins) | 62.03 | 85.16 | 0.00 | 805.82 | | | | |
| Distance to Interstate (mins) | 207.97 | 167.52 | 0.00 | 993.61 | | | | |
| Surrounding devel. (Rural (1)-Urban(4)) | 2.19 | 0.759 | 1.00 | 4.00 | | | | |
| Market Remoteness Index | | | | | 0.25 | 0.92 | −1.87 | 3.86 |
| New West Index | | | | | −0.42 | 0.41 | −1.61 | 0.48 |
| Climate Index (100 km Buffer) | | | | | −0.46 | 0.98 | −1.69 | 1.46 |
| 1990 Population (people) | | | | | 27,682 | 29,849 | 10,125 | 189,925 |
| Observations | 2829 | | | | 91 | | | |

probability of a plot being developed depends on the characteristics of the communities to which they are tied, in addition to the characteristics of the plots themselves. Furthermore, including explanatory variables measured at the individual plot level as well as the community level can address both aspects of land use change simultaneously and allows for the testing of hypotheses between scales (Overmars and Verburg, 2006; Snijders and Bosker, 2012). Multilevel studies have been used to model hierarchical influences on land use change in the context of deforestation in tropical countries (Gray et al., 2008; Overmars and Verburg, 2006; Pan and Bilsborrow, 2005; Vance and Iovanna, 2006), but not low-density residential land conversion.

We begin our analysis with an unconditional model that is 'empty' of explanatory variables. Eq. (1) consists of the general intercept $\gamma_{00}$ as well as a random term $U_{0j}$, which is a group dependent intercept that accounts for the effect of plots being linked to the same county, and a plot-specific error term $R_{ij}$.

$$Pr\left(y_{ij}=1\right) = \gamma_{00} + U_{0j} + R_{ij} \tag{1}$$

This model partitions the total variation in the probability of a plot being developed into its between and within-level components (Polsky and Easterling, 2001), and shows the proportion of variance in the dependent variable that is accounted for by the group level (Snijders and Bosker, 2012).

We then estimate random intercept models, which relate the probability of development for plot $i$ in community $j$ to the plot-level covariates ($x_{ij}$), and allow the intercept to vary randomly ($U_{ij}$) across communities (Eq. (2)).

$$Pr\left(y_{ij}=1\middle|x_{ij}\right) = \gamma_{00} + \sum\nolimits_{p=1\ldots P}\gamma_{p0}x_{pij} + U_{0j} + R_{ij} \tag{2}$$

Our main specification decomposes the effects of natural amenities and other explanatory variables into effects on the probability of development of an individual plot and effects on the general probability of development around a given community. Eq. (3) is a random intercept model with natural amenity variables and other covariates measured at the plot level ($x_{ij}$), and natural amenity variables and other covariates measured at the community level ($z_j$).

$$Pr\left(y_{ij}=1\middle|x_{ij},z_j\right) = \gamma_{00} + \sum\nolimits_{p=1\ldots P}\gamma_{p0}x_{pij} + \sum\nolimits_{q=1\ldots Q}\gamma_{0q}z_{qj} + U_{0j} + R_{ij} \tag{3}$$

By including variables measured at the individual level and group averages, differences between within-group and between group regressions can be explicitly modeled (Snijders and Bosker, 2012). This allows for tests of significance at both levels, providing insight into which natural amenities are associated with between-community differences in the probability of development, and which natural amenities are primarily associated with within-community differences in the probability of development.

As well as common influences on development probabilities at the community level, there may be unobserved similarities between plots in the same state or in the same grid cell. The small number of transitions from undeveloped to developed prevents us from estimating multilevel models with more than two levels. We therefore include state fixed effects and use clustered standard errors in all specifications to address spatial correlation at multiple levels.

## 4. Results

### *4.1. Which natural amenities are most strongly related to the location of low-density residential development within a community?*

The plot-level and multilevel models (Table 5, columns 2–4) both show that proximity to public land and lakes, and distance from National Parks, all increase the probability that agricultural or wild land in 1990 was converted to developed uses by 2010. A mix of forest and non-forest in the landscape is also associated with a higher likelihood of development. We do not observe substantive differences in plot influences on development between the full sample (Table 5, column 3) and the rural-only sample (Table 5, column 4).

Due to the relatively small number of plots that transition from undeveloped to developed, our main results are based on parsimonious models of only the most important correlates with development at the plot and community scale. Columns (1) and (2) of Table 6 show coefficients and marginal effects respectively for the parsimonious model with all plots included, and Columns (3) and (4) show coefficients and marginal effects with initially undeveloped land located in urban areas omitted on the basis that we are primarily concerned with rural land development given the larger potential ecological costs. Our preferred specification, due to the explanatory power and the focus of our research question, is the multilevel model with the rural-only sample of plots.

The marginal effects from this model suggest that the relationship between natural amenities and the likelihood that land is developed for residential purposes is strong. The marginal effects of the explanatory variables are non-linear due to both the use of the probit model and the IHS transformation of the distance variables. However, we can calculate marginal effects at specific values to understand the magnitudes of the relationships. For instance, the average travel time from a plot to the nearest public land is 47 min in our sample. A plot that was 10 min closer than average, with otherwise the same characteristics, had a probability of development that was 0.024 percentage points higher.[2] This appears small, but given that the probability of any given plot transitioning from undeveloped to developed is also small (0.036 on average) it amounts to approximately a 67 % increase in the probability of development. Plots that were 75 min closer than average to a large lake (average distance 280 min) had a 0.05 percentage point (139 %) higher probability of development, and those with forest/non-forest variation that was one standard deviation higher than average had a probability of development that was 0.016 percentage points (44 %) higher than average.

### *4.2. Which natural amenities are associated with differences in low-density residential development between communities?*

The unconditional model (Table 5, column 1), decomposes the

[2] Marginal effect of a change in distance to public land = 0.008. This indicates that an increase in IHS(distance to public land) of 3 would increase the probability of development by 0.024 percentage points. Hyperbolic sine transformation of 3 = 10 minutes.

**Table 5**
Coefficients of probit model of the probability of a plot becoming developed between 1990 and 2010.

| | (1) Unconditional Model | (2) Plot level only | (3) Plot and community level, full sample | (4) Plot and community level, rural sample |
|---|---|---|---|---|
| P: IHS (Distance to Public Land) | | −0.158** | −0.122* | −0.143** |
| | | (0.071) | (0.070) | (0.070) |
| P: IHS (Distance to National Parks) | | 0.151 | 0.237** | 0.211* |
| | | (0.110) | (0.117) | (0.124) |
| P: IHS (Distance to NHD River) | | −0.055 | −0.026 | −0.043 |
| | | (0.079) | (0.077) | (0.076) |
| P: IHS (Distance to Waterbody > 1 km$^2$) | | −0.209*** | −0.227*** | −0.197*** |
| | | (0.072) | (0.067) | (0.071) |
| P: Forest/Non-Forest Variation | | 0.023*** | 0.021*** | 0.019*** |
| | | (0.006) | (0.006) | (0.007) |
| P: Topographic Complexity | | −0.000 | 0.000 | 0.000 |
| | | (0.000) | (0.000) | (0.000) |
| P: IHS (Distance to Census Place) | | 0.075 | 0.051 | 0.057 |
| | | (0.099) | (0.095) | (0.112) |
| P: IHS (Distance to Highway) | | −0.149** | −0.165** | −0.162** |
| | | (0.068) | (0.067) | (0.070) |
| P: IHS (Distance to Interstate) | | 0.069 | 0.078 | 0.103 |
| | | (0.061) | (0.057) | (0.065) |
| P: Rural Transitional | | 0.593 | 0.673 | 0.635 |
| | | (0.448) | (0.430) | (0.440) |
| P: Transitional | | 1.209*** | 1.265*** | 1.259*** |
| | | (0.426) | (0.424) | (0.435) |
| P: Urban | | 2.009*** | 2.064*** | |
| | | (0.501) | (0.501) | |
| CP: IHS (Distance to Public Land) | | | −0.202* | −0.292** |
| | | | (0.122) | (0.143) |
| CP: IHS (Distance to National Parks) | | | −0.257* | −0.300** |
| | | | (0.132) | (0.138) |
| CP: IHS (Distance to NHD River) | | | 0.107 | 0.122 |
| | | | (0.106) | (0.128) |
| CP: IHS (Distance to Waterbody > 1 km$^2$) | | | 0.036 | 0.055 |
| | | | (0.074) | (0.080) |
| CP: Ski resort within 2 h | | | 0.525** | 0.738*** |
| | | | (0.240) | (0.225) |
| CP: Forest/ Non-Forest Variation | | | −0.022 | 0.008 |
| | | | (0.016) | (0.018) |
| CP: Topographic Complexity in100 km | | | −0.000 | −0.000 |
| | | | (0.000) | (0.000) |
| CP: IHS (1990 Population) | | | −0.085 | −0.071 |
| | | | (0.113) | (0.126) |
| CP: New West Index (1990) | | | −0.083 | −0.237 |
| | | | (0.210) | (0.210) |
| CP: Market Remoteness Index | | | −0.225** | −0.198* |
| | | | (0.111) | (0.117) |
| CP: Climate Index (100 km) | | | 0.392* | 0.153 |
| | | | (0.203) | (0.205) |

(*continued on next page*)

**Table 5** (*continued*)

| | (1) Unconditional Model | (2) Plot level only | (3) Plot and community level, full sample | (4) Plot and community level, rural sample |
|---|---|---|---|---|
| Community-level random effect | 0.305** | 0.163* | 0.000 | 0.000 |
| | (0.138) | (0.089) | (0.000) | (0.000) |
| Observations | 2829 | 2829 | 2829 | 2756 |
| McKelvey and Zavoina Pseudo $R^2$ | | 0.401 | 0.435 | 0.471 |
| *AIC* | 886.171 | 725.861 | 724.678 | 651.286 |
| *BIC* | 898.066 | 844.814 | 903.108 | 823.011 |
| Intra-class correlation coefficient | 0.234 | 0.140 | 0.000 | 0.000 |

Standard errors in parentheses.
Variables with P prefix are calculated at the plot scale; variables with CP prefix are calculated at the census place scale. Variables denoted IHS($x$) use the Inverse Hyperbolic Sine transformation of the original variable to account for non-linearity in the effect of distance. All models estimated with state fixed effects, community random effects and clustered standard errors.
* $p< .10$.
** $p< .05$.
*** $p < .01$.

variance in plot probability of development into variation that occurs between communities and variation that occurs within communities. In partitioning the variation in the probability of development this model shows that variance between communities is significant at the 5% level, implying the need for a model that includes factors explaining variation in the likelihood of land use change both among plots tied to the same community and between communities. Furthermore, the intra-class correlation coefficient, which indicates what proportion of the total variation occurs at the group level, suggests approximately 23 % of the variation in probability of plot development occurs between communities. Thus, although plot characteristics influence where development occurs around a community, community characteristics also play a significant role in patterns of land use change.

In the multilevel models (Table 5, columns 3 and 4), communities with greater proximity to National Parks and other public land, and with a ski resort within 2 h travel time, have higher probabilities of development on their associated plots. The inclusion of the census place characteristics considerably reduces the community-level random effect, indicating that this model explains the majority of the variation in development between communities.

The marginal effects from our preferred model (Table 6, column 4) show that plots associated with communities that are 75 min closer to a National Park than the average distance of 236 min had a 0.06 percentage point (167 %) higher probability of development than average; those associated with communities that were 10 min closer to other public land (relative to the average distance of 26 min) were 0.048 percentage points (133 %) more likely to transition to developed; and those associated with communities within 2 h of a ski resort were 0.021 percentage points (58 %) more likely to become developed than those without access to ski resorts.

### *4.3. How important are natural amenities compared with other influences on low-density residential land conversion such as access to urban centers and socio-demographic characteristics?*

In addition to the role of natural amenities discussed above, at the plot level, prior development nearby and access to highways also increase the probability of development. At the community level, the remoteness of the community is significantly related to the probability of development, with more remote communities experiencing less development.

**Table 6**
Multilevel probit models of the probability of a plot becoming developed between 1990 and 2010; coefficients and marginal effects of parsimonious models for the full sample and with urban plots omitted.

| | (1) Coefficients (Full sample) | (2) Average marginal effects (Full sample) | (3) Coefficients (Rural plots only) | (4) Average marginal effects (Rural plots only) |
|---|---|---|---|---|
| P: IHS (Distance to Public Land) | −0.125* | −0.008* | −0.136** | −0.008** |
| | (0.065) | (0.004) | (0.066) | (0.004) |
| P: IHS (Distance to National Parks) | 0.219* | 0.014* | 0.192 | 0.011 |
| | (0.118) | (0.007) | (0.121) | (0.007) |
| P: IHS (Distance to Waterbody > 1 km$^2$) | −0.187** | −0.012** | −0.172** | −0.010** |
| | (0.073) | (0.005) | (0.076) | (0.005) |
| P: Forest/Non-Forest Variation | 0.018*** | 0.001*** | 0.019*** | 0.001*** |
| | (0.005) | (0.000) | (0.006) | (0.000) |
| P: IHS (Distance to Highway) | −0.171*** | −0.011*** | −0.165*** | −0.010*** |
| | (0.060) | (0.004) | (0.061) | (0.004) |
| P: IHS (Distance to Interstate) | 0.075 | 0.005 | 0.086 | 0.005 |
| | (0.065) | (0.004) | (0.076) | (0.004) |
| P: Rural Transitional | 0.623 | 0.015* | 0.649 | 0.015** |
| | (0.430) | (0.008) | (0.443) | (0.007) |
| P: Transitional | 1.226*** | 0.054*** | 1.268*** | 0.055*** |
| | (0.388) | (0.009) | (0.394) | (0.009) |
| P: Urban | 1.972*** | 0.169*** | | |
| | (0.406) | (0.054) | | |
| CP: IHS (Distance to Public Land) | −0.251** | −0.016** | −0.282** | −0.016** |
| | (0.111) | (0.007) | (0.122) | (0.007) |
| CP: IHS (Distance to National Parks) | −0.226* | −0.014* | −0.210* | −0.012* |
| | (0.123) | (0.008) | (0.113) | (0.007) |
| CP: Ski resort within 2 h | 0.320** | 0.020** | 0.370*** | 0.021*** |
| | (0.154) | (0.010) | (0.131) | (0.007) |
| CP: Market Remoteness Index | −0.138 | −0.009 | −0.107 | −0.006 |
| | (0.100) | (0.006) | (0.103) | (0.006) |
| CP: Climate Index (100 km) | 0.220 | 0.014 | 0.214 | 0.012 |
| | (0.152) | (0.009) | (0.158) | (0.009) |
| Observations | 2829 | 2829 | 2756 | 2756 |
| McKelvey and Zavoina Pseudo $R^2$ | 0.415 | | 0.463 | |
| *AIC* | 714.415 | . | 641.180 | . |
| *BIC* | 845.264 | . | 765.532 | . |
| Intra-class correlation coefficient | 0.008 | | 0.006 | |

Standard errors in parentheses.
Variables with P prefix are calculated at the plot scale; variables with CP prefix are calculated at the census place scale. Variables denoted IHS($x$) use the Inverse Hyperbolic Sine transformation of the original variable to account for non-linearity in the effect of distance. All models estimated with state fixed effects, community random effects and clustered standard errors.
* $p < .10$.
** $p < .05$.
*** $p < .01$.

To illustrate the relative impacts of different scales and categories of influence on plot development probabilities, Fig. 3 shows the predicted probabilities that a plot transitions from undeveloped to developed given its characteristics. Based on the significant correlates with

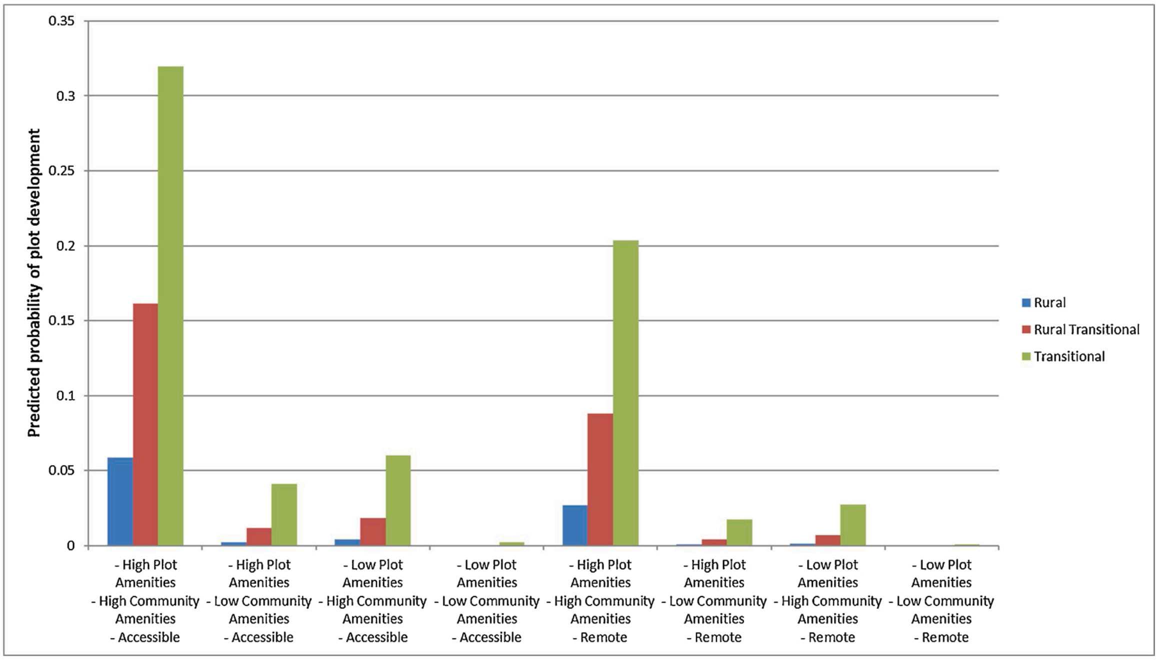


**Fig. 3.** Predicted probabilities of plot development by plot and community natural amenities and accessibility.
**High plot amenities:** lake >1 km$^2$ within 30 min; public land within 30 min; forest/non-forest variation at 75th percentile.
**Low plot amenities:** lake >1 km$^2$ further than 2 h; public land further than 2 h; forest/non-forest variation at 25th percentile.
**High community amenities:** public land within 30 min; National Park within 30 min; ski resort within two hours.
**Low community amenities:** public land further than two hours; National Park further than two hours; ski resort further than two hours.
**Accessible:** Community remoteness index at 25th percentile; highway within 10 min of plot.
**Remote:** Community remoteness index at 75th percentile; highway further than one hour from plot.

development, plots are considered to have ‘high’ natural amenities if they are within 30 min travel time of a lake larger than 1 km$^2$ and the nearest area of public land, and have forest/non-forest variation at the 75$^{th}$ percentile. Plots have ‘low’ natural amenities if they are 4 h travel time from the nearest lake and public land, with forest/non-forest variation at the 25$^{th}$ percentile. The lack of forest/non-forest variation could mean no forest or large tracts of undisturbed forest. Communities are considered to have ‘high’ natural amenities if they are within 30 min travel time from a National Park and from other public land, and have a ski resort within 2 h travel time; and ‘low’ natural amenities if they are 4 h travel time from a National Park and from other public land, with no ski resort within 2 h. Plots and communities with some but not all of the listed natural amenities, for example a plot near a lake but not a ski area or a community in the mountains but far from the nearest National Park, have intermediate development probabilities. Plot accessibility is captured by whether the highway is within 10 min (accessible) or 1 h (remote), and by the density of surrounding development. Community accessibility is captured by the Remoteness index: ‘accessible’ communities have an index value at the 25th percentile and ‘remote’ communities have an index value at the 75th percentile.

As indicated by the individual marginal effects discussed above, plot-scale natural amenities, community-scale natural amenities, and the accessibility of the plot and the community all positively affect the likelihood of development. Fig. 3 provides comparisons of the effects that these categories of variables have in combination. One finding that it highlights is the extent to which plot-scale and community-scale natural amenities matter in combination with one another. Plots with high levels of natural amenities that are also located near to communities with high levels of natural amenities are considerably more likely to be developed than other plots, even if the plot or the community is relatively remote. For example, although Transitional (i.e. suburban) plots consistently have a higher development probability than Rural Transitional or Rural plots all else equal, Rural plots with combined high plot and community natural amenities have approximately the same likelihood of development as Transitional plots with only high plot natural amenities or only high community natural amenities. Similarly, plots associated with remote communities that have high natural amenities at both the plot and community scale are more likely to be developed than plots associated with accessible communities that have high plot natural amenities or high community natural amenities alone. A second finding is that plots with high natural amenities at the plot level but not the community level, and plots with high natural amenities at the community level but not the plot level have similar likelihoods of being developed, and these are moderately high, particularly for Transitional plots in accessible communities. Finally, rural plots without natural amenities at either the plot or community scale are very unlikely to be developed, regardless of their accessibility.

## 5. Discussion

Land development in scenic or ecologically significant locations can have negative impacts in those places. Managing such threats requires information on where development is most likely to occur. Low-density rural residential development can be particularly damaging because of the large spatial footprint of disturbance relative to the number of houses or the size of the supported population, but it is also difficult to model empirically due to measurement challenges. We use a unique dataset based on photo-interpretation of high-resolution imagery to capture residential land use at the scale of a single house as well as denser development patterns. Over the period 1990–2010, we find that the average probability of a given plot of land transitioning from undeveloped to developed was very low overall, as the region includes large tracts of inaccessible mountainous land and inhospitable rangeland that are far from any urban center. However, the probabilities of development vary in systematic ways that can be explained by our model.

### 5.1. Relationship between natural amenities and residential development

Previous studies have found that natural amenities including the presence of water bodies, public lands, scenic view and favorable climates are associated with population growth (e.g. Deller et al., 2001; Tong and Qiu, 2020; Ulrich-Schad, 2015) and with higher land values (Bastian et al., 2002; e.g. Izón et al., 2016; Liu et al., 2020). These suggest that pressures for conversion of land to residential use are likely to be higher in locations with better access to these amenities, but the empirical literature on whether land conversion actually occurs at higher rates near to natural amenities is more limited. One reason for this is that data are typically only available to measure either aggregate patterns of housing development, or parcel-scale conversion within small geographic areas such single counties. For example, census housing statistics can provide aggregate information on density at the county or municipality level, but not on how those houses are distributed across the landscape. Techniques have been developed that combine satellite imagery and census data to estimate land use change (Morzillo et al., 2015; Theobald, 2014), but it is more difficult to accurately predict low-density than high-density housing development using this approach.

The majority of work on natural amenities and land conversion has focused on private land surrounding National Parks and other protected areas. Brambilla and Ronchi (2016) studied land use change within 5 km of protected areas in Northern Italy during the period 1999/2000−2012. They found that loss of open land to residential use was higher within 1.5 km of parks than beyond 1.5 km. Along similar lines, Radeloff et al. (2010) compared housing growth within 50 km of protected areas. In the 1990s, housing growth was faster within 1 km of protected areas (20 % per decade) than the national average (13 % per decade). Growth within 50 km of protected areas was also faster than national averages. Our results also show a strong relationship between proximity to protected areas and probability of residential land conversion. Treating proximity as a continuous rather than categorical variable, we find in general that proximity to protected areas is associated with more conversion: communities near National Parks and other public lands experienced more land conversion, and individual plots near public lands are more likely to be converted. However, conditional on community proximity to a National Park, the plots nearest the park are not more likely to be converted than those further away. This suggests that conservation planning for the private lands surrounding National Parks should focus on the communities nearest the park rather than on individual landowners at the park boundaries.

Some studies have examined the role of natural amenities other than protected areas, with mixed results. Gude et al. (2006) studied the Greater Yellowstone Ecosystem, and found that increases in home density between 1970 and 1999 were higher in locations that were close to water, isolated areas and National Parks, although land near to other public lands saw lower increases in density. Liu and Robinson (2016) conducted similar analysis for the peri-urban fringes of Adelaide, Australia, and found that the effects of elevation and proximity to parks and the coast on development varied over time and were relatively small overall. Newburn and Ferris (2017) found that in Baltimore County, Maryland, there was no relationship between forest cover and parcel development. Zipp et al. (2017) found that being ¼ mile closer to conserved open space was associated with a 0.45−0.7 percentage point increase in the probability of development for residential zoned parcels in Door County, Wisconsin between 1978 and 2009. Overall, these studies suggest that natural amenities are associated with residential development in some cases, but not in all places or time periods. Our study examines patterns of development across a larger area, with more variation in natural amenities, than previous analyses. We find that some natural amenities (e.g. ski resorts, National Parks) influence broad-scale patterns of development, while others influence which individual parcels of land are most likely to be developed (e.g. proximity to water, forest/non-forest mix in the landscape). Since previous studies looked at individual counties, cities or other relatively small areas, they can only identify the latter set of relationships and therefore will not necessarily identify the full influence of natural amenities.

We find that the probability of conversion of undeveloped land is consistently higher for plots that were initially either within areas of urban or suburban density or close to such areas than for plots in remote rural locations. Remoteness is therefore related to the probability of development at the plot scale. This is consistent with the findings from fine-scale analysis by Gude et al. (2006) and Newburn and Berck (2006) in the US. However, beyond 20 km from urban boundaries, we do not find that development probabilities vary with distance from the urban center. Similarly, Carrion-Flores and Irwin (2004) find that development in a single county in Ohio is positively related to proximity to the main urban center within 14 km of the urban boundary, but otherwise negatively related to urban proximity. This finding, which is consistent with our results, is attributed to ‘leapfrog development’ due to a desire for open space.

### 5.2. Application of findings

The analysis in this paper contributes to the literature on systematic conservation planning (Margules and Pressey, 2000) by highlighting the locations that are most threatened by low-density residential development. Numerous studies have shown that in a context of budgetary constraints on conservation, it is important to prioritize efforts towards places that are of high conservation value and that have high risks of conversion in the absence of intervention (Boyd et al., 2015; Carwardine et al., 2012; Withey et al., 2012). Our results provide evidence on the second of these, indicating that accessible locations with high natural amenities are most likely to be developed, with moderate risk for both accessible locations with low natural amenities and inaccessible locations with high natural amenities. In this study we do not explicitly examine which places have the highest ecological values. However, it is likely that those with less disturbance from prior development, and those that are high in natural amenities such as mixed forest/non-forest vegetation, National Parks and other public lands, and bodies of water will tend to have higher ecological value. The overall implication of this is that the highest priority for conservation efforts and the target for conservation funding should be remote locations near to public lands, forests and lakes, since the probability of development in remote, relatively undisturbed landscapes that are high in natural amenities is estimated to be as high as, or higher than, the probability of development in or around existing urban locations without natural amenities.

Our findings can also be used by city and state governments to inform efforts to balance conservation with economic activity. In many rural communities, natural amenity-driven population growth provides new economic opportunities, particularly where resource-extraction based industries are in decline. At the same time, our analysis shows that increased demand for residential land may threaten the natural amenities that in-migrants are seeking. Our results show that residential development is most likely to occur around communities that have good accessibility to both natural amenities and urban services. Around these communities, the plots that are most likely to be developed are those that are both near to some prior development and near to natural amenities. This finding, that the demand for accessibility to some degree offsets the demand to be near natural amenities, offers direction for how local zoning regulations can be used to allow for housing growth while mitigating some of the potential ecological damage from low-density development. Specifically, joint goals of economic growth and environmental protection can be managed by encouraging residential development in accessible locations where prior development has occurred, and simultaneously limiting development in relatively remote locations that are high in natural amenities.

Understanding the scale at which particular types of natural amenities affect development informs the scale at which land-use planning decisions must be made. The community variables provide information on which communities experience the greatest development pressures on both plots with good access to natural amenities and those without. We find that the high-development communities are near to National Parks and ski resorts, and have good access to transportation and other urban centers. Their challenge is therefore to manage development pressures by directing development that does occur to less sensitive locations within their surrounding landscape, for example fill-in development in urban or suburban locations, or in parts of the landscape that are less important for the integrity of the local natural amenities. As these high-development communities grow, the plot-scale results indicate that the parts of the landscape that are nearest to lakes, public lands and forests are likely to have the most urgent need of protection through zoning regulations or conservation easements in order to maintain the natural amenities that the residents value. Around low-pressure communities, high-amenity plots are also more likely to be developed than low-amenity plots, but the overall development probabilities will be lower and some development of rural lands near natural amenities may be acceptable from the point of view of a community seeking to encourage economic and population growth.

### 5.3. Limitations and scope of study

While our sample size is relatively large for the type of photo interpretation data that we use, the low frequency of transitions from undeveloped to developed land limits the complexity of the models that we can feasibly estimate. Given this, we emphasize the results from our parsimonious models, including only the natural amenities that are of general relevance across the study region, and using indices to capture broad measures of overall community accessibility, socio-demographics and climate. This means that we cannot isolate the impacts of individual elements of the indices, for example the role of temperature vs. rainfall, or of access to large urban areas vs. access to airports.

A second limitation is that while we control for many variables that are likely to influence the probability of development, there are some that we do not include in our models. Most notably, we do not explicitly include measures of policy instruments such as zoning or conservation easements, although we consider the potential for these in the discussion of our results. The state fixed effects control for state-level policy differences, but we do not have complete data on local land use policy instruments. Furthermore, introduction of these measures is likely to be endogenous to the location and natural amenities of a given community or plot. Our results must therefore be interpreted as reduced-form models that identify the types of locations where the pressures on undeveloped land are both intrinsically high and are less likely to be addressed by local policy measures.

Other variables that could in principle be correlated with both the probability of development and the amenity and accessibility variables that we are interested in include locations of businesses, value of agricultural land and siting of disamenities such as landfill sites. We therefore use the models to understand overall patterns of residential conversion, and where threats from low-density development are highest, rather than estimating causal influences of particular variables.

## 6. Conclusions

Much of the existing evidence used for conservation planning is focused on ecological values of undeveloped land. In contrast, we capture the variation in the likelihood of development within and between communities by quantifying land conversion at both fine- and broad-scale across a large study region. By doing so, we demonstrate how patterns of low-density residential development and resulting threats to rural ecosystems can be driven by economic and social values and preferences operating at different spatial scales. The result of this is that planners will obtain different answers about which locations are most likely to be developed depending on the scale of the analysis. This ties in with recent evidence showing that estimates of conservation costs based on coarse resolution data are considerably different from estimated based on high resolution data (Nolte, 2020). The key next step is to link these findings with analysis of the scales at which low-density development, particularly in natural amenity-rich locations, affects ecological integrity.

## CRediT authorship contribution statement

**Dawson Reisig:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. **Katrina Mullan:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **Andrew Hansen:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition. **Scott Powell:** Conceptualization, Methodology, Investigation, Writing - review & editing, Funding acquisition. **David Theobald:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Rachel Ulrich:** Investigation, Data curation.

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