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David A. Newburn
University of California, Berkeley

Peter Berck
University of California, Berkeley

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This paper investigates how land-use regulations differentially influence suburban versus rural residential development. Particular emphasis is centered on how both the provision of municipal services (e.g., sewer and water) and zoned maximum density constrain higher density residential development. We estimated a spatially explicit model with parcel data on recent housing development in Sonoma County, California. To account for heterogeneity in compliance with zoning regulations, we used a random parameter logit model. The designation of sewer and water services was the most important determinant of suburban development. Meanwhile, it did not significantly affect the likelihood of rural residential development, which actually leapfrogged into areas well beyond them.

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Keywords: housing development, land-use regulation, spatial modeling

Introduction

Prior studies have focused on the variation in housing densities among the metropolitan regions of the United States (Fulton et al. 2001), and considerable discussion has been generated regarding the causes and remedies for low-density urban and suburban development (Brueckner 2000; Nechyba and Walsh 2004). However, exurban development[1], particularly rural residential properties located outside of large central cities and their associated edge cities, uses a great deal more land than urban and suburban development (Heimlich and Anderson 2001; Theobald 2002; Sutton, Cova and Elvidge 2004). According to Heimlich and Anderson (2001), "…About 5 percent of the acreage used by houses built between 1994 and 1997 is for existing farms, and about 16 percent is in existing urban areas within Metropolitan Statistical Areas (MSA) defined by the Bureau of the Census. Thus, nearly 80 percent of the acreage used for recently constructed housing – about 2 million acres – is land outside urban areas or in non-metropolitan areas. Almost all of this land (94 percent) is in lots of 1 acre or larger, with 57 percent on lots of 10 acres or larger [i.e., 10-22 acres]". Many of the undesirable characteristics used to define urban and suburban sprawl, such as low-density and non-contiguous development, are even more pronounced for rural residential properties in the exurban area.

Exurban development has a large impact on farmland and habitat. Farming operations typically are not viable on properties at rural residential densities, except for "hobby" farms. Given the extent and rate of development in exurban areas, it poses a greater challenge to farmland preservation efforts than urban and suburban development (Long and DeAre 1988;

[1] Nelson and Sanchez (1997) define the exurban area as follows, "…exurbia extends beyond the built-up urban and contiguously developed suburban areas, but not into the true hinterlands beyond the commuting range of the city centers and their edge cities." Rural residential properties located in the exurban area mainly are built on large lots and almost invariably are serviced by private wells and septic systems. Leapfrog development is common in exurban areas because these homes are not bound to existing sewer and water service areas. In this study, we define "rural residential" by the housing density at a parcel level (greater than one acre per house), whereas "exurban" is defined as a conceptual region at a landscape level.

Heimlich 2001). The ecological impacts of rural residential development on native wildlife populations are also substantial, due to a loss in habitat quality (Swenson and Franklin 2000). In addition, the spaces between rural residential homes are often modified with landscaping and rural roads, thereby exacerbating the spread of invasive species (Odell et al. 2003).

To mitigate these impacts, it is important to understand what factors influence the spatial pattern of residential development. Parcel-level models of residential land-use change have successfully demonstrated the significance of spatial heterogeneity in the landscape and other factors (Bockstael 1996; Irwin and Bockstael 2002; Irwin, Bell and Geoghegan 2003). These models rely on tax assessment parcel records to observe individual landowner conversion decisions. Explanatory variables include spatially articulated data on parcel attributes, such as physical landscape features, access to public services, neighboring land uses, and regulatory constraints. These models estimate the influence of these variables on the likelihood that undeveloped farmland or forest parcels will be converted to residential development.

Nonetheless, the choice set in these residential land-use change models is always cast as a binary dependent variable – developed or remain undeveloped. By lumping conversion events spanning a wide range of densities, binary choice models implicitly assume that the same development process operates for all types of residential conversion. However, land-use regulations may have different effects on different residential densities. For instance, limits on sewer and water service extension, the primary mechanism of an urban growth boundary, may reduce suburban development outside the boundary, but may have little or no influence on rural residential development.

The purpose of this paper is to investigate how land-use regulations differentially influence suburban versus rural residential development. Particular emphasis is placed on how both the provision of municipal services (e.g., sewer and water) and zoned maximum density constrain higher density residential development. To find these effects, we estimated a spatially explicit model with parcel data on recent single-family housing development in the unincorporated area of Sonoma County, California.[2] Using a random parameter logit model, we modeled the individual landowner's decision to convert an undeveloped land parcel to residential use as a function of parcel attributes. Our model allows for multiple residential density classes, and the main break between suburban and rural residential classes was defined as one house per acre, since this is a typical limit on residential density with septic systems. The parcel attributes, which were extracted within a geographic information system (GIS), include accessibility to major highways and employment centers, physical land quality, neighboring land use externalities, provision of sewer and water services, and zoned maximum density.

Zoned maximum density, often stated as the minimum lot size restriction, may constrain development at higher residential densities but allow development at lower densities. Thus, we determined to what extent recent residential conversion events occur at or below the zoned maximum density.[3] A random parameter logit model was used because zoning regulations under the pre-existing General Plan may not be applied uniformly. Zoning variables specified with random parameters measure unobserved heterogeneity in compliance with zoning designations, due to upzoning or variances. We also differentiated the effects of zoning regulations for four regions, defined according to the type of access to sewer and water service areas.

In the next section of this article, we describe how the random parameter logit model is used to estimate the probability of residential development. The third section outlines the

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[2] The 1989 Sonoma County General Plan covers only the unincorporated area for the County. For this reason, we restricted our analysis to parcels in the unincorporated region outside 1990 city boundaries.

[3] Wallace (1988) found that zoning designations were not binding for urban development, including zoning categories for commercial/manufacturing, residential multiple uses, and residential family uses. Using very different methods, we examine zoning in the unincorporated area.

methods for the case study, including a description of the land-use patterns and zoning regulations in Sonoma County, data on housing development and explanatory variables, and methodology to implement the random parameter logit model. The fourth section discusses the main results of the residential land-use change model. We conclude by discussing policy implications for managing both suburban and rural residential development.

Residential land-use change model

Consider the individual landowner's decision to convert a land parcel from an undeveloped to a developed state. A parcel is considered "undeveloped" if it currently has no residential use or extremely low residential density associated with extensive land uses (e.g. agriculture, forestry). The landowner is assumed to be a utility-maximizing agent who makes a discrete choice in the current period on whether to convert the undeveloped parcel to residential use. There is a set of J alternatives, the $J-1$ residential density alternatives and the alternative that the parcel remains undeveloped.

A random utility model is used to formulate the individual landowner's conversion decision. The utility that the owner of parcel n would obtain from the land being in alternative use j is U_{nj}, $j = 1, \ldots, J$. Conditional on the parcel being in the undeveloped alternative in the current period, the landowner will choose the residential density alternative in following period with the highest level of utility. That is, choose alternative i if and only if $U_{ni} > U_{nj}, j \neq i$. Let $U_{nj} = V_{nj} + \varepsilon_{nj}$, where V_{nj} is an observable function of the parcel attributes that are hypothesized to influence the likelihood of conversion to residential density alternative j and ε_{nj} is an independently and identically distributed extreme value error term.

For parcel *n*, the attributes Z_{nj} in relation to alternative *j* form a *K* x 1 vector that is categorized into two types of variables. The first type, of which there are *M* variables, vary over the alternatives. In this study, zoning regulations on maximum residential density have this property. That is, zoned maximum residential density on parcel *n* can restrict the conversion to some higher density alternatives, while it does not affect conversion to the lower density alternatives. The other $K-M$ parcel attributes do not vary over alternatives. For instance, the slope of a parcel is the same regardless of whether the parcel is developed at a high or low density. For the *M* zoning variables, β^k are the corresponding parameters, $k=1,...,M$. There are $J-1$ alternative-specific coefficients that must be estimated for each of the remaining variables, $k=M+1,...,K$. The parameter β_j^k corresponds to alternative *j* on variable *k*. Note that if the value of β_j^k were the same for all *j*, then variable *k* would cancel out and have no effect on the probability of residential development. One alternative must be omitted for model identification, and so the undeveloped state is chosen as the baseline alternative (i.e., $\beta_j^k=0$ for all *k* in the undeveloped alternative). Hence, the index V_{nj} is expressed as:

$$V_{nj}(\beta)=\sum_{k=1}^{M}\beta^k Z_{nj}^k+\sum_{k=M+1}^{K}\beta_j^k Z_n^k \qquad [1]$$

The logit probability, L_{nj}, is:

$$L_{nj}=\frac{e^{V_{nj}(\beta)}}{\sum_{j=1}^{J}e^{V_{nj}(\beta)}} \qquad [2]$$

Zoning is an imperfect constraint since zoning regulations may be applied with varying strictness. For instance, the zoned maximum density in an area may be increased (i.e., upzoning).

The local planning board may also grant a variance for a given landowner's parcel, thereby permitting higher density than specified in the comprehensive general plan.

To account for heterogeneity in compliance with zoning regulations, a random parameter logit (RPL) model is used (Train 2003). The RPL model, also known as "mixed logit", generalizes logit by allowing parameters to take on different values for different parcels. In this study, we let the parameters β^k for $k = 1,...,M$ on the zoning variables be randomly distributed. We take the density of β^k for $k = 1,...,M$ to be an independent normal distribution with mean b^k and variance w^k, such that the density for each parameter distribution is $f\left(\beta^k \mid b^k, w^k\right) \sim N\left(b^k, w^k\right)$. The alternative-specific parameters β_j^k for $k = M+1,...,K$ are taken as fixed parameters (i.e., $w_j^k = 0$). Hence, the parameter density distribution $f\left(\beta_j^k \mid b_j^k, 0\right) = 1$ if $\beta_j^k = b_j^k$, and otherwise zero for $\beta_j^k \neq b_j^k$. Let b and w represent the respective K x 1 vectors of parameters b^k and w^k, and the joint density of parameters is $f\left(\beta \mid b, w\right)$. The RPL probability, P_{nj}, is the integral of the logit formula L_{nj} in Equation [2] evaluated over the density of parameters $f\left(\beta \mid b, w\right)$:

$$P_{nj} = \int L_{nj}\left(\beta\right) f\left(\beta \mid b, w\right) d\beta \qquad [3]$$

RPL models have two sets of parameters. First, there are the parameters β that enters into L_{nj} and are specified to have a density $f\left(\beta \mid b, w\right)$. Second, there are the deep parameters that characterize the function $f\left(\beta \mid b, w\right)$, such as mean b and variance w in the normal density as described above. Simulation methods are needed to estimate b and w because the integral in Equation [3] does not have a closed form solution. Maximization on b and w is thus done for the RPL model using the simulated log-likelihood (SLL) function (Hajivassiliou and Ruud 1994).

For the empirical analysis, we used software code that was written by Ken Train in GAUSS for estimating random parameter logit models.[4] The zoning variables were specified as a normal distribution with the mean and standard deviation parameters.[5] The mean on this normal mixing distribution was expected to be negative, because if zoning does act as a binding constraint, then it lowers the likelihood of development for those housing density classes which exceed the designated zoned density. The standard deviation on the mixing distribution measured the unobserved heterogeneity in how strictly zoning is applied to different locations. The left-hand tail of the mixing distribution provided the proportion of parcels for which zoning was not binding.

All other explanatory variables were estimated using fixed parameters. These other variables were tested for random parameter specification using a likelihood-ratio test on the standard deviation parameters. All these standard deviation parameters were found to be insignificant, implying that fixed parameters for these variables was adequate. This occurred most likely because each of these variables already has $J - 1$ alternative-specific coefficients.

Here we explain how the estimated parameters on $\hat{b}$ and $\hat{w}$ are used to simulate the choice probability P_{nj}. Specifically, step 1 is to draw β randomly from the density $f\left(\beta \mid \hat{b}, \hat{w}\right)$. In step 2, L_{nj} in Equation [2] is calculated for this value of β. Steps 1 and 2 are repeated Q times with each iteration q being a different random draw, labeled β^q. The average on L_{nj} is taken as the estimated choice probability:

[4] See http://elsa.berkeley.edu/~train for more information.
[5] We also tried to specify the zoning variables with a lognormal distribution. A lognormal specification has the desired property of the same sign for the entire parameter distribution. Because the lognormal distribution is defined over the positive range and the coefficient on zoning is expected to have negative sign, the negative of the zoning variable enters the model. None of the model runs based on this lognormal specification were found to converge. The difficulty in convergence has been found in many other empirical studies, primarily due to the fact that the log-likelihood surface is highly non-quadratic when using a lognormal specification (Revelt and Train 1999).

$$\hat{P}_{nj} = \frac{1}{Q}\sum_{q=1}^{Q} L_{nj}\left(\beta^{q} \mid \hat{b}, \hat{w}\right). \qquad [4]$$

The odds ratio are simulated by calculating the ratio of P_{nj}, in which L_{nj} in Equation [4] is evaluated with and without a unit change in a given explanatory variable. For instance, the ratio of P_{nj} is simulated with and without a one kilometer increase in the distance to nearest major highway for each parcel *n*, conditional on holding all other parcel attributes at their original values. The average odds ratio for alternative *j* is determined as the odds ratios averaged across all parcels.

Data and methods

Housing development and zoning regulations in Sonoma County

Sonoma County spans a region between 30 and 100 miles north of San Franscisco, California. As of 2000, over two-thirds of the 450,000 county residents lived within incorporated cities, such as Santa Rosa, Petaluma and seven smaller cities. While the majority of people live within incorporated cities, these cities cover only 4.0 percent of the County's land area. The unincorporated area, under the jurisdiction of the county government, covers the vast majority of the land area (4,112 square kilometers). Most land is devoted to agricultural and natural resource uses, including grazing, timber, and vineyard use. Rural residential development is also a significant type of land use. For instance, low-density (1 unit per 1 to 5 acres) and very-low-density (1 unit per 5 to 40 acres) residential development comprises, respectively, 9.8 percent and 4.4 percent of the total housing units in the County. More importantly, these two housing densities occupy 3.5 percent and 9.4 percent of the land area, more than three times the incorporated area (Figure 1).

The Sonoma County General Plan, originally adopted in 1978 and updated in 1989, is the dominant regulatory regime within the unincorporated area. The General Plan is composed of spatially articulated zoning units, which specify land-use designations and minimum lot size restrictions. Parcels located in designated areas for non-residential uses (e.g., public land, commercial, and industrial areas), in addition to properties under easement contract or enrolled in the Williamson Act, were excluded from the analysis.[6] For zoning types in which housing development was allowed, the zoned maximum housing density was determined from the inverse of the zoned minimum lot size restriction.

The provision of sewer and water services acts indirectly as a zoning regulation. For public health reasons, future development at greater than 1 housing unit per acre is restricted for areas without municipal water and sewer. There are two broad types of sewer and water service areas (SWSA) – those associated with the nine incorporated cities and those associated with the ten unincorporated rural towns. In 1989, these two types of SWSA covered only a small portion of the total land area in the County, 5.8 percent and 1.2 percent respectively. In comparison, the commutershed covers a much greater area and spans well beyond the extent of the 1989 SWSA. Approximately 59 percent of the total land area is located within less than a 40-minute commute time to either Santa Rosa or San Francisco. All SWSA existed prior to the adoption of the 1978 General Plan, and subsequent expansion has occurred contiguously to existing SWSA and built urban areas. Thus, the SWSA expansion is determined as part of the annexation process by incorporated cities.

Relative to SWSA boundaries in the 1989 General Plan, we define four mutually exclusive regions: 1) the annexation region of incorporated cities, meaning the areas outside

[6] Development is restricted on properties with 10-year agricultural conservation contracts under the California Land Conservation Act of 1965, commonly known as the Williamson Act. Parcels enrolled in the Williamson Act are ultimately developable, but were not during the estimation period in 1994-2001.

1990 incorporated city boundaries but located within the designated 1989 SWSA boundary; 2) existing SWSA associated with rural unincorporated towns; 3) unincorporated areas without sewer service but located within one kilometer of any 1989 SWSA boundary; and 4) unincorporated areas without sewer service and located further than one kilometer from any designated SWSA boundary (Figure 2). Development at suburban densities was expected to be less likely for both regions outside the SWSA, relative to the annexation region. The purpose of the third region is to account for whether parcels in the vicinity of a pre-existing SWSA boundary may have higher likelihood for suburban development than the fourth region.

In order to slow or stop the annexation process, eight of the nine cities in Sonoma County have now passed urban growth boundaries (UGB).[7] The new legislation stipulates that the growth boundary is fixed for a 20-year horizon. These UGB were set to match closely with the existing sphere of influence and SWSA at the time of passage. No urban development is permitted beyond the boundary, defined as development that requires one or more basic municipal services such as water, sewer, or storm drains.

An UGB is often conceived to create a sharp boundary between urban communities and farmland or natural resource areas. However, prior to the enactment of UGB in the 1990's, there existed a wide range of zoned housing densities within the unincorporated area. In fact, the majority of the housing units built in the County predate the original 1978 General Plan. These historic housing density patterns and other land uses strongly influenced the zoning designations within the unincorporated area. Rural residential properties that are recently built outside the

[7] Incorporated cities and year of enacted UGB are as follows: Cotati in 1991; Santa Rosa, Healdsburg and Sebastopol in 1996; Petaluma and Windsor in 1998; Rohnert Park and Town of Sonoma in 2000. Seven city UBG were passed by voter initiative, while Cotati was decided by the City Council. Only Cloverdale, the most remote city, has not yet enacted an UGB.

SWSA can be serviced by private well and septic systems, rather than relying on the extension of municipal services, and therefore only need to comply with the existing zoned housing density.[8]

Description of housing development and parcel subdivision data

Land parcel records from the Sonoma County Tax Assessor's Office provided micro-level data on housing development and subdivisions. The assessor database contains lot size, date of last subdivision starting in 1993, number of single-family housing units, year built and other characteristics for each current parcel. Parcel records were linked to a parcel map within a GIS. The data was then compiled to determine the undeveloped parcels in 1993 and to assess whether these undeveloped parcels were converted to one of several housing densities during the 1994-2001 period.

Data on parcel subdivisions and housing development were compiled in two stages. First, parcel boundaries in 1993 were determined from the date of last subdivision and adjacency between parcels. That is, the original 1993 parcel boundaries were reconstructed from adjacent current parcels that also have the same date of subdivision.[9] These parcel boundaries were then used to determine whether the parcel was recently developed in 1994-2001, conditional on being "undeveloped" in 1993. A parcel was considered undeveloped if either the parcel was vacant in 1993 or the pre-existing housing density in 1993 was less than 1 unit per 40 acres. The data set contains 19,090 undeveloped parcels in 1993. For each parcel, the observed housing density was calculated as the number of housing units in 2001 divided by the 1993 parcel lot size. These observed housing densities were categorized into one of five density classes: very-high density

[8] Federal regulations on development, including floodplain and Clean Water Act requirements, are largely incorporated in the General Plan.

[9] These 1993 parcel boundaries were visually checked with the exact date of subdivision for current parcels, and also using a separate 1999 parcel map, in order to assess the accuracy of this process. The process was verified to work well.

(≥ 4 units per acre), high density (1 to 4 units per acre), low density (0.2 to 1 unit per acre), very-low density (0.025 to 0.2 units per acre), and remain undeveloped (< 0.025 units per acre).

Table 1 shows the numbers of parcels, housing units built, and land area developed by density class within the four SWSA regions. Consider the differences between the annexation region and region beyond one kilometer from any SWSA boundary. The majority of recent housing units were built at suburban densities in the annexation region. There were 1845 homes built at very-high density on 244 parcels in this region, indicating that these housing developments were primarily large and dense subdivisions. In contrast, rural residential homes built without subdivision were the dominant form of housing development located in the region beyond one kilometer from any SWSA boundary. There were 282 homes built at very-low density on 216 parcels. Another major difference between these two regions was the relative amount of land area developed in 1994-2001. In the annexation region, only 243 and 197 acres developed at the two suburban densities, despite the fact that the majority of homes were built here. Meanwhile, 4372 and 775 acres were developed at the two rural residential densities within the region beyond one kilometer from any SWSA boundary.

Description of explanatory variables

This section describes the construction of the explanatory variables. Data on zoned maximum residential density were taken from the 1989 General Plan, which was predetermined relative to recent housing development in 1994-2001. To assess whether zoning acts as a binding constraint on parcel *n*, the zoned maximum residential density, d_n, was compared to each of the five housing density classes. Denote the lower bound of housing density class *j* as h_j. "Bind" is a dummy variable that represents whether the lower bound for housing density class *j* was greater than the zoned maximum density on parcel *n*, $h_j > d_n$. For example, consider a parcel located on a zoning designation with 20-acre minimum lot size restriction, indicating a zoned maximum density at 1 housing unit on 20 acre. Housing development would not be permitted for very-high, high, and low density classes. For instance, the low-density class (1 unit on 1 to 5 acres) spans a range of housing densities at 0.2 – 1.0 units per acre. The lower bound on this range is 0.2 units per acre, which exceeds the zoned maximum density of 0.05 units per acre. Therefore, the bind variables for these three classes are equal to one. This zoned maximum density, however, would allow housing development at the very-low density class (1 unit on 5 to 40 acres), and thus the bind variable equals zero. Bind is always zero for the alternative to remain undeveloped.

Compliance with the 1989 General Plan may differ for these four respective SWSA regions in the degree to which zoning acts as a binding constraint on housing development. Therefore, dummy variables were created to specify into which SWSA region each parcel centroid was located, and then interaction terms were made between the bind variable and the four dummy variables on the respective SWSA regions. We expect that recent development in the area outside the 1989 SWSA boundaries has been constructed at housing densities built in accordance with the 1989 General Plan, which would indicate that minimum lot size requirements are binding in almost the entire area of the county.

An important exception to zoning constraints must be made for grandfathered lots. Grandfathering occurs when the pre-existing lot size was already smaller than the minimum lot size restriction. In this case, county planners said that the General Plan allows one house to be built, but no subdivision is allowed. That is, grandfathering takes into account both the actual lot size (*a*) and zoned minimum lot size (*s*), such that the maximum allowed density on parcel *n* is expressed as $g_n = \max\left(1/a_n, 1/s_n\right)$. A dummy variable, called “grandfather bind”, was created for each alternative *j* to specify whether $h_j > g_n$. For example, consider again the parcel zoned with a 20-acre minimum lot size restriction, and now assume that it was a 3-acre property. The maximum allowable residential density with grandfathering is 0.33 (i.e. 1 housing unit on 3 acres), categorized into the low-density class. In other words, grandfather bind would not allow high and very-high density classes, whereas it would allow housing development for very-low and low-density classes. The grandfather bind variable is thus slightly different from the bind variable, because only the former would allow low-density development for this example. These grandfathered lots were very common within the unincorporated area located outside the 1989 SWSA. [10] Therefore, we created interaction terms between the grandfather bind variable and each of the two regions outside the SWSA.

Unlike the bind and grandfather bind variables, all other explanatory variables were parcel attributes that do not vary over the housing density alternatives. Hence, four alternative-specific coefficients are estimated for each of these parcel attributes (remain undeveloped is omitted as the baseline alternative). A set of dummy variables was made to indicate into which SWSA region each parcel centroid was situated. Logit coefficients on the suburban density classes were expected negative for the two regions outside the SWSA regions because this type of development is less likely in areas without municipal services.

The distance from each parcel centroid to the nearest major highway in kilometers was calculated. This variable represents access to the local centers because all incorporated cities, and most unincorporated towns, are located along these transportation corridors (Figure 2). Minimum travel time from each parcel to San Francisco also was calculated. An optimal routing algorithm within the GIS was used to determine the minimum travel time in minutes along the road

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[10] In 1993, grandfathered lots represented 57 percent of the total remaining development rights outside the 1989 SWSA.

network, utilizing weighted travel speeds of 55 miles per hour on major highways and 25 miles per hour on county roads. Logit coefficients on travel time and distance measures were expected to be negative because parcels with lower accessibility to regional and local employment centers should decrease the returns to residential uses, thereby lowering the likelihood for housing development. In particular, suburban residents in higher density classes were expected to seek locations close to employment centers.

The average percent slope and elevation in meters were calculated for each parcel. Slope coefficients are expected to be negative because steeper slopes raise the site construction costs for all types of housing development. The expected sign on elevation parameters is ambiguous because there are two effects with opposite expected signs. Elevation may serve as another indicator for steeper slope because higher elevation sites are located in mountainous areas. On the other hand, higher elevation may reflect a better view. A dummy variable was used to represent whether a parcel is located in the 100-year floodplain. New housing construction is highly restricted in floodplain areas because of higher risk for structural damage and increased home insurance rates. Therefore, all the floodplain coefficients were expected to be negative.

A set of explanatory variables was used to assess the amenities (or disamenities) created by neighboring land uses. The percentages of both protected open space and urban development within a 500 meter radius of the parcel were calculated. Protected open space includes parks, reserves and easements. Urban development consists of higher-intensity uses, including commercial, industrial, and residential use (> 1 unit per acre). These variables were created from the 1993 land-use distribution and therefore are predetermined relative to the time period used to model land-use change.

Results and Discussion

Results from the random parameter logit model of residential development are presented in Table 2. Table 2a shows the alternative-specific parameter estimates for the explanatory variables that do not vary over the residential density alternatives. Table 2b displays the parameter estimates on the mixing distribution for the zoning variables. In general, the parameter estimates in Table 2a are quite different between the density classes. When the parameters in Table 2a are restricted across density classes, the chi-squared statistic is 1519.2 with 33 degrees of freedom ($p < 0.0001$). This indicates that residential development should be separated into several density classes, not solely a binary variable for develop or remain undeveloped. Zoning variables with parameter estimates on the mixing distribution in Table 2b also are different for the four SWSA regions. As expected, the two regions outside the SWSA were found more likely to constrain higher density residential development than either the annexation regions or rural towns with existing SWSA (Table 2b). Below we first discuss the explanatory variables with fixed parameters in Table 2a, followed by a more detailed discussion on the zoning variables with random parameters in Table 2b.

Logit results for variables with fixed parameters

The first set of variables listed in the left-hand column of Table 2a includes the dummy variables that indicate the parcel's location by SWSA region. These parameter estimates for each SWSA region are interpreted relative to the annexation region, which served as the baseline region. For instance, housing development at the two suburban density classes was much less likely to occur for the region beyond one kilometer from any SWSA boundary. That is, very-high and high density classes had negative and significant parameter estimates for this region, relative to the annexation region (Table 2a). Parameter estimates only convey the direction of the effect of the variable on the probability of development for a given density class. The average odds ratio was calculated to determine the magnitude of effect from this SWSA variable.[11] To do this, the probability P_{nj} in Equation [4] was calculated for each parcel under two situations, conditional on holding all other parcel attributes constant. The first situation is that each parcel is located in the region beyond one kilometer from any SWSA boundary, and the second situation is that it is located in the annexation region. The average odds ratio is determined as the ratio of P_{nj} for these respective situations, which is done for each parcel and then averaged across all parcels. Calculating the average odds ratios, the probability of development decreased on average by a factor of 0.056 and 0.149 for the very-high and high density classes respectively, Specifically, the average odds ratio implies that the average probability of development at these density classes is only 5.6% and 14.9% for parcels located in the region beyond one kilometer from any SWSA, with respect to the average probability on the same parcels when they are located in the annexation region. These results are consistent with public health regulations requiring municipal water and sewer services for development at the two suburban densities.

The corresponding parameter estimates in Table 2a were not significant for the very-low and low density classes in this region. The two rural residential densities are typically serviced by private wells and septic systems, and thus are not bound to SWSA. The implication for land use is that rural residential development is more likely than suburban development to leapfrog into the vast region well beyond the SWSA boundary.

Similar results were found for the SWSA region situated less than the one kilometer from any SWSA boundary (Table 2a). Both suburban density classes were negative and significant,

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[11] Average odds ratios were calculated for all variables with fixed parameters in Table 2a. The full table is not presented in this paper for brevity, but it is available upon request from the authors.

and the average odds ratios were 0.085 and 0.149 respectively. Meanwhile, neither rural residential density classes was significant. Hence, parcels located either within or beyond one kilometer of the SWSA boundary are highly restricted for suburban development. The reason is that the 1989 SWSA could have been extended, particularly between 1989 and the date prior to enactment of urban growth boundaries. However, only 5.2 percent of the county land area lies within one kilometer of any 1989 SWSA boundary, and only 1.7 percent of this ring region was designated as SWSA during 1989-2001.

The parameter estimate on unincorporated towns was not significant for the very-high density class, and the high density class was negative but much less significant than both regions outside the SWSA. Hence, the likelihood of suburban development within unincorporated towns is more similar to the annexation region than to the unincorporated area outside the SWSA. This result is interesting because annexation regions have UGB and SWSA, whereas unincorporated towns only have the SWSA.[12] The likelihood of suburban development is similar regardless of whether the parcel is situated inside an UGB associated with an incorporated city or located outside the UGB but within a historic rural town. The reason is that a UGB is only capable of limiting SWSA expansion into regions that have not already been serviced.

Several of the locational characteristics were found to be significant (Table 2a). Parameter estimates on distance to nearest major highway are negative and significant for very-high, high, and low density classes. Conditional on holding all other parcel attributes constant, the average odds ratio was calculated under the two situations with and without a one kilometer increase in distance to major highway for each parcel. The probability of development decreased with longer distance on average by a factor of 0.711, 0.667, and 0.873 for these respective

[12] We utilized the SWSA variable for the annexation region, rather than UGB, because it was pre-determined relative to the 1994-2001 housing development. Most UGB were enacted between 1996 and 2000 and thus would be endogenous for this period of development.

density classes. This indicates that households in higher density development are more likely to be situated closer to local employment centers. This result was expected because approximately 80 percent of residents are locally employed within Sonoma County. Parameter estimates on travel time to San Francisco are negative and highly significant for very-low, low and very-high density classes. The probability of development decreased with an extra minute of travel time to San Francisco on average by a factor of 0.975, 0.969, and 0.986 respectively. This result indicates that some households value being situated closer to San Francisco and the greater Bay Area to gain better access to the regional employment opportunities. Nonetheless, it should be noted that the local accessibility (i.e., distance to nearest major highway) has a much stronger influence on the likelihood of development, as compared to regional accessibility (i.e., travel time to San Francisco). That is, a kilometer of distance is roughly equal to a minute of travel time, but the probability of development decreased much more significantly for an extra kilometer of distance to the nearest major highway.

Physical land characteristics also were found to be significant (Table 2a). Parameter estimates on average percent slope were negative and significant for the very-high, high, and low-density classes. According to the average odds ratios, a one unit increase in slope would decrease the probability of development on average by a factor of 0.923, 0.939, and 0.970 respectively. Steeply sloped parcels were less likely to be converted to higher density development because site construction costs rise with increased slope. In fact, parameter estimates on slope were found to be most negative in the higher density classes, indicating that the slope constraints have the largest influence on denser suburban development. The parameter estimate on elevation was negative and significant for very-high density development, while estimates were positive and significant for the high and low density classes. Parameter estimates on elevation have different signs because higher elevation has two effects with opposite expected signs. Elevation as an indicator of steeper slopes, and thus higher construction costs, appears to dominate for very-high density development, whereas the importance of better views was apparently the dominant factor for the lower density classes. Parameter estimates on the 100-year floodplain were negative and significant for the very-high and high density classes. Parcels inside the floodplains, as compared to outside floodplains, had lower probability of development on average by a factor of 0.262 and 0.134, respectively.

Spatial externality effects from prior urban development were negative and significant for all four density classes. A one unit increase in the percentage of neighboring urban development would lower the probability of development on average by a factor of 0.993, 0.973, 0.950, and 0.845 (in order of highest to lowest density). As expected, these spatial externalities were quite pronounced for rural residential density classes because these homeowners often seek to live farther away from nearby urban areas (Crumb 2003). The percentage of neighboring protected open space was not significant for all four density classes.

Logit results for zoning variables with random parameters

Table 2b provides estimated mean and standard deviation parameters on the normal mixing distribution for the zoning variables. Consider first the region further than one kilometer from any SWSA boundary. The estimated mean on the bind variable was -6.73 and highly significant. Thus, for the majority of parcels in the region, zoning lowers the likelihood of development at housing densities that are not permitted under the designated maximum housing densities in the General Plan. However, the corresponding standard deviation parameter estimate was 5.64 and significant, indicating variation in how strictly zoning regulations were applied within this region. Similarly, the estimated mean and standard deviation parameters on the grandfather bind variable were -14.30 and 7.7 respectively. This indicates that grandfathering creates an additional zoning effect by further restricting development of more than a single home on the current lot.

Table 3 shows the average probabilities with and without the effect from zoning variables for the respective SWSA regions, conditional on holding all other parcel attributes constant. The average probabilities were calculated using only the parcels within a given SWSA region, since zoning variables are specific to the SWSA region. Consider again the region further than one kilometer from any SWSA boundary. The average probability with zoning was less than the probability without zoning, particularly for the higher density classes. For instance, the average probabilities with and without zoning at very-high density were 0.00099 and 0.00157 respectively. That is, very-high density development already was unlikely for this region because there was no sewer service, and zoning regulations further lowered the likelihood for this class of suburban development. Rural residential development at low-density was more likely in this region because it does not require sewer service. But zoning regulations lowered the average probability of low-density development from 0.01424 to 0.01167.

Now consider the region within one kilometer from any SWSA boundary. For the bind variable, the estimated mean and standard deviation parameters were -4.80 and 4.4 respectively (Table 2b). The mean and standard deviation parameters on the grandfather bind variable were not significant; however, they were approximately the same sign and magnitude, -12.63 and 6.99 respectively, as the corresponding parameters for the region beyond one kilometer from any SWSA boundary. In sum, the compliance with zoning regulations were relatively similar for the two regions outside the SWSA, especially when compared to the annexation region and unincorporated towns with SWSA. For the annexation region, the estimated mean and standard deviation parameters were only -0.542 and 0.089, respectively. Nonetheless it is interesting that the mean parameter was negative and significant for this region. The implication is that zoning regulations lower the likelihood of development, albeit by a relatively small amount. Our result contrasts with the finding in Wallace (1988) that zoning designations on single-family residential use were not binding (i.e. zoning follows the market).

Policy scenario on SWSA expansion

Table 4 shows how the average probabilities of development would be changed as a result of SWSA expansion. Here we consider only parcels within one kilometer of the annexation region. Average probabilities are calculated for the same set of parcels; however, we use parameter estimates for two different zoning regimes – annexation region with SWSA and the ring region within one kilometer of any SWSA boundary. The objective is to understand how extending sewer and water services to this region, which currently may be constrained by the existing UGB, would alter the average probabilities for the different density classes.

When the sewer and water service is extended, the two suburban densities are much more likely (Table 4). For instance, the average probability of very-high density development would increase from 0.00277 to 0.05106. This increase may be attributed to two effects. First, the sewer and water service has a direct effect on the likelihood of suburban development. Second, zoning regulations were less stringently applied within the annexation region, as compared to outside the annexation region. To see the direct effect of sewer service, consider the average probability outside versus inside the annexation region, and for the moment, ignore the second effect from zoning regulations (i.e., probability without zoning). The average probability at very-high density development was estimated to increase by roughly an order of magnitude, 0.00809 versus 0.07935 respectively. When the second effect from zoning regulations was taken into account, the average probability of development decreased from 0.00809 to 0.00277 outside the annexation region (i.e., a factor of 0.342), whereas it only decreased from 0.07935 to 0.05106 inside the annexation region (i.e., a factor of 0.643). Rural residential development is largely unaffected by the sewer and water service extension. In fact, low-density development was slightly lower within the annexation region than outside the annexation region, 0.01749 and 0.01402 respectively. This indicates that landowners outside the annexation region are more likely to build rural residential homes at low density as a substitute because they are more constrained in constructing suburban homes at higher densities.

Implications for rural residential and suburban growth management and concluding remarks

Suburban and rural residential development respond differently to land-use regulations. The designation of SWSA is the most important determinant of suburban development. Suburban development was found to be approximately an order of magnitude less likely in regions outside the SWSA, as compared to the annexation region. The land-use implication is that suburban development is largely constrained to the 7 percent of the County with designated SWSA, including existing incorporated cities, annexation regions, and rural towns. Because rural residential development requires only the installation of private groundwater wells and septic systems, it was not affected by the designated SWSA and actually leapfrogged into areas well beyond them. Zoning regulations on maximum residential density also were found to significantly lower the likelihood of higher density development, particularly in the vast majority of the landscape that was outside the designated SWSA. There was an additional zoning effect from grandfathered lots. As a consequence, most parcels developed outside the SWSA consisted of a single home built on a large lot without subdivision. In contrast, the majority of homes built in the annexation region were in large dense subdivisions (Table 1).

These land-use regulations have strongly influenced the landscape-level patterns of residential development. Sewer and water service lines are extended physically from a central facility, and therefore the designation of SWSA acts as a strong attractant force to guide the location of future suburban development. Large subdivisions on recently developed parcels within the annexation region were relatively contiguous. In contrast, most rural residential homes were not built adjacently. These recent homes with septic systems do not require contiguity. Zoning regulations also do not provide an attractant force to guide rural residential development. Rather, they specify minimum lot size restrictions to repel development from certain areas. However, a major issue is that most rural residential homes were built prior to the original 1978 General Plan. Therefore, zoning designations had to consider the existing rural residential land-use patterns that had already occurred under the low regulatory environment that prevailed before 1978. The result was that remaining farms intermixed with rural residential areas were granted many development rights.

Land-use policies should be tailored to guide either suburban or rural residential development. Priority funding for sewer infrastructure can be used to accommodate future suburban growth in designated target areas (Irwin, Bell, and Geoghegan 2003). Furthermore, UGB have been effective at restricting suburban development. Only minor amounts of suburban development occur outside the annexation region. However, rural residential development converted more than five times the land area of suburban development in Sonoma County during 1994-2001, despite the enactment of urban growth boundaries. In fact, rural-residential zoning based on minimum lot size restrictions may encourage low-density sprawl, because when zoning is binding, future homeowners are required to consume more land than desired, thereby increasing the amount of habitat and farmland conversion.

A new focus is needed on managing rural residential development outside the SWSA. There are three commonly used options – downzoning, purchase of development rights (PDR), and transfer of development rights (TDR). These tools are used for managing both suburban and rural residential development, but they are particularly useful for limiting rural residential development because growth boundaries on municipal services are not effective. Downzoning is relatively unpopular with existing landowners and can be difficult to implement due to the Takings Clause in the United States Constitution. PDR programs are increasingly popular and often funded through local or state ballot initiatives, as well as non-profit organizations, such as The Nature Conservancy. These programs have the capacity to purchase existing rural residential development rights. TDR programs can be used to create a market between properties with existing rural residential development rights located in environmentally sensitive areas or prime farmland (sending areas) and annexation regions that are serviced for dense suburban development (receiving areas). For instance, local planners in Montgomery County, Maryland downzoned properties with five-acre minimum lot sizes and credited the landowner with the development rights. Then, these development rights could be sold to developers who wanted to build at very-high density within areas that had already been serviced (Johnston and Madison 1997). Despite the success in Montgomery County, these programs have not been used commonly. Further research is needed on how to implement TDR programs in order to exploit the high degree of heterogeneity in the returns to land between suburban development in annexation regions and rural residential development in outlying areas.

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Table 1: Parcels, housing units, and acreage by housing density class within the four SWSA regions.

Parcels developed in 1994-2001

	Housing density class					
SWSA region	Very-high	High	Low	Very-low	Remain undeveloped	Total
Beyond 1 km of SWSA boundary	12	62	237	216	10129	10656
Within 1 km of SWSA boundary	15	34	83	46	3356	3534
Unincorporated town with SWSA	156	227	15	1	2268	2667
Annexation region with SWSA	244	136	30	6	1817	2233
Total	427	459	365	269	17570	19090

Housing units built in 1994-2001

SWSA region	Very-high	High	Low	Very-low	Remain undeveloped	Total
Beyond 1 km of SWSA boundary	17	93	304	282	60	756
Within 1 km of SWSA boundary	21	61	120	62	2	266
Unincorporated town with SWSA	204	296	16	1	0	517
Annexation region with SWSA	1845	431	109	13	0	2398
Total	2087	881	549	358	62	3937

Acreage developed in 1994-2001

SWSA region	Very-high	High	Low	Very-low	Remain undeveloped	Total
Beyond 1 km of SWSA boundary	3	61	775	4372	395204	400415
Within 1 km of SWSA boundary	3	38	274	976	32752	34043
Unincorporated town with SWSA	31	155	28	7	2915	3136
Annexation region with SWSA	243	197	204	293	4061	4999
Total	280	451	1281	5648	434932	442592

Table 2: Random parameter logit estimation results for housing development during 1994-2001 on undeveloped parcels in Sonoma County, California (Note to reviewers: Results from Table 2 are jointly estimated. The results would not fit on one page, so we had to report these results on separate pages in Tables 2a and 2b.)

Table 2a: Variables with fixed parameters

	Housing density classes [a]			
Variables with fixed parameters	**Very-high**	**High**	**Low**	**Very-low**
Sewer and water service areas (SWSA) [b]				
Beyond 1 km of SWSA boundary	-2.9094**	-1.9335**	0.0652	-0.3059
	(0.5553)	(0.3229)	(0.2559)	(0.4541)
Within 1 km of SWSA boundary	-2.4877**	-1.9272**	-0.0346	-0.1197
	(0.4907)	(0.3862)	(0.2395)	(0.4668)
Unincorporated towns with SWSA	0.2315	-0.6555*	0.0214	-1.3535
	(0.2098)	(0.2457)	(0.3436)	(1.0922)
Locational characteristics				
Distance to nearest major highway	-0.3496**	-0.4126**	-0.1443*	0.0004
	(0.0903)	(0.0688)	(0.0579)	(0.0425)
Travel time to San Francisco	-0.0149**	0.0002	-0.0313**	-0.0256**
	(0.0039)	(0.0032)	(0.0050)	(0.0058)
Physical land characteristics				
Slope	-0.0811**	-0.0642**	-0.0325**	0.0092
	(0.0105)	(0.0088)	(0.0081)	(0.0072)
Elevation	-0.0051*	0.0045**	0.0039**	0.0007
	(0.0025)	(0.0014)	(0.0014)	(0.0008)
Floodplain	-1.3766**	-2.0443**	-0.9921	-0.8271
	(0.3198)	(0.4678)	(0.5391)	(0.6753)
Neighboring land uses in 1993				
% Urban	-0.0087*	-0.0296**	-0.0524**	-0.1702**
	(0.0039)	(0.0045)	(0.0069)	(0.0152)
% Protected land	0.0049	-0.0077	-0.0166	-0.0174
	(0.0064)	(0.0044)	(0.0089)	(0.0097)
Constant	0.8232*	-0.2069	-0.1762	-0.9459
	(0.3990)	(0.3560)	(0.4264)	(0.6448)

N = 19,090 parcels
Log-likelihood = - 5721.1

Note: Standard errors are in parentheses and significance at the 1 % and 5% level are represented by ** and * respectively.
[a] Remain undeveloped is the baseline alternative.
[b] The annexation region is the baseline SWSA region, defined as outside 1990 incorporated city boundaries but within the designated 1989 SWSA boundaries for these incorporated cities.

Table 2b: Zoning variables with random parameters by the SWSA region

Variables with random parameters	Parameters on normal mixing distribution Mean	Standard deviation
Bind variable by SWSA region		
Beyond 1 km of SWSA boundary	-6.7368**	5.6400**
	(1.8111)	(1.1187)
Within 1 km of SWSA boundary	-4.8053*	4.4106**
	(2.2203)	(1.3559)
Unincorporated towns with SWSA	-1.6148	1.4487
	(1.1898)	(1.1759)
Annexation region with SWSA	-0.5417**	0.0888
	(0.1890)	(2.4012)
Grandfather bind variable by SWSA region		
Beyond 1 km of SWSA boundary	-14.3048**	7.7166**
	(3.8927)	(1.9370)
Within 1 km of SWSA boundary	-12.6398	6.9879
	(10.2165)	(5.0763)

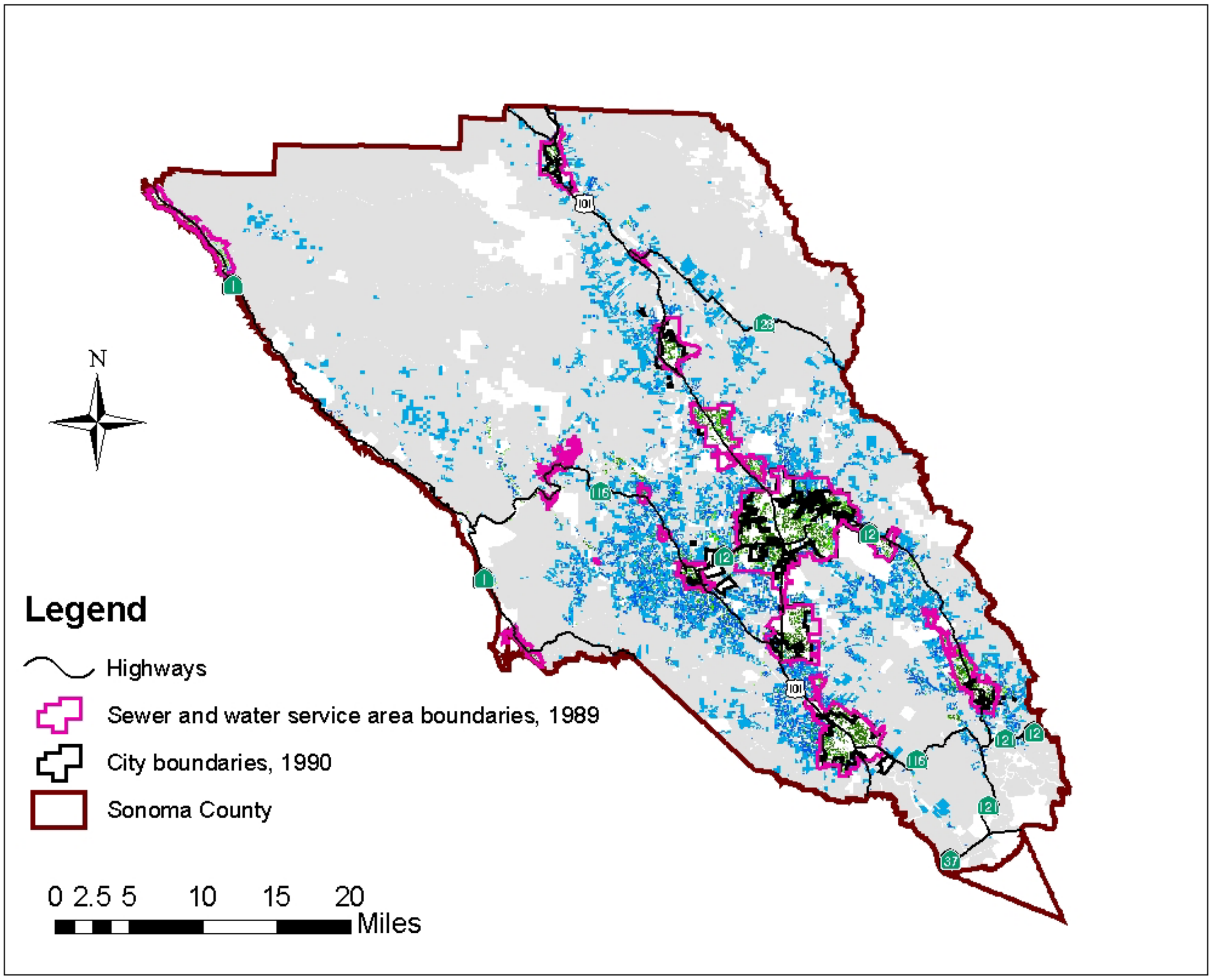
Table 3: Average probabilities with and without zoning for the four SWSA regions

SWSA region	*Density class* Very-high	High	Low	Very-low	Remain undeveloped
Beyond 1 km of SWSA boundary					
Probability with zoning	0.00099	0.00464	0.01167	0.01007	0.97264
Probability without zoning	0.00157	0.00623	0.01424	0.01056	0.96740
Within 1 km of SWSA boundary					
Probability with zoning	0.00240	0.00483	0.01102	0.00545	0.97630
Probability without zoning	0.00515	0.00883	0.01234	0.00542	0.96826
Unincorporated towns with SWSA					
Probability with zoning	0.02722	0.03602	0.00231	0.00015	0.93430
Probability without zoning	0.04149	0.03575	0.00230	0.00015	0.92031
Annexation region with SWSA					
Probability with zoning	0.04836	0.02653	0.00511	0.00115	0.91885
Probability without zoning	0.06383	0.03579	0.00621	0.00110	0.89308

Table 4: Average probability of residential development for policy scenario on sewer and water service expansion into the one kilometer ring around the annexation regions

	Density class				
Zoning regime	Very-high	High	Low	Very-low	Remain undeveloped
Within 1 km from SWSA boundary					
Probability with zoning	0.00277	0.00749	0.01749	0.00753	0.96472
Probability without zoning	0.00809	0.01292	0.01900	0.00754	0.95245
Annexation region with SWSA					
Probability with zoning	0.05106	0.04776	0.01402	0.00747	0.87969
Probability without zoning	0.07935	0.07306	0.01662	0.00751	0.82347

Figure 1: Residential density patterns in 2001 for Sonoma County, California



Land use legend

Suburban

very-high density (≥ 4 units per acre) = Dark green

high density (1 to 4 units per acre) = Light green

Rural residential

low density (0.2 to 1 unit per acre) = Dark blue

very-low density (0.025 to 0.2 units per acre) = Light blue

Remain undeveloped (< 0.025 units per acre) = Grey

Non-residential areas such as public lands and commercial = White

Figure 2: Sewer and water service area boundaries in 1989 and incorporated city boundaries in 1990 for Sonoma County, California.