EXURBIA AS PHYSICAL AND SOCIAL SPACE:

LANDSCAPE DRIVERS AND ECOLOGICAL IMPACTS OF AMENITY MIGRATION IN THE NEW WEST

by

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DEDICATION

To the only constants in my life

– the love and support of my family.

I thank my parents, Dragic and Vesna, for their unwavering support.

Thank you for teaching me not to accept the world for what it is,

but what it could be and for believing that I can part of that change.

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ABSTRACT

The American West, once characterized by open spaces, low population densities, and the dominance of primary sector activities, is experiencing high rates of population growth related to amenity migration. Those same natural amenities that attract migration are often degraded by housing growth and associated development; however the extent of impacts and the specific features of the environment that attract amenity migration are poorly understood. This change in land use was investigated by first examining the impacts of exurbanization on three ecosystem indicators (fire hazard, water availability, and distance effects of houses and roads) and secondly by considering the socio-cultural and aesthetic drivers of amenity migration in the Sonoita Plain, Arizona, USA. When the impacts of houses and roads on ecosystem function were considered, 98% of exurban areas were "highly" or "very highly" impacted, compared to 100% for suburban areas and 35% for rural areas. These results were striking because exurban areas have impacts on ecosystem function comparable to those of suburban areas, despite the fact that they support significantly lower population densities. The importance of privacy in the spatial distribution of exurban development was examined through GIS viewshed analysis. Desire for privacy was manifested in the home locations selected by exurbanites, with the large majority of homes located where the inhabitants see few, if any, neighbors. Scenic beauty is a common pull factor for amenity and this study examined three visual quality metrics (naturalness, visual scale and complexity) in relation to the location of exurban houses. Exurban households see significantly more vegetation, more rugged terrain, and a larger viewshed than would be expected if they were randomly distributed. There is

evidence that visual complexity throughout the viewshed may be more important than seeing the very highest peaks. These results call into question the use of county-level scales of analysis for the study of landscape preferences, which may miss key landscape aesthetic drivers of preference. Amenity drivers have important implications for the distribution of development and can inform growth strategies designed to minimize negative ecological impacts and protect visual quality of the environment.

CHAPTER 1: INTRODUCTION

I. Explanation of the Problem and its Context

Rural regions throughout North America and Europe are progressing through a striking and sustained post-industrial/post-productivist transition (Smith and Kannich 2000; Rudzitiz et al. 2011; Taylor 2011). The emphasis has changed from material production and extractive industries to the production and consumption of experiences (Taylor 2011; Hines 2011). Across the United States, amenity-rich regions are experiencing rapid land-use change in the form of low-density residential development or exurbanization. Exurbia, as both physical space and social phenomenon, describes very-low-density, amenity-seeking, post-productivist residential settlement in rural areas (Taylor 2011). This settlement is often spurred by amenity migration, which refers to "the purchasing of primary or secondary residences in rural areas valued for their aesthetic, recreational, and other consumption-oriented use values" (McCarthy 2008). In the United States, exurban land use occupies five to seven times more area than land with urban and suburban densities, and has increased at a rate of about 10 to 15% per year (Theobald 2005).

The American West, long characterized by open spaces, low population densities, and the dominance of primary sector activities, such as mining, logging, and ranching, is experiencing high rates of population growth related to amenity migration (Rudzitis 1999; Shumway and Otterstrom 2001; Vias and Carruthers 2005; Travis 2007). Extractive and manufacturing activities that were once at the center of western economics are now overshadowed by service-sector and high-tech industries (Power and Barrett 2001; Vias and Carruthers 2005; Gosnell and Abrams 2011). In the New West, scenic landscapes are increasingly valued more for the aesthetic and recreational amenities they provide than for mineral resources, forage or timber (Riebsame 1997; Power 1996; Rasker and Hansen 2000; Power and Barrett 2001; Hansen et al. 2002; Winkler et al. 2007). Amenity migration to the ranching landscapes of the American West has largely driven the transformation of rangelands from low-value productive lands to high-value positional goods (Travis 2007). A study of ranching activities in southern Arizona points to a combination of low-density residential development, specific tax policies, and the commodification of the ranching lifestyle idyll in the transformation of rural landscapes (Sayre 2002).

The rapid and dispersed nature of exurban development raises numerous ecological concerns, including reduction of water availability to biota, habitat fragmentation, disrupted fire regime, alteration of the food network, and change in vegetation owing to invasive species (Ewing 1994; Theobald 2004; Hansen et al. 2005; Clark et al. 2009). Houses, roads, and other infrastructure have impacts on ecological processes beyond their physical boundaries. Some modifications, such as mowing grass around houses, are immediately obvious, whereas others may manifest far off-site and substantially lagged in time, such as the slow transport of road-related pollutants into ground water systems (Forman et al. 2003). Findlay and Bourdages (2000) found that the full effects of road construction (restricted movements, increased mortality, habitat fragmentation, edge effects, invasion by exotic species, and increased human access to wildlife habitats) on wetland biodiversity may be undetectable in some taxa for decades. The spatial arrangement of houses, and their associated infrastructure, therefore has important implications for ecosystem function.

The drivers of exurbanization are numerous, and people move to rural areas for a variety of economic and non-economic reasons. Drivers include both push- (crime, crowding, poor education systems, etc.) and pull- (affordable or desirable housing, privacy, better schools, etc.) factors (Marans et al. 2001). These drivers have been augmented by technological advancements and increases in tele-commuting (Green 2002), and transportation and road-network improvements (Stewart and Johnston 2006). In the case of amenity migrants, studies have shown that non-economic pull-factors are often most important (Marcouiller et al. 2002). Social and cultural connections to small-town rural life can be a draw for some amenity-migrants (Walker and Fortmann 2003; Hines 2007). For many exurbanites, natural amenities, such as scenic beauty, expansive vistas, wilderness, recreational opportunities, and climate, play an important role in the decision to migrate (McCarthy 2008; McGranahan 2008; Gosnell and Abrams 2011).

The post-productivist transformation of rural economies reflects both economic forces and societal concerns about extractive uses in threatened landscapes. However, it is not clear to what extent amenity-based communities and the environmental conditions and aesthetics that they have come to enjoy can be sustained. As residential development drives the growth of infrastructure and nearby commercial developments, the number and complexity of land-use transitions tend to increase, and with them, the potential for detrimental impacts (Vogt 2011). Despite its large spatial extent, exurbanization is seldom guided by growth management plans (Kondo et al. 2012) and has received much less study than land-use change in suburban or urban areas (Hansen et al. 2005).

Despite the enormous potential impacts on ecosystem function arising from this wide-spread land-use change, exurbanization has received much less study than land-use change in suburban or urban areas (Hansen et al. 2005). Where there have been attempts to quantify the impacts of exurbanization, the arguments largely have been inferred (e.g., more roads per house create a larger area of disturbance and therefore must have more impact) rather than being measured (e.g., an empirical comparison of the impacts of different housing-density classes on specific ecosystem processes) (Theobald 2005; Vogt 2011). Similarly, there have been limited attempts to integrate what has been learned directly from exurbanites about their reasons for moving to rural landscape and the spatial pattern of actual exurban development (Walker 2011). Work has been done to identify the drivers of exurbanization, but very little is known about the spatial distribution of these preferences. The specific features of the environment that attract amenity migration are poorly understood and the relative contributions of different elements to the appeal of an area are unclear.

This study starts by examined the impacts of exurbanzation on three ecosystem function indicators and compared them to areas with rural and suburban housing densities. Three indicators were chosen to assess whether trends in impact are consistent across multiple indicators for an area. The three indicators, fire hazard, water availability, and generalized distance effects of houses and roads, were employed to assess the impacts of exurbanization in southeastern Arizona. Next, this study explored drivers of amenity migration by documenting the physical manifestations of exurban home site locations relative to the sites of other homes through a viewshed-based geographical representation and analysis. By looking at where people actually chose to build and live, it is possible to examine which drivers are optimized and which are compromised. Two groups of drivers were examined: privacy and social environment as cultural drivers, and visual quality metrics of landscape aesthetics. The data gathered were used to answer five fundamental questions:

1) Is there a difference in fire risk between exurban and other housing density classes (rural and suburban)?

2) Do the number of wells and the depth to water differ between housing density classes?

3) Houses and roads have effects on ecological processes beyond their physical boundaries and the distances outward that effects extend from infrastructure were considered in defining “effect zones”. How does the proportion of the landscape impacted by these generalized distance effects differ between housing density classes?

What is the cumulative impact of generalized distance effects for each housing density class?

4) In terms of physical distribution across the landscape, the desire for privacy stands juxtaposed against the desire for social-environment with its strong attachment to the built environment. Are exurban amenity-migrants selecting housing sites that afford privacy and where few, if any, neighbors were visible?

5) What is the relationship between the location of exurban homes and aesthetic landscape preference, as exemplified through three visual quality concepts (naturalness, visual scale, and complexity) and represented by three corresponding metrics (greenness, viewshed size, and terrain ruggedness)?

II. Study Area

The Sonoita Plain lies in a predominantly semiarid grassland located in northwestern Santa Cruz County, Arizona, USA. The Sonoita Plain is surrounded by the Santa Rita Mountains to the west, the Huachuca Mountains to the south-east, the Empire Mountains to the north, the Whetstone Mountains to the northeast and the Canelo Hills to the south . This constrained geographic area is entirely ringed by mountains that provide vertical visual boundaries. The unique topography makes this area especially well-suited to viewshed analysis since the mountains effectively constrain what is visible to those living in the Sonoita Plain to the interior Plain and the sides of the mountains facing the Plain, reducing the risk of potentially confounding influences beyond the mountains.

The Sonoita Plain is acknowledged to be a prime example of high plain southwestern grassland (Bock and Bock 2000). This is largely characterized by the desert grassland, plains grassland and desert scrub communities, with some riparian forest and riparian woodland communities along Cienega Creek in the northern part of the study. Upland regions ringing the central Plain are dominated by oak communities, while agricultural and developed areas are located near towns. Mean temperatures range from a January minimum of -2^{o}C to a June maximum of 33^{o}C (1971–2000), and average annual rainfall is 460 mm, with more than 50% occurring during the summer (July to September) monsoon (Kupfer and Miller 2005). Much of the Sonoita Plain has not burned within historic fire return intervals, suggesting an accumulation of organic fuels (Vukomanovic et al. 2013).

In recent years, residential developments have sprung up on land historically used for cattle ranching. People are relocating to the Sonoita Plain in increasing numbers and houses are being constructed as vacation homes, retirement homes, and primary residences for those who commute to jobs in the relatively nearby municipalities of Tucson, Nogales and Sierra Vista, Arizona. Overall, the residents of the Sonoita Plain are older and wealthier than residents in the rest of Santa Cruz County or the state Arizona overall. These trends are in keeping with those observed for amenity-migrants elsewhere (Smith and Kannich 2000; reviewed in Rudzitis et al. 2011) and suggest the ability or freedom on the part of Sonoita Plain exurbanites to make choices about housing location.

III. Explanation of Dissertation Format

The main body of this dissertation is contained in three appendices (A, B, and C). These are individual research manuscripts that are logically connected and integrated into the dissertation as a whole. All three manuscripts are based on data collected for the Sonoita Plain, Arizona, USA.

A. Relationship of the Appended Manuscripts

In the first manuscript, exurbia was examined as a spatial category and the impacts of amenity migration on ecosystem function were explored. A variety of factors contribute to making the movement of affluent urban populations to scenic rural areas desirable. Exubia is more than a physical delineation –it is also a cultural landscape constructed over time- and the second and third manuscripts explored the residential preferences of exurbanites in order to better understand the drivers of exurbanization. The second manuscript examined privacy and social environment as socio-cultural drivers, while the third manuscript explored the role of visual quality metrics and landscape aesthetics.

B. Contribution of the Author

With guidance from the dissertation committee, the conceptual design, research design, and interpretations for all three manuscripts were original contributions provided entirely by the author. The author collaborated with the co-authors of the first manuscript on data collection and data analysis. The author collaborated with co-authors on data analysis (validation of results) on the second and third manuscripts. Finally, the author collaborated with the co-authors of all three manuscripts in the verification of results.

CHAPTER 2: PRESENT STUDY

I. Summary

The methods, results, and conclusions of this study are presented in the papers appended to this dissertation/thesis. The following is a summary of the most important findings in this document.

II. Methods

Spatial analysis and modeling was conducted using ArcGIS v. 10.0 (ESRI, Redlands, CA, USA). Validation tests were performed and output figures created (Figures 5-8) using MATLAB 7.12.0 (The MathWorks Inc., Natick, Massachusetts). In lightly-settled landscapes, houses are not evenly distributed across census blocks and simple housing-density measures do not capture real location distribution or settlement patterns. To address this, locations of all houses in the Sonoita Plain study area were manually digitized from 2010 high resolution (1 m) aerial imagery obtained from the USDA Farm Service Agency, National Agricultural Imagery Program (NAIP). In 2010, the Sonoita Plain had 1,867 homes (U.S. Bureau of the Census) and supported three different housing-density classes. Following Theobald (2005) and Leinwand et al. (2010), the study area was divided into the following housing-density classes: rural (0-0.0618 units/ha), exurban (0.0618-1.47 units/ha), and suburban (1.47-10 units/ha). This study focused on the 998 houses classified as exurban.

In the first manuscript, the impacts of exurbanization of three ecosystem function indicators (fire hazard, water availability, and generalized distance effects of houses and roads) were examined relative to areas with rural and suburban housing densities. The Fire Return Interval Departure (FRID) for an area is a metric derived from an inferred normal fire-return interval (the historical average, in years, between fires), and the elapsed years since the last fire. This metric is identifies areas determine areas that have gone without a fire longer than expected and are likely to be overloaded with fuel and was used to assess fire risk. Information about well location, well depth, water depth, and drill/registration date came from the Arizona Department of Water Resources Well Registry (ADWR 2011). Water depths from wells were used to interpolate water level below land surface using the Kriging interpolation method. Houses and roads have effects on ecological processes beyond their physical boundaries and the distances outward that effects extend from infrastructure were considered in defining “effect zones”. Effects zone extents were derived from a review of the literature or were directly estimated from 1-m NAIP images. To visualize and measure the area of the concentrated-effects zones, buffers were created around each house and road in the study area. Buffer distances were defined by the effects zones. The cumulative impact of generalized distance effects provides a measure of the area surrounding each point that is affected by roads or houses. Cumulative impacts were determined by calculating the percentage of the landscape, within a 500-m radius circular neighborhood, that falls within a diffuse distance-effects zone.

Viewshed analysis was used in both the second and third manuscripts. A viewshed is composed of the areas of land, water, and other environmental elements that can be seen from a fixed vantage point (Fisher 1991; Gimblett 2013). Viewshed analysis identifies the cells in an input raster that can be seen from an observation point. In our viewshed analysis, each exurban house served as an observation point and the viewshed for each house represents the portions of the landscape visible from that location. The mountains surrounding the Sonoita Plain provide vertical visual boundaries and all viewsheds were contained within the central Plain. To our knowledge, viewshed analysis has not been used previously to assess housing location choice.

In the second manuscript, the viewshed for each of the 998 exurban homes in the Sonoita Plain was calculated and the number of neighboring houses that fell within each viewshed tabulated. The rolling topography of the Sonoita Plain presents the possibility that the ability to see (or not see) neighbors may be a feature of the landscape, rather than the outcome of house-location choice. In order to test whether the privacy findings for exurban homes (number of visible neighbors) reflect location choice on the part of homeowners, we tested the actual exurban distribution against simulated, random house location distributions. We simulated ten random house location distributions on portions of the study area deemed “developable”. Each simulated distribution included 998 houses, which matched the number of actual exurban houses in the study area. We calculated the viewshed for each house in each of the ten simulated distributions and then tabulated the number of neighboring houses that fell within each viewshed. Two-sample

Kolmogorov-Smirnov tests were performed to compare the cumulative distribution functions (CDFs) of the two data sets (actual exurban homes and simulated house distribution) at the 5% significance level.

For the third manuscript, viewshed analysis was combined with additional metrics (greenness, viewshed size, and terrain ruggedness) to compare the landscape characteristics visible from each vantage point. The Normalized Difference Vegetation Index (NDVI) was used to provide a measure of greenness. A decadal average value for each pixel was calculated and NDVI values that fell within each viewshed (i.e., are visible from that house) were averaged to calculate a mean viewshed NDVI value. Viewshed size provides a measure of how expansive the view is from each vantage point and the number of pixels in each viewshed was tabulated to calculate the size of the viewshed. The Terrain Ruggedness Index (TRI) provides a quantitative measure of terrain heterogeneity and is computed for each grid cell of a DEM by calculating the sum change in elevation between the central grid cell and the mean of an 8-cell neighborhood of surrounding cells. The grid cell-level TRI values that fell within each viewshed were averaged for a total TRI. The maximum TRI value in each viewshed was also calculated.

In order to test whether the findings for each of the three visual quality metrics (greenness, viewshed size, and ruggedness) reflect location choice on the part of homeowners, the actual exurban distribution were tested against a simulated, random house location distribution. Two-sample Kolmogorov-Smirnov (K-S) tests were used to compare the cumulative distribution functions (CDFs) of the two data sets (actual exurban homes and simulated house distribution) at the 5% significance level.

III. Results

Each manuscript is appended (Appendices A, B, and C). Their findings are summarized here in direct reference to the five fundamental research questions posed.

1) *Is there a difference in fire risk between exurban and other housing density classes (rural and suburban)?*

Exurban areas have the highest average FRID values (1.48), followed by rural areas (1.28); both positive values correspond to a moderate to high potential for fire. The suburban housing density class has an average FRID value of -0.55 and corresponds to low fire hazard. The high FRID value in exurban areas suggests that fire suppression measures associated with exurban development have increased fire hazard in the area.

2) *Do the number of wells and the depth to water differ between housing density classes?*

As of 2010, there were 1,243 wells for 1,867 households, which corresponded to 0.67 wells per household. When considered by housing-density class, there has been little increase in the number of new wells in suburban areas, with just three wells added in the last decade. Conversely, there has been a steady increase in the number of wells added in exurban areas (174 wells from 2000 through 2009). This growth is closely followed by the increase in the number of wells in rural areas (166 wells added from 2000 through

2009). Depths to water were lowest in the most densely populated area; however there is little difference in the depths to water between housing-density classes in the study area.

3) *Houses and roads have effects on ecological processes beyond their physical boundaries and the distances outward that effects extend from infrastructure were considered in defining "effect zones". How does the proportion of the landscape impacted by these generalized distance effects differ between housing density classes? What is the cumulative impact of generalized distance effects for each housing density class?*

About 35 percent of this sparsely populated landscape fell within the generalized distance effects zone of houses, roads, and highways. The effects zones mainly followed the highways (State Routes 82 and 83) and areas with highest housing densities. When the cumulative effects of these distance effects are considered, 100% of the suburban density class was highly impacted. The percentage of area within the exurban density class that was "Very Highly" impacted was 81%, which is comparable to that of areas with suburban densities. When both "Highly" and "Very Highly" impacted areas were considered, 98% of exurban areas fell within these cumulative-effects categories. The cumulative effects of rural density classes were substantially lower, with only 12% of the area being "Very Highly" impacted.

(4) *In terms of physical distribution across the landscape, the desire for privacy stands juxtaposed against the desire for social-environment with its strong attachment to the*

built environment. Are exurban amenity-migrants selecting housing sites that afford privacy and where few, if any, neighbors were visible?

The great majority of exurban homes in the Sonoita Plain see few, if any, neighbors. The logarithmic regression R^2 of 0.932 suggests that exurbanites are more likely to select house locations with fewer visible neighbors. The comparison of these results with each of ten simulated house distributions showed that the actual exurban households see significantly fewer neighbors than would be expected if the houses were placed randomly on potentially developable land without consideration for the visibility of neighbors.

5) *What is the relationship between the location of exurban homes and aesthetic landscape preference, as exemplified through three visual quality concepts (naturalness, visual scale, and complexity) and represented by three corresponding metrics (greenness, viewshed size, and terrain ruggedness)?*

Actual exurban households can see significantly more vegetation (higher average Normalized Difference Vegetation Index (NDVI) values) and a more rugged terrain (higher mean Terrain Ruggedness Index (TRI) values) than simulated houses. The actual exurban viewsheds have a higher mean TRI value, but a lower maximum TRI value than the simulated viewsheds, suggesting that the actual exurban homes see a more rugged terrain, but don’t necessarily see the highest peaks. This provides some evidence that visual complexity throughout the viewshed may be more important than seeing the very highest peaks. The viewsheds visible from the actual exurban houses were significantly larger than those visible from the simulated houses, indicating that visual scale is important to the general aesthetic experiences of exurbanites.

IV. Conclusions

The influence of exurban development on fire hazard and general effects on ecosystem function documented in this study suggest that it is the presence of people, rather than higher densities of people, that create significant impact. When the per-capita impacts are considered, exurban development appears to present substantial risk to natural-resource sustainability. The findings here support earlier work on the ecological impacts of exurbanization (Theobald 2005).

Much of the study area has not been affected by fire for at least 25 years and fire potential presently appears to be a moderate to major threat to ecosystems and ecosystem function. Even in rural areas, the quick response to extinguish fires means that much of the Sonoita Plain has not burned within normal fire-return intervals and that the build-up of organic fuels represents significant risk of large, high-intensity fires. The high FRID value in exurban areas suggests that it is the presence of people rather than the density that increases fire hazard. This high fire hazard, combined with the large amount of land required to accommodate people at such low population densities, calls into question the widely-held view that exurbanization is a conservation compatible land use.

The detrimental effects of excessive ground water use are already evident in other communities in southeastern Arizona. Although the Sonoita Plain has not reached a critical point in its water use, the experiences of neighboring communities provide a sobering window into the future. Immediately northwest of the Sonoita Plain, the Tucson area (Pima County) is experiencing ground water withdrawal-related land subsidence, in the form of sinks, on and near farmlands. Adjacent to the Sonoita Plain, flows of the Sand Pedro River, upon which the San Pedro National Riparian Conservation Area depends, are threatened by ground water withdrawals in the Sierra Vista area (Glennon and Maddock III 1994). A key ecosystem provision of grasslands is water for wildlife, and the water cycle controls this critical service. Important also is that the water balance of semiarid ecosystems can change dramatically in response to changing climate (Mote 2006; Overpeck and Udall 2010). Research indicates that warming and drying in the Southwest will continue (Notaro et al. 2012). The trends in water withdrawal and availability reported here may provide area residents with additional water management information, which in turn may help to avoid some of the problems experienced by other communities in the region

Exurban areas support lower population densities than do suburban areas, but the associated houses and roads appear to have comparable impacts on ecological processes. Given the rapid growth of exurban housing throughout the United States, these impacts are potentially enormous. The results of this study support earlier work that found that development patterns that are more contiguous, higher density, and more compact have reduced overall effects on natural resources (Theobald 2005). The dispersed settlement patterns of exurban areas create practical complications for natural resource management and planning. The cumulative-effects method described here could be used as a rapid-assessment tool to compare alternative growth scenarios or for other planning applications. The specific parameters (effects zones, neighborhood size, impact categories, etc.) can be easily modified, and this approach has the advantage of being spatially explicit.

Viewsheds with few, if any, visible neighbors are preferred by amenity-migrants in the Sonoita Plain. The ideals of the frontier and the search for “a more authentic existence” based on the homesteader experience, of which a central component is the desire for privacy and solitude (Hines 2007; Kondo et al. 2012), appear to be important drivers of amenity migration in this area. Although it is likely that both the privacy of the frontier and the social environment of rural small towns are appealing to at least some amenity-migrants, in the case of the Sonoita Plain, privacy appears to be a more important driver. This study provides some evidence that the development in this region may be masked, at least in part, by the desire for privacy. The widespread selection of housing sites where few neighbors are visible means that the effects of exurbanization are largely hidden from most inhabitants of the Sonoita Plain.

The Sonoita Plain is widely considered a prime example of a healthy high-plain southwestern grassland (Bock and Bock 2000), with high ecological value. The “social environment" migrant's connection to the built environment could mean that those exurbanites would be content with – or even prefer - to live at higher housing densities. The privacy requirements of "frontier" migrants, on the other hand are less conducive to communities with higher housing densities. Given the impacts on ecosystem function from exurbanization, the communities of the Sonoita Plain might consider actively targeting "social-environment" migrants. If the same number of amenity-migrants can be accommodated in a smaller area, the ecological impacts are minimized.

Actual exurban households can see significantly more vegetation (higher average Normalized Difference Vegetation Index (NDVI) values) and a more rugged terrain (higher mean Terrain Ruggedness Index (TRI) values) than simulated houses. It is not clear which of these two metrics, greenness or terrain ruggedness, is the primary driver of aesthetic preference in this study area. In addition to mountains, the other landscape type that supports a lot of woody vegetation and has higher NDVI values in southeastern Arizona is riparian areas (Arizona Game and Fish Department Natural Vegetation 1976). The boom of residential development along riparian areas in Arizona (Germaine et al. 1998) lends support to the importance of greenness in exurban house location selection, but terrain ruggedness is also important for landscape preference (Stamps 2004; McGranahan 2008). It could be that where there are trade-offs between greenness and ruggedness, we find different groups of amenity migrants. Birding enthusiasts, for example, may be drawn to areas that have more vegetation and can support a greater number and diversity of birds, such as riparian corridors, while avid hikers might be drawn to more mountainous terrain. Further study could help to tease apart these landscape preferences.

It is interesting to note that the actual exurban viewsheds have a higher mean TRI value, but a lower maximum TRI value than the simulated (validation) viewsheds. The actual exurban homes see a more rugged terrain, but don’t necessarily see the highest peaks. This provides some evidence that visual complexity throughout the viewshed may be more important than seeing the very highest peaks. It also suggests that the viewsheds with the highest peaks may not necessarily have the most visually complex views, which may be an important consideration when evaluating the desirability of a location. Exurbanites in the Sonoita Plain also favor extensive views over the landscape and it appears that visual scale is important to the general aesthetic experience.

To date, most studies that have examined the spatial distribution of exurbanization in the context of amenity drivers have been at the county-level scale (Mueser and Graves 1995; Hansen et al. 2002; McGranahan 2008; Rudzitis et al. 2011). The findings of this study challenge the idea that regional landscape features are important independently of the particular setting of a housing unit (Luttik 1999; McGranahan 2008) and calls into question the use of county-level scales of analysis for the study of landscape preferences. The fact that there are differences in the visual quality metric values between actual exurban viewsheds and simulated viewsheds indicate that county-level comparisons may miss key landscape aesthetic drivers of preference. Although informative of broad trends, county-level scales of analysis may miss the specific features of a region that attract amenity migration. It is not just the general characteristics of the area that are important, but also the visual quality from each vantage point. County-level metrics may be especially problematic for counties in the Western US, which tend to be large and where aggregate measures may mean the loss of valuable information. The Sonoita Plain itself is a wealthy island of exurban development in a county where 24.5% of the population has incomes below the poverty level and the median household income in 2010 was $13,038 lower than for the state of Arizona. County-level analysis of amenity-migration drivers would have missed this area entirely.

Residents in very high amenity areas, displaying “last settler syndrome” and seeing further in-migration as a threat to the very landscape qualities that drew them initially, may adopt regulations to constrain further growth (McGranahan 2008; Hines 2010; Kondo et al. 2012). Housing prices are inordinately high in the most scenic rural counties and they no longer have the highest rates of migration (Rudzitis 2011). This suggests that in rural areas that have long experienced amenity migration (US examples include Aspen, Sun Valley, Park City, and the Hamptons), further in-migration will increasingly be shaped by efforts to preserve valued landscape aesthetics rather than by the landscape preferences of potential new in-migrants. However, in areas that have more recently started to experience amenity migration, and where land availability and price still allow at least some choice, information about landscape drivers and exurban preference could prove helpful to planning and management efforts.

The post-productivist economic shift from traditional resource industries to a New West economy based on a mix of the traditional industries and new sectors such as real estate and recreation (Hines 2007; McCarthy 2008) reflects not only changing economic forces, but also societal concerns about extractive uses in threatened landscapes. Many amenity-migrants view dispersed, low-density residential development as a conservation-compatible land use and certainly preferable to material production. Despite this pervasive view, Radeloff et al. (2010) have argued that it is not material extraction/production but housing growth that poses the main threat to protected areas in the United States. The spatial arrangement of exurban houses, roads and associated infrastructure will depend on the primary drivers of migration, and different spatial distributions will have different impacts on both social systems and ecosystem function. Information about landscape drivers may be of interest to local government officials, planners, and policy makers, as it may enable growth strategies designed to minimize negative ecological impacts on private and public lands.

V. Recommendations for Future Study

To inform policy reliably, planning must consider a wide range of ecological processes or risk grave reductions of vital functions. Assessing the spatial extent of threats to ecosystem services is an important step for understanding the vulnerability of the systems and guiding decisions on the fate and best use of grassland ecosystems. A great deal of work still remains to be done to understand the impacts of exurban development on ecosystem function. The large impact of road networks, for example, warrants closer study; are there differences between paved and unpaved roads? How does ancillary infrastructure affect impacts? How are mitigation measures, such as wildlife crossings, viewed by exurbanites? Exurban developments are springing up across many different landscapes, from the Florida everglades to rangelands in Arizona to farmland in Oregon. Each of these landscapes will experience exurbia differently and regional impact assessments are needed.

The specific elements of visual quality that attract amenity migration are poorly understood and the relative contributions of different elements to the appeal of an area are unclear. Our results suggest that in this region, the desire for privacy supersedes the desire for social-environment and its attachment to the built environment. Future research that looked to tease apart differences in preference within the desire for privacy would strengthen our understanding of this landscape driver. Efforts to separate choice between what exurbanites want and what they wish to remain hidden could elucidate how people made decisions and better our understanding of how land development takes place.

As a phenomenon, exurbanization is part of broader set of rural transitions. These transitions are blurring the divide between rural and urban and raise opportunities to reimagine ways to view this new continuum and the transitions in land uses. Panarchy theory provides a conceptual framework to account for the dual, and seemingly contradictory, characteristics of all complex systems – stability and change. It is the study of how economic growth and human development depend on ecosystems and institutions, and how they interact. As an integrative framework, panarchy brings together ecological, economic and social models of change and stability, to account for the complex interactions among both these different areas, and different scale levels. Study of the exurban phenomenon through the lens of panarchy theory could prove to be an informative way of rethinking the rural-urban divide.

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APPENDIX A

HOUSING DENSITY AND ECOSYSTEM FUNCTION: COMPARING THE IMPACTS OF RURAL, EXURBAN, AND SUBURBAN DENSITIES ON FIRE HAZARD, WATER AVAILABILITY, AND HOUSE AND ROAD DISTANCE EFFECTS

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I. Abstract

Many amenity-rich regions are experiencing rapid land-use change in the form of low-density residential development. This widespread land-use change, exurbanization, has profound implications for regional biological diversity and ecosystem function. Those same natural-resource amenities that attracted migration are often degraded by housing growth and associated development. This study examines the impacts of exurbanization on three ecosystem indicators and compares them to areas with rural and suburban housing densities. Three indicators (fire hazard, water availability, and generalized distance effects of houses and roads) were chosen to assess whether any trends in impact are consistent across multiple indicators for the same area (Sonoita Plain, southeastern Arizona). We found that although they support significantly lower population densities, exurban areas have impacts on ecosystem function comparable to those of suburban areas. Exurban areas had the highest potential for fire, suggesting that it is the presence of

people rather than the density that increases fire hazard. The increase in the number of wells in exurban areas far exceeded suburban areas and matched increases for agricultural use in rural areas. When the impacts of houses and roads on ecosystem function were considered, 98% of exurban areas were “highly” or “very highly” impacted, compared to 100% for suburban areas and 35% for rural areas. These results were striking because development in the area is not readily visible. Assessing the spatial extent of ecosystem function impacts is an important step for understanding the vulnerability of systems and guiding decisions on the fate of grassland ecosystems in the path of potential development.

II. Introduction

Large areas of grassland in semiarid/arid parts of the southwestern United States and northern Mexico are yielding to low-density, non-urban housing. In the United States, exurban land use occupies five to seven times more area than land with urban and suburban densities, and has increased at a rate of about 10 to 15% per year (Theobald 2001; 2005). Vogt (2011) and Rudzitis et al. (2011) provide thorough reviews of the drivers of exurbanization, which include technological advancements and increases in tele-commuting (Green 2002), transportation and road-network improvements (Stewart and Johnston 2006), and push- (crime, crowding, poor education systems, etc.) and pull- (affordable or desirable housing, privacy, better schools, etc.) factors (Marans et al. 2001 in Vogt 2011). The rapid and dispersed nature of exurban development raises numerous ecological concerns, including reduction of water availability to biota, habitat fragmentation, disrupted fire regime, alteration of the food network, and change in vegetation owing to invasive species (Ewing 1994; Theobald 2004; Hansen et al. 2009; Clark et al. 2009). Those same natural-resource amenities that attracted an influx of humans are often degraded by increases in housing and associated development.

The per capita land conversion in exurban areas is much greater than in urban locations (Hasse and Lathrop 2003; Vias and Carruthers 2005), which has profound implications for regional biological diversity and ecosystem function. Theobald (2005) found that development patterns that are contiguous, of high density, and less dispersed have reduced overall effects on natural resources. The reduced effect on natural resources comes from smaller footprints or “disturbance zones”, lower percentage of impervious surfaces, and reduced pollution because fewer vehicle miles were generated. Exurban growth displays the opposite development pattern, suggesting a greater impact on natural resources. Some types of human activity, such as mono-crop agriculture and urban uses, affect broad expanses of the landscape and result in land-cover conversion that can be readily detected through remote sensing. These activities are typically well documented through land-cover maps. However, low-intensity land uses, such as low-density rural development, are more difficult to discern through land-cover assessments. This form of development is therefore more challenging to map and is typically not included in land-cover data (Ward et al. 2000). Given its important ecological implications, research is needed to improve our understanding of the patterns, rates, and extent of exurban development.

Despite the enormous potential impacts on ecosystem function arising from this wide-spread land-use change, exurbanization has received much less study than land-use change in suburban or urban areas (Hansen et al. 2005). Where there have been attempts to quantify the impacts of exurbanization, the arguments largely have been inferred (e.g., more roads per house create a larger area of disturbance and therefore must have more impact) rather than being measured (e.g., an empirical comparison of the impacts of different housing-density classes on specific ecosystem processes) (Theobald 2005; Vogt 2011). In this study, we examined the impacts of exurbanzation on three ecosystem function indicators and compared them to areas with rural and suburban housing densities. Three indicators were chosen to assess whether trends in impact are consistent across multiple indicators for an area. The three indicators, fire hazard, water availability, and generalized distance effects of houses and roads, were employed to assess the impacts of exurbanization in southeastern Arizona; these indicators, as well as the specific research questions related to each, are discussed below.

Integral to management and planning efforts is an understanding of land-use changes on natural resources and ecological processes (Ricketts and Imhoff 2003). Many exurbanites see themselves are stewards of the land and there is a strong, pervasive view that dispersed, low-density residential development is a conservation-compatible land use. Vogt and Marans (2003) report that some of the benefits of exurban development, according to residents, include preserving flora and fauna through nature watching, environmental education for children, a more solid appreciation of nature owing to proximity, and houses serving as buffers between nature and other land uses. An additional stewardship role is the funding of conservation efforts and helping to create, or return to, a natural-resource based economy that is not extractive (Vogt 2011). Through a comparison with suburban and rural housing-density classes, this research will contribute to the discussion on whether exurbanization is a conservation-compatible land use. This study focuses on threats to ecosystem function in the Sonoita Plain, southeastern Arizona, and examines the effects, as well as the potential for long-term biophysical degradation, of exurban development in a semiarid grassland of southwestern North America.

III. Study area

The Sonoita Plain (696 km^2) lies in a predominantly semiarid grassland located in northwestern Santa Cruz County, Arizona, between the Santa Rita and Huachuca Mountains (31° 32-44’ N/110° 28-44’ W). Elevations range from about 1100 to 1600 m, while elevations of upland areas, especially the Canelo Hills in the south-central part of the study area, approach 2900 m (Figure 1). Land ownership is roughly 50 percent public (United States Forest Service, Bureau of Land Management, State Lands) and 50 percent private. The Sonoita Plain is largely characterized by the desert grassland, plains grassland and desert scrub communities (501 km^2 / 72% of study area), with some riparian forest and riparian woodland communities along Cienega Creek in the northern part of the study area (22 km^2 / 3% of study area) (Arizona Game and Fish Department Natural Vegetation 1976). Dominant grasses are blue grama, black grama, threeawn grass, wolftail grass, and plains lovegrass; herbs and shrubs included burroweed, groundsel, copper leaf, fleabane, malvastrum, and caltrop (Bock and Bock, 2000). Upland regions ringing the central Plain are dominated by oak communities (172 km^2 / 25% of study area) (Arizona Game and Fish Department Natural Vegetation 1976), while agricultural and developed areas (3 km^2 / 0.4% study area) are located near towns (USGS National Gap Analysis Program 2004). Mean temperatures range from a January minimum of -2^{o}C to a June maximum of 33^{o}C (1971–2000), and average annual rainfall is 460 mm, with more than 50% occurring during the summer (July to September) monsoon (Kupfer and Miller 2005). This location is acknowledged to be a prime example of high plain southwestern grassland (Bock and Bock 2000).

Although humans have occupied the Sonoita Plain for at least the past 10,000 years, cattle did not arrive in significant numbers until 1832, when most of this area became part of the San Ignacio del Babocomari land grant. By the 1880s, tens of thousands of cattle were grazing the Sonoita Plain and livestock had become a dominant ecological force in the region. The severe and prolonged droughts of the 1890s, coupled with extensive overgrazing, contributed to severe land degradation (Sheridan 1995). Over time, the grasslands of the Sonoita Plain have recovered to some degree, with smaller-scale grazing and introduction of conservation practices better accounting for variability in climate (Bock and Bock 2000). In recent years, residential developments have sprung up on land historically used for cattle ranching. People are relocating to the Sonoita Plain in increasing numbers and houses are being constructed as vacation homes, retirement homes, and primary residences for those who commute to jobs in the relatively nearby municipalities of Tucson, Nogales and Sierra Vista, Arizona.

The study area was delineated using an impervious surface layer developed by the Water Resources Research Center, University of Arizona for the state of Arizona. The imperviousness of the substrate was selected as the defining study area characteristic because it has important consequences for the availability of water. Wells are mostly limited to the unconsolidated material of the Plain, with a handful of wells drawing water from shallow aquifers in the mountains. Given that ground water is the sole source of potable water in the area, this demarcation corresponds well to human settlement in the area. The Sonoita Plain was classified as either pervious (unconsolidated material/soil) or impervious (rock) and the area within the delineated "study area" outlined in Figure 1 corresponds to unconsolidated material/soil. As the Sonoita Plain is entirely ringed by mountains, this study area classification delineates the interior of the Plain and separates the study area from communities on the other sides of the mountains. Here "Sonoita Plain" and "study area" are used interchangeably to describe the interior of the Plain, as shown in Figure 1.

With 1,867 households and approximately 2,930 residents (U.S. Bureau of the Census), the Sonoita Plain currently supports three different housing densities, which makes it an ideal location to compare the impacts of exurban development to land use at other housing densities. Following Theobald (2005) and Leinwand et al. (2010), the area contains rural housing densities (0-0.0618 units/ha), exurban housing densities (0.0618-1.47 units/ha), and suburban housing densities (1.47-10 units/ha). These housing densities are shown in Figure 1.

IV. Ecosystem Function

A. Fire

Fire is critical to ecosystem health and stability across much of the United States, and the health of semiarid grasslands is particularly dependent on periodic burning. Fire ensures that fuel storage does not become excessive, helps maintain the food network, and prevents invasion by both native and exotic plant species (Wright and Bailey 1982; McPherson 1995). However, decades of fire suppression have resulted in fires being largely excluded over a significant portion of the landscape for much of the twentieth century (Allen et al. 2002). These decades of fire suppression, combined with periodic climatic stresses and changing land-use patterns, have combined to produce highly hazardous conditions. The associated accumulation of fuels increases the probability of large, high-intensity wildfires and poses a threat to the long-term sustainability of these ecosystems (Graham et al. 2004).

The increase in fire hazard is especially apparent in the western United States where rapid population growth, changing land tenures, and related increases in economic activity have contributed significantly to the nature and extent of fire risk. The urban-wildlife interface is expanding (Schoennagel et al. 2009), bringing people and structures in closer proximity to fire-prone environments and posing serious challenges to fire management. Exurbanization can alter fire frequency and promote intense fires owing to fire suppression and irrigation, which combine to increase the growth and storage of organic fuels. Natural fire frequencies for grasslands in southeastern Arizona have been estimated at between 10-20 years (Wright and Bailey 1982; McPherson 1995; Swetnam and Betancourt 1998; Theobald and Romme 2007); however, over the last 100 years, fire suppression has been largely successful, leading to few fires and leaving most areas unburned (Bahre 1991; Robinett 1994). In this research we examine whether there is a difference in fire risk between housing density classes.

B. Water

The semiarid grasslands of the Sonoita Plain maintain a delicate water balance. Most rainfall quickly evaporates, some is absorbed by plants as soil moisture and is transpired to the atmosphere, some infiltrates and becomes ground water, and a minor proportion in the Sonoita Plain results in runoff and stream flow. About six to seven percent (or approximately 13.6 x 10^6 m^3/year) of the 43 cm of precipitation falling in upland areas contributes to aquifer recharge (Bota 1996). Greatest depths to water generally are in uplands, whereas the least depths to water are near low-lying stream-corridor areas. Areas where depths to water are less than 20-m are underlain by thin deposits of unconsolidated alluvium, while upland areas, with large depths to water, are underlain by bedded rocks (ADWR 2009; Vukomanovic et al. 2013). Depletion of stored water and lowering of the water table will occur if ground water withdrawals exceed annual recharge. Disruption of recharge in uplands such as the Santa Rita Mountains, or pumping of water from wells at rates greater than the recharge rate, jeopardizes water availability in wells and the water required for ecosystem function. Over time, streams will dry up, riparian plant community composition will change, there will be less water available for wildlife, and residents will be forced to seek alternative sources of water (Glennon et al. 1994).

In this research, the depth to water and the number of wells, by housing-density class, is investigated to compare the impacts of exurbanzation on water availability to that of other housing-density classes. If the water withdrawal rates have started to deplete stored ground water, we would expect that depth to water in wells is greater where there are higher population densities. We might also expect that there are more new wells in exurban and suburban areas, which are experiencing rapid growth.

C. Generalized Distance Effects of Houses and Roads

Houses and roads have effects on ecological processes beyond their physical boundaries. In order to delineate generalized effects zones, the distances outward that the effects extend were taken into consideration. Forman et al. (2003) introduced the “road-effects zone” concept as an assessment and planning tool to synthesize diverse results (i.e., separate patterns of interactions of roads with plants, animals, water, sediment, and other ecosystem characteristics) and detect overall patterns of how far road effects extend outward. We incorporated this concept and expanded it to include effects zones for houses. Some effects, such as mowing grass around houses, are immediately obvious, whereas others may manifest far off-site and substantially lagged in time, such as the slow transport of road-related pollutants into ground water systems. Findlay and Bourdages (2000) found that the full effects of road construction (restricted movements, increased mortality, habitat fragmentation, edge effects, invasion by exotic species, and increased human access to wildlife habitats) on wetland biodiversity may be undetectable in some taxa for decades. As such, effects were divided into categories of “concentrated” and “diffuse” effects; reported literature values, aerial photography, and ground observations were synthesized to generalize patterns of how far effect zones extend.

Roads and houses can produce cumulative effects on animal populations (Boarman and Sazaki 2006), hydrologic systems (Jones 2000), stream networks (Forman et al. 2003), and other components of landscapes in which they are embedded. For example, where road networks are dense, the disturbance effects of traffic on bird populations may be compounded. Peris and Pescador (2004) found that traffic noise constitutes a serious problem for breeding densities of some passerine birds. Populations of many species of large wildlife, including wolves (Mech et al. 1988; Mladenoff et al. 1995) and mountain lions (van Dyke et al. 1986) only thrive where road density is less than 0.6 km/km^2. Similarly, branching road networks can fragment the landscape in a way that amplifies habitat fragmentation beyond the impact of a single road. The effects zones described above do not adequately consider these compounding effects. As such, we also attempted to provide a measure of the cumulative impacts of generalized distance effects by estimating the area surrounding each point on the landscape that is affected by the placement of roads and houses. These generalized distance effects, both separate and cumulative, were evaluated for each of the housing density classes.

V. Methods

Spatial analysis and modeling was conducted using ArcGIS v 10 (ESRI, Redlands, CA, USA). All maps are displayed in geographic-coordinate system, GCS North American 1983, datum D North American 1983; all analysis layers were projected to NAD 1983 UTM Zone 12N.

A. Deriving Contextual Variables

A.1 House locations

It is common to measure and express the pattern and extent of development through population or population density. However, population data from the US Bureau of the Census are tied to the primary residence and such measures underestimate landscape changes because vacation and second homes are not represented. Therefore, housing density is a more complete and consistent measure of landscape change than population density (Theobald 2005). In lightly-settled landscapes, houses are not evenly distributed across large census blocks, and census-based housing-density measures do not capture real location distribution or settlement patterns. To address this, locations of all houses in the Sonoita Plain study area were manually digitized from 2010 high resolution (1 m) aerial imagery obtained from the USDA Farm Service Agency, National Agricultural

Imagery Program (NAIP). These locations were cross-checked against 2010 U.S. Bureau of the Census data to ensure that the number of homes digitized in each census block matched the number of homes reported in the 2010 US Census. By digitizing the location of each house, a representation of how houses are distributed across the landscape emerges.

A.2 Roads, towns, elevation

Road information was obtained from 2010 census data (U.S. Bureau of the Census) for Santa Cruz, Cochise, and Pima counties in Arizona. The locations of the three towns within the study area, Sonoita, Elgin, and Patagonia, came from the Arizona State Land Department (2006). The elevation model used was the 1/3-arcsecond digital elevation model provided by the U.S. Geological Survey (USGS National Geospatial Program 2011).

B. Fire

Efforts to protect ecosystem function require the development of wildfire-management plans. One way to inform fire management it through the use of historic fire data to determine areas that have gone without a fire longer than expected and are likely to be overloaded with fuel. The Fire Return Interval Departure (FRID) for an area is a metric derived from an inferred normal fire-return interval (the historical average, in years, between fires), and the elapsed years since the last fire. Maps of where and when fires have occurred in the past provide the foundation for calculating the average fire return intervals for each vegetation type class. A derived index can then be calculated for each map pixel, using the time that has elapsed since the last fire, to quantify the departure of an area from its average fire return interval (Caprio et al., 1997; Keifer et al., 2000). The FRID index is: [(Years since last fire - Natural Fire-return Interval) / Natural Fire-return Interval]. A positive index value indicates that the time since the last burn has exceeded historic fire return intervals. A negative index value indicates that the area has burned within its historic fire return interval. The FRID index does not consider fire severity.

Fire perimeters for the study area were compiled from 1984 through 2011. Fire perimeters for those fires that occurred from 2001 through 2009 and covered over 40.5 hectares were compiled from the Wildland Fire Decision Support System (NIFC 2011). Older fires and those that burned less than 40.5 hectares were compiled from the Monitoring Trends in Burn Severity (MTBS) project (WFLC 2011). MTBS covers 1984-2010 and the earliest fire in our study area obtained from this database occurred in 1985. The fire perimeters of the three 2011 fires were manually digitized from two Landsat images. The first image came from Landsat 5 TM (path 35; row 38) on March 11, 2011, using bands 2, 4 and 7 (30-m resolution). The second image came from Landsat 7 ETM+ (path 35; row 38) on May 6, 2011, using bands 2, 4 and 7 (30-m resolution). Using composite images, the burned areas were easily visible and were used to draw the fire perimeter.

Fire Return Intervals are from Schussman et al. (2006). Where a range was given for the FRI, the average maximum was used in FRID calculations (Caprio et al. 1997). Vegetation types used in the FRID calculations came from the Southwest Regional Gap Analysis Program (SWReGap) (USGS National Gap Analysis Program 2004) and were reclassified to match those used by Schussman et al. (2006). Riparian-zone and marsh vegetation FRIs were set to 10 years, as were those of the semi-desert grasslands that surround most riparian-zone locations in our study area. The FRIs of agricultural and developed areas were set to 500 years, as the objective is to prevent fires entirely in these areas. The number of years since last fire was calculated as (2011 - year of fire).

C. Water

Information about well location, well depth, water depth, and drill/registration date came from the Arizona Department of Water Resources Well Registry (ADWR 2011). Using the coordinates provided in the ADWR Well Registry, the locations of all registered wells in the Sonoita Plain were mapped; in cases where wells were re-registered, only the most recent registration was used. Average water depth for the study area was derived using the Kriging interpolation method from well points (100-m output cell; variable search radius with 36 points) (Zimmerman et al. 1998). Water depths from all wells through 1970 were used to interpolate water level below land surface for 1970, whereas water depths from all wells registered from 2001 through 2010 were used to interpolate water level below land surface for 2010. Changes in water depth over 40 years were calculated as (2010 interpolated water level – 1970 interpolated water level). Where reported, drill date was used for the year, otherwise the application date was used.

D. Generalized Distance Effects of Houses and Roads

The effects of road networks and houses on the surrounding land depend on whether the interactions are above or below ground, diffuse or concentrated, and whether they follow gravitational flow paths. The processes involved and the transport medium, such as wind, ground water, or animal locomotion, determine the lateral extent of effect zones. In general, effect zones typically extend further into grassland ecosystems than into forests (Forman et al. 2003). Roads were divided into highways and single-lane roads. Owing to their larger size and a larger cleared roadside area, ability to accommodate much greater volumes of traffic, and role as transportation corridors, highways were assigned larger effect zones than regular roads. The different effects of highways and roads are especially well illustrated in terms of traffic disturbance on bird populations (Tables 1 and 2). Diffuse effects extend over the same area as “concentrated effects” plus the additional area defined as “diffuse effects”.

D.1 Concentrated Effects:

Concentrated effects are those that are substantial or striking, but only extend a short distance beyond the house or the road. Examples include lawns and gardens, mowing of grass, outside areas accessible to pets, driveways, road shoulders, fences, and other infrastructure. Many of the significant effects from roads that are limited to short distances are due to particulates and aerosols deposited from local air movements. Some road effects involving species and the transfer of energy and materials also extend over short to medium distances. The data presented in Table 1 were used to derive a generalized concentrated-effects zone of 30 meters for roads and 100 meters for highways.

The concentrated effects of houses on ecological processes were directly estimated from 1-m NAIP images to extend 50 meters outward from houses. The concentrated-effects zone includes driveways, outbuildings, gardens, and mowed lawns, and represents intensive modification to the landscape. Some of the effects listed above for roads also apply to houses (e.g., microclimate change, inhibition of seed germination). This 50-m concentrated effects zone includes the 4.6-m to 9.1-m recommended as Zone 1 and the 22.9-m to 38.1-m recommended for Zone 2 for Wildfire-Defensible space around homes by Arizona Firewise Communities (2007). Zone 1 includes maximum modification and treatment, in which all flammable vegetation is removed from around the home, while Zone 2 is an area of fuel reduction where the continuity and arrangement of vegetation is modified. In addition, sources of water found near houses can serve as oases in water-limited grassland systems, which can increase species diversity and abundance (Bock et al. 2008). On the other hand, pets can have detrimental effects on native species, especially ground-nesting birds. All of these modifications to the landscape have a concentrated effect on ecological processes. The concentrated-effects distances defined above were used to create buffers to visualize the concentrated-effects zone around each house and road in the study area. To visualize and measure the area of the concentrated-effects zones, buffers were created around each house and road in the study area. Buffer distances were defined by the effects zones described above.

D.2 Diffuse Effects:

Diffuse effects are effects on ecological processes that are more subtle than concentrated effects, and typically extend much further away from the house or road. Examples of diffuse effects include noise, chemical transport, erosion, and incursion/spread of invasive species. Most of the effects of roads that extend outward over longer distances involve human-access disturbances, exotic/invasive species spread, and the disruption of wildlife corridors. The data presented in Table 2 were used to derive a generalized diffuse-effects zone for roads at 100 meters and for highways at 500 meters.

The diffuse effects of houses on ecological processes were estimated by examining 1-m NAIP images, as well as direct field observations, to extend 100 meters away from a house. The diffuse-effects zone includes the areas around a house that are used less intensely or frequently than those immediately surrounding the house and represents moderate modification to the landscape. Structural modifications can include outbuildings and water tanks. This area is also used by pets, as well as by grazing animals such as horses or goats. As they are spatially dispersed, these modifications to the landscape have a moderate effect on ecological processes. To visualize and measure the area of the diffuse-effects zones, buffers were created around each house and road in the study area. Buffer distances were defined by the effects zones described above.

D.3 Cumulative Impacts of Distance Effects

The cumulative impact of generalized distance effects provides a measure of the area surrounding each point that is affected by roads or houses. Cumulative impacts were determined by calculating the percentage of the landscape, within a 500-m radius circular neighborhood, that falls within a diffuse distance-effects zone. In other words, in an area where there is a “High” impact from the cumulative effects of houses, 25-50% of the area surrounding each point falls within 100 m of a house, 100 m of a road, or 500 m of a highway.

VI. Results

The study area is 695 km^2 (69,519 ha) and has 943 km of roads. Within in, 1,867 housed were identified and mapped, which is equal to the number reported in the 2010 Census. Both houses and roads are concentrated in and around the three towns in the study area (Sonoita, Elgin, and Patagonia). Following the housing density classes put forth by Theobald (2005) and defined above, of the 69,519 ha study area, 91.5 percent (63,607 ha) is rural, 8.3 percent (5,762 ha) is exurban, and 0.2 percent (150 ha) is suburban.

A. Fire

The derived FRID values for the study area by housing-density class are shown in Table 3. They includes the mean FRID value, the percent area with positive and negative FRID values, and the mean years since fire. Positive FRID values indicate fuel storage and moderate to high potential for fire, whereas negative numbers indicate a limited amount of fuel storage and low potential for fire.

B. Water

The numbers of wells added in the study area, by decade from 1970 through 2010, are shown in Table 4. In 2010, there were 1,243 wells in the area. The average depth to water, by housing-density class, is also shown in Table 4. Depths to water in 2010 are compared to the depths to water in 1970 to evaluate possible water-table lowering due to ground water extraction. It should be noted that many of the current houses didn’t exist in 1970, and therefore housing densities were lower throughout the study area irrespective of density class (i.e., exurban areas were likely rural in 1970). However, the housing-density classes were used to compare the effects of wells on ground water resources. The number of new wells registered from 2000 through 2009, by housing-density class is also reported in Table 4.

C. Generalized Distance Effects of Houses and Roads

The areas impacted by the concentrated and diffuse effects from houses, roads, and highways, as well as the percentage of the study area that each represents is shown in

Table 5. Note that there is some overlap in the areas covered by roads and houses (e.g., roads lead to houses, so where they meet, the impact zones of houses and roads overlap).

The cumulative impacts represent the area surrounding each point that is affected by roads and house, calculated as the percentage of area within a 500-m radius circular neighborhood that has concentrated or diffuse impacts from houses or roads. Table 5 groups the cumulative impacts by impact category and lists them for each housing-density class.

VII. Discussion

A. Fire

Much of the study area has not been affected by fire for at least 25 years and fire potential presently appears to be a moderate to major threat to ecosystems and ecosystem function. Where they have occurred, recent fires in the Sonoita Plain mostly have been confined to bottomland areas, where stores of organic fuels have been relatively large, in areas of relatively high elevation with trees, and near towns, where the fires may have been started by humans (Vukomanovic et al. 2013). Exurban areas have the highest average FRID values (1.48), followed by rural areas (1.28); both positive values correspond to a moderate to high potential for fire. The suburban housing density class has an average FRID value of -0.55 and corresponds to low fire hazard. The high FRID value in exurban areas suggests that fire suppression measures associated with exurban development have increased fire hazard in the area. Suburban areas have more impervious surface, organic material tends to be cleared way, and there is a quick response to extinguish fires, and as such suburban areas have a much higher expected fire return interval (FRI) than exurban areas. Suburban ("Developed" according to SWReGap classification) areas are expected to burn on average every 400+ years, while exurban areas (various "grassland" classes) naturally burn on average every 8-100 years.

Even in rural areas, the quick response to extinguish fires means that much of the Sonoita Plain has not burned within normal fire-return intervals and that the build-up of organic fuels represents significant risk of large, high-intensity fires. The high FRID value in exurban areas suggests that it is the presence of people rather than the density that increases fire hazard. This high fire hazard, combined with the large amount of land required to accommodate people at such low population densities, calls into question the widely-held view that exurbanization is a conservation compatible land use.

B. Water

The Sonoita Plain has experienced substantial change over the past 100 years due to increased ground water withdrawals for irrigation and domestic purposes (Bahre 1977; Glennon et al. 1994). Over the past 70 years, technological advances enabled deeper wells with increasingly powerful pumps (Glennon et al. 1994), and as water became a less limiting factor, more people settled in the Sonoita Plain. In addition to exurban development, this historically cattle ranching area has emerged as a viniculture center and is promoted as the wine capital of Arizona. The area is currently home to ten vineyards. The period from 2000 through 2009 includes the largest housing boom in the region (2004-2006) and corresponds to the emergence of the three housing-density classes (Dokko et al. 2009).

The number of wells in the study area was larger than expected. As of 2010, there were 1,243 wells for 1,867 households, which corresponds to 0.67 wells per household. When considered by housing-density class, there has been little increase in the number of new wells in suburban areas, with just three wells added in the last decade. Conversely, there has been a steady increase in the number of wells added in exurban areas (174 wells from 2000 through 2009). This growth is closely followed by the increase in the number of wells in rural areas (166 wells added from 2000 through 2009), which may be partly driven by the viniculture boom in the region. Depths to water were lowest in the most densely populated area, which likely reflects historic technological constraints and the siting of towns, as well as differences in underlying soil and bedrock (Vukomanovic et al. 2012). There is little difference in the depths to water between housing-density classes and the study area.

A recent study of water use in the Sonoita Plain revealed that residential developments and vineyards use significantly more water than do cattle ranches, where wells are widely spaced around the property to provide water for livestock (Naesar and St. John 1998). The study results estimate that the average annual recharge around the town of Sonoita

(282 km^2 area) is 4.91 x 10^6 m^3 per year. Of this, 3.28 x 10^6 m^3 of water are accounted for, leaving approximately 1.62 x 10^6 m^3 available for future use. Under current zoning, that area could accommodate an additional 8,213 homes, withdrawing 4.82 x 10^6 m^3 of ground water annually. That withdrawal rate is three times greater than the surplus of water available for future development. Although annual recharge is not for areas outside of the town of Sonoita, these rates are assumed applicable throughout the Sonoita Plain.

The detrimental effects of excessive ground water use are already evident in other communities in southeastern Arizona. Although the Sonoita Plain has not reached a critical point in its water use, the experiences of neighboring communities provide a sobering window into the future. Immediately northwest of the Sonoita Plain, the Tucson area (Pima County) is experiencing ground water withdrawal-related land subsidence, in the form of sinks, on and near farmlands. The sinks occur in alluvial deposits along the flood plain of the Santa Cruz River and in some cases have made farmlands dangerous and unsuitable for farming. Hoffmann et al. (1998) identified more than 1,700 sinks and concluded that these sinks were likely caused by water-table decline and channel incision. Adjacent to the Sonoita Plain, flows of the Sand Pedro River, upon which the San Pedro National Riparian Conservation Area depends, are threatened by ground water withdrawals in the Sierra Vista area (Glennon et al. 1994).

A key ecosystem provision of grasslands is water for wildlife, and the water cycle controls this critical service. Important also is that the water balance of semiarid ecosystems can change dramatically in response to changing climate (Mote 2006; Overpeck and Udall 2010). Recently, the Southwest has experienced pronounced drought that has reduced rates of streamflow and ground-water recharge, and has caused tree death in savannas owing to deficient soil moisture and increased vulnerability to insects. Research indicates that warming and drying in the Southwest will continue (Notaro et al. 2012). The trends in water withdrawal and availability reported here may provide area residents with additional water management information, which in turn may help to avoid some of the problems experienced by other communities in the region.

C. Generalized Distance Effects of Houses and Roads

Although the generalized distance effects selected were conservative, about 35 percent of this sparsely populated landscape fell within the diffuse-effects zone of houses, roads, and highways. About 10% of the landscape fell within a concentrated-effects zone and has been intensely modified. The effects zones mainly followed the highways (State Routes 82 and 83) and areas with highest housing densities.

When the cumulative effects of these distance effects are considered, the impacts of dispersed housing, and its associated road networks are striking. An area was considered to be “Very Highly” impacted if 50-100% of the 500-m circular neighborhood surrounding each point fell within a road, highway, or house-impact zone. Not surprisingly, 100% of the suburban density class was highly impacted. However, the percentage of area within the exurban density class that was also “Very Highly” impacted was 81%, which is comparable to that of areas with suburban densities. When both "Highly" impacted (25-50% of the neighborhood lies within an effects zone) and "Very Highly" impacted areas were considered, 98% of exurban areas fell within these cumulative-effects categories. The cumulative effects of rural density classes were substantially lower, with only 12% of the area being "Very Highly" impacted.

Exurban areas support lower population densities than do suburban areas, but the associated houses and roads appear to have comparable impacts on ecological processes. Given the rapid growth of exurban housing throughout the United States, these impacts are potentially enormous. The results of this study support earlier work that found that development patterns that are more contiguous, higher density, and more compact have reduced overall effects on natural resources (Theobald 2005). The dispersed settlement patterns of exurban areas create practical complications for natural resource management and planning. The cumulative-effects method described here could be used as a rapid-assessment tool to compare alternative growth scenarios or for other planning applications. The specific parameters (effects zones, neighborhood size, impact categories, etc.) can be easily modified, and this approach has the advantage of being spatially explicit.

VIII. Conclusions

The influence of exurban development on fire hazard and general effects on ecosystem function documented in this study suggest that it is the presence of people, rather than higher densities of people, that create significant impact. When the per-capita impacts are considered, exurban development appears to present substantial risk to natural-resource sustainability. The findings here support earlier work on the ecological impacts of exurbanization (Theobald 2005). There is mounting evidence that, despite popular perception, exurbanization may not be a conservation compatible land-use. The comparisons between different housing density classes in this study were limited because there is only one suburban area (around the town of Patagonia) that was compared to multiple exurban and rural areas. The findings here may be a product of some particular characteristics of the town of Patagonia rather than general suburban characteristics. It is difficult to find multiple occurrences of the three different housing classes within a constrained geographic area. Given current trends, it seems likely that within 20 years, housing densities in the towns of Sonoita and Elgin will reach suburban densities. A reassessment of trends at that time could be informative.

The impact of exurban development will depend on the ecosystem service considered, highlighting the challenge both of predicting and managing ecosystem function under changing land-use patterns. For example, in order to avoid mining of stored groundwater, which then remains available to carry the population through severe droughts and prevents damage to the ecosystem, Naesar and St. John (1998) recommend a minimum lot size of 5 hectares around the town of Sonoita. While larger lot sizes, and therefore lower housing density, may be better for protecting water yield, if the rate of migration into the area continues and it is zoned at these lower housing densities, much more of the Sonoita Plain will be inhabited. This dispersed housing would likely result in many more kilometers of roads and their accompanying effects on ecological processes. Attempts to minimize impacts on water availability increase the impacts on other ecological processes through the production of road networks. The area described here is a healthy grassland ecosystem that is threatened by continuing development; nearby areas that have suffered ecosystem degradation provide comparisons and an ability to evaluate management approaches to avoid or mitigate further ecosystem compromise. To inform policy reliably, planning must consider a wide range of ecological processes or risk grave reductions of vital functions.

Grasslands provide many services, most of which currently have limited market value. Native grasslands contribute to maintaining the composition of the atmosphere by sequestering carbon, absorbing methane, and reducing emissions of nitrous oxide. Grasslands maintain a large genetic library, ameliorate regional climate, and preserve soil from devastating erosion (Sala and Paruelo 1997). The soils of these systems contain large quantities of carbon in their soils that is rapidly released into the atmosphere when plowed. However, the reverse process of accruing carbon is very slow (Burke et al. 1989). Similarly, native grasslands represent a reservoir of biological diversity, which is rapidly depleted after cultivation or overgrazing (McNeely et al. 1995). Recovery is very slow, or may never occur, depending of the size of the disturbed area. Failure to value the services provided by grasslands has important consequences for decision-makers, researchers, and society. Assessing the spatial extent of threats to ecosystem services is an important step for understanding the vulnerability of the systems and guiding decisions on the fate and best use of grassland ecosystems.

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Table 1: Concentrated-effect distances from roads for a range of factors impacting ecosystem services and processes. Adapted from Forman et al. 2003.

Effects on ecological factors	Distance from road surface (m)	References
Roadside mowing	0 – 25	Forman et al. 2003
Earth-and-fill area formed by road construction equipment	3 – 25	Ellenberg et al. 1981†
Microclimate change	10-40	Ellenberg et al. 1981†; Mader 1981†; Pauritsch et al. 1985†
Direct mortality effects on animal populations	2-15	Forman et al. 2003
Seed germination inhibited	12	Fluckiger et al. 1978†
Habitat fragmentation (patch-size effects): carabid beetles	1-20	Koivula and Vermeulen 2005
Rubber deposits from tires	15-40	Keller and Preis 1967†; Fidora 1972†; Hoffman et al. 1989†; Reinirkens 1991†
Dioxins	10-40	Unger 1991†
Erosion and sedimentation caused by road construction	30-50	Forman and Deblinger 2000
Heavy metals	2-200	Ellenberg et al. 1981†; Keller and Preis 1967†; Fidora 1972†; Hoffman et al. 1989†; Reinirkens 1991†; Santelmann and Gorham 1988.
Road density and decline in species abundance: amphibians	1-200	Houlahan and Findlay 2003
Traffic disturbance (noise, vibration, light): arthropod diversity	40-55	Maurer 1974†; Przybylski 1979†; Port and Hooton 1982†
Traffic disturbance: attraction effect of light	25-100	Meier 1992†
Traffic disturbance: woodland birds near moderately busy road	1-300	R. Reijnen et al. 1995; M. Reijnen et al. 1995; Peris and Pescador 2004.
Traffic disturbance: grassland birds near local road	1-400	Clark and Karr 1979; Reijnen et al. 1996; Forman et al. 2002
Population depression (direct mortality): desert tortoise	1-400	Boarman and Sazaki 2006

†cited by Forman et al. 2003.

Table 2: Diffuse-effect distances from roads for a range of factors impacting ecosystem services and processes. Adapted from Forman et al. 2003.

Effects on ecological factors	Distance from road surface (m)	References
Erosion and sedimentation caused by road construction	30-50	Forman and Deblinger 2000
Heavy metals	2-200	Ellenberg et al. 1981†; Keller and Preis 1967†; Fidora 1972†; Hoffman et al. 1989; Reinirkens 1991†; Santelmann and Gorham 1988.
Road density and decline in species abundance: amphibians	1-200	Houlahan and Findlay 2003
Traffic disturbance (noise, vibration, light): arthropod diversity	40-55	Maurer 1974†; Przybylski 1979†; Port and Hooton 1982†.
Traffic disturbance (noise, vibration, light): snakes	150	Rudolph et al. 1999
Traffic disturbance: attraction effect of light	25-100	Meier 1992†
Traffic disturbance: woodland birds near moderately busy road	1-300	R. Reijnen et al. 1995; M. Reijnen et al. 1995; Peris and Pescador 2004
Traffic disturbance: woodland birds near busy highway	200-800	R. Reijnen et al. 1995; M. Reijnen et al. 1995
Traffic disturbance: grassland birds near local road	1-400	Clark and Karr 1979; Reijnen et al. 1996; Forman et al. 2002
Traffic disturbance: grassland birds near moderately busy road	300-700	Raty 1979; M. Reijnen et al. 1995; Green et al. 2000; Forman et al. 2002;
Traffic disturbance: grassland birds near busy highway	800-1200	Raty 1979; van der Zande et al. 1980; M. Reijnen et al. 1995; Reijnen et al. 1996; Green et al. 2000; Forman et al. 2002;
Population depression (direct mortality): desert tortoise	1-400	Boarman and Sazaki 2006
Decline in species richness & decades-long lag-times in biodiversity loss: herptiles, birds, vascular plants	1-200	Findlay and Houlahan 1997; Findlay and Bourdages 2000.
Nitrogen levels and decline in species richness: amphibians	1-2000	Houlahan and Findlay 2003
Habitat fragmentation/isolation, smaller populations, local extinction risk	500 – 1000+	Forman and Deblinger 2000

Disruption of wildlife movement corridors	500 – 1000+	Forman et al. 2003
Invasion by roadside weeds & non-native species	500 – 1000+	Forman et al. 2003

†cited by Forman et al. 2003.

Table 3: Fire Return Departure (FRID) index values by housing-density class

Housing-Density Class	Mean FRID	Area with Positive FRID (%)	Area with Negative FRID (%)	Mean Time Since Fire (years)
Study Area	1.29	83.2	16.8	24.6
Rural	1.28	82.5	17.5	24.4
Exurban	1.47	92.7	7.3	26.4
Suburban	-0.55	14.9	85.1	27.0

Table 4: Cumulative number of wells and average depth to water by housing-density class

Number of wells

	up to 1970	up to 1980	up to 1990	up to 2000	up to 2010
Study Area	161	320	646	931	1243

Average depth to water in existing wells and new wells by housing-density class

	2010 Depth (m)	1970 Depth (m)	Difference in depth 1970-2010 (m)	New wells (2000-2009)
Study Area	48.92	35.52	13.40	343
Rural	48.69	35.31	13.38	166
Exurban	52.18	38.57	13.61	174
Suburban	26.88	12.86	14.01	3

Table 5: Generalized distance effects of houses, roads and highways

Total area impacted by generalized distance effects.

	Concentrated Effects (ha)	Study Area (%)	Diffuse Effects (ha)	Study Area (%)
Highways	1,893	2.7	7,887	11.3
Roads	4,538	6.5	13,754	19.8
Houses	961	1.4	3,014	4.3

Effects Zones by Housing-Density Class (Concentrated and Diffuse Effects)

	House Effects Zones (% within zone)	Road Effects Zones (% within zone)	Highway Effects Zones (% within zone)	All Effects Zones Combined (% within zone))
Study Area	4.3	19.8	11.4	28.5
Rural	1.4	16.1	9.8	24.2
Exurban	34.6	58.9	26.2	73.7
Suburban	90.7	95.8	85.7	99.6

Cumulative Impacts by Housing Density Class

	Unaffected (0%)	Low (0-12.5%)	Medium (12.5-25%)	High (25-50%)	Very High (50-100%)
Study Area	26.2	16.3	16.7	25.7	15.1
Rural	36.3	14.1	14.3	22.9	12.4
Exurban	0.0	0.2	1.8	17.3	80.7
Suburban	0.0	0.0	0.0	0.0	100.0

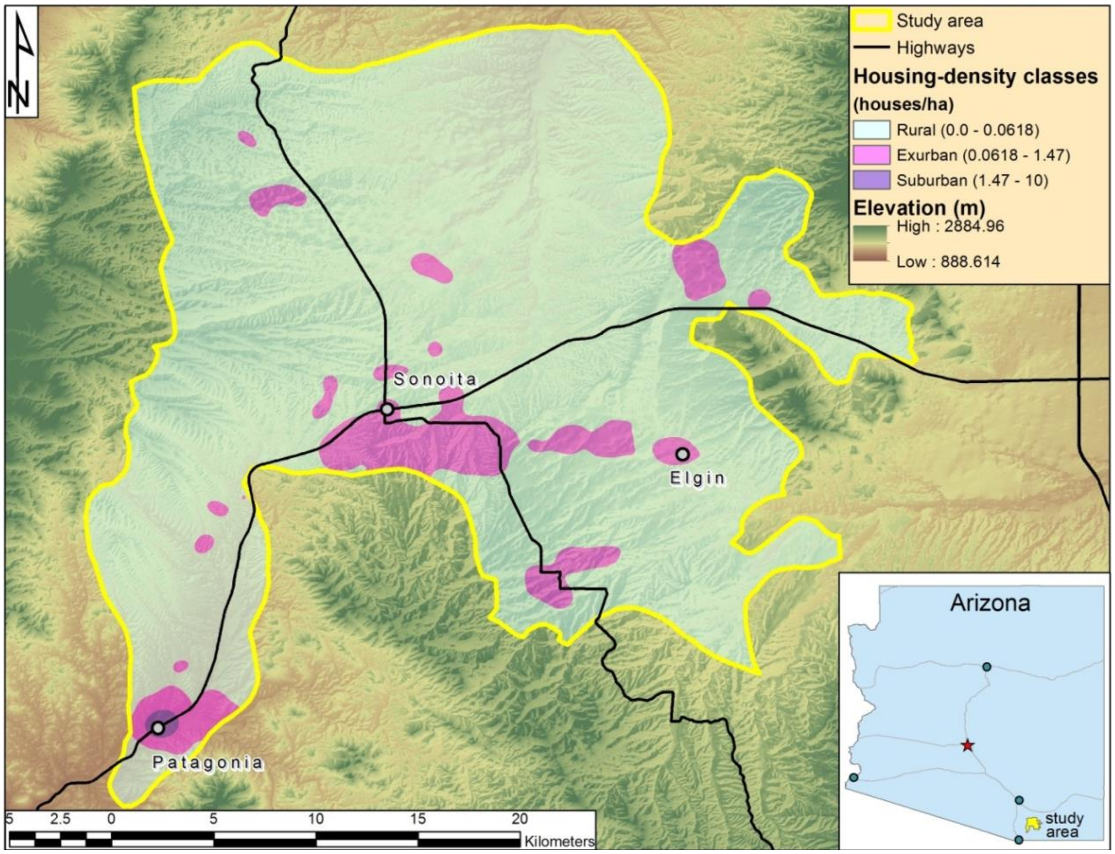

Figure 1: Housing-density classes in the Sonoita Plain, southeastern Arizona.

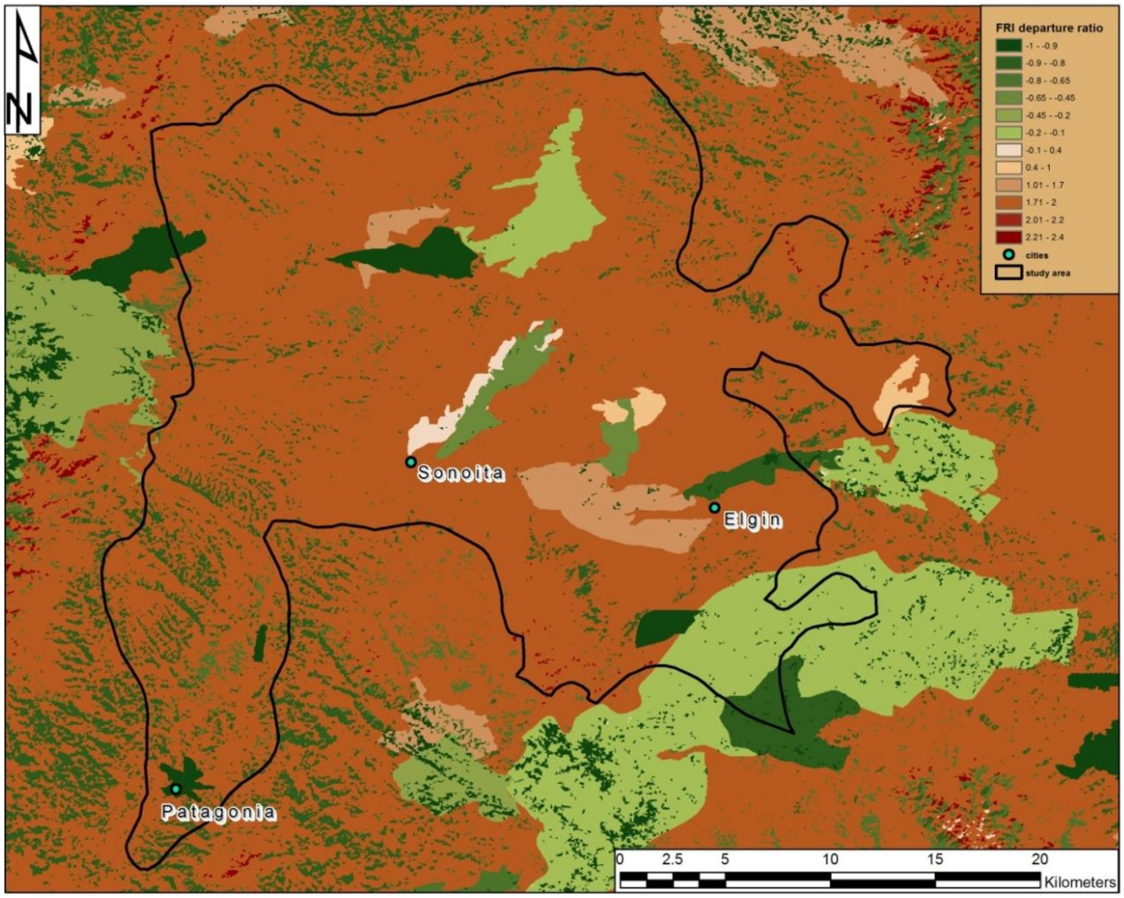

Figure 2: Fire Return Interval Departures (FRID) values for the Sonoita Plain, Arizona. Green represents low risk of fire, while reds and browns represent moderate to high risk.

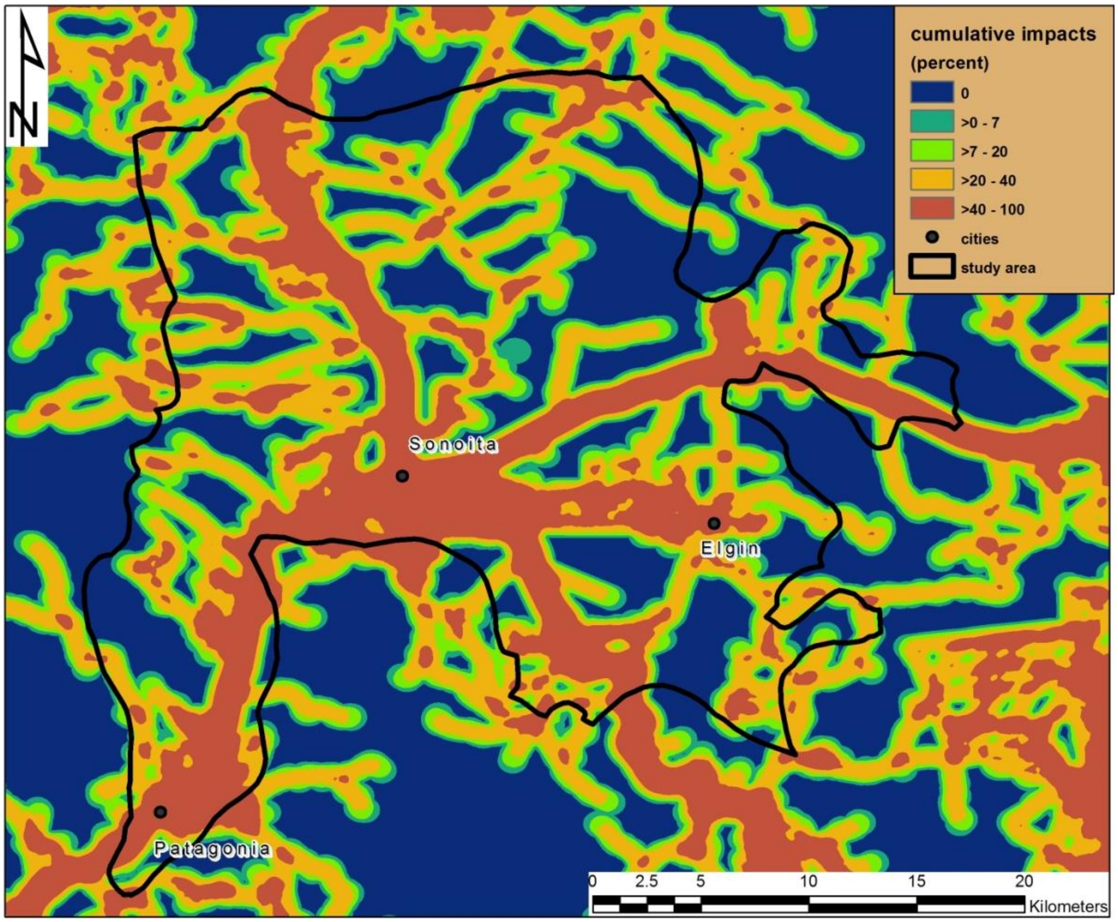

Figure 3: Cumulative impacts of houses and roads on ecosystem function. The impacts represent the area within a 500-m circular neighborhood that lies within the impact zone of a house, road or highway.

APPENDIX B

THE SEARCH FOR SOLITUDE: PRIVACY AS A DRIVER IN EXURBAN HOUSE LOCATION SELECTION

To be submitted to *Landscape and Urban Planning*

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I. Abstract

Rural regions are progressing through a sustained post-industrial transition, where the emphasis has changed from material production and extractive industries to the production and consumption of experiences. This transition has resulted in the increased presence of amenity-driven migrants, who are motivated in large part by a desire to be geographically isolated in an amenity-rich environment. Ethnographic studies of the American West have found that the image of "the frontier" plays a strong role in rural gentrification, but there has been little effort to integrate ethnographic and geospatial representations. Using the Sonoita Plain in southeastern Arizona as a case study, we hypothesized that privacy influences the spatial pattern of exurban development, supporting the idea that privacy is a primary driver of exurbanization as a whole.

Our objective was to examine whether privacy is manifest in the home locations actually selected by exurbanites. Through GIS viewshed analysis, we found that the great majority of homes are located where the inhabitants see few, if any, neighbors. When tested against the number of neighbors that each house would see, given a random distribution

of houses on potentially developable land, we find that the actual homes see significantly fewer neighbors. These findings suggest that most exurbanites in the Sonoita Plain selected housing sites where few neighbors are visible. As an amenity driver, privacy has important implications for the distribution of development and may inform future patterns of growth.

II. Introduction

Rural regions throughout North America and Europe are progressing through a striking and sustained post-industrial/post-productivist transition (Smith and Kannich 2000; Rudzitiz et al. 2011; Taylor 2011). The emphasis has changed from material production and extractive industries to the production and consumption of experiences (Taylor 2011; Hines 2011). This transition has resulted in the increased presence of amenity-migrants and retirees and an associated increase in low-wage seasonal work. Across the United States, amenity-rich regions are experiencing rapid land-use change in the form of low-density residential development or exurbanization. Exurbia, as both physical space and social phenomenon, captures very-low-density, amenity-seeking, post-productivist residential settlement in rural areas (Taylor 2011). This settlement is often spurred by amenity migration, which refers to “the purchasing of primary or secondary residences in rural areas valued for their aesthetic, recreational, and other consumption-oriented use values” (McCarthy 2008). In the United States, exurban land use occupies five to seven times more area than land with urban and suburban densities, and has increased at a rate of about 10 to 15% per year (Theobald 2001; 2005). Brown et al. (2005) found that the conversion of agricultural lands, forests, rangelands, and other underdeveloped lands to low-density residential uses was the main form of land development in the United States in 2005.

The post-productivist transformation of rural economies from resource extraction to the current emphasis on amenity-based industries (Hines 2007; McCarthy 2008) reflects both economic forces and societal concerns about extractive uses in threatened landscapes. Many exurbanites see themselves are stewards of the land and there is a strong, pervasive view that dispersed, low-density residential development is a conservation-compatible land use. Vogt and Marans (2003) report that some of the benefits of exurban development, according to residents, include environmental education for children, a more solid appreciation of nature owing to proximity, and houses serving as buffers between nature and other land uses. An additional stewardship role is the funding of conservation efforts and helping to create, or return to, a natural-resource based economy that is not extractive (Vogt 2011). However, it is not clear to what extent amenity-based communities and the environmental conditions and aesthetics that they have come to enjoy can be sustained. As residential development drives the growth of infrastructure and nearby commercial developments, the number and complexity of land-use transitions tend to increase, and with them, the potential for detrimental impacts (Vogt 2011). Despite its large spatial extent, exurbanization is seldom guided by growth management plans (Kondo et al. 2012) and has received much less study than land-use change in suburban or urban areas (Hansen et al. 2005).

The rapid and dispersed nature of exurban development raises numerous ecological concerns, including reduction of water availability to biota, habitat fragmentation, disrupted fire regime, alteration of the food network, and change in vegetation owing to invasive species (Ewing 1994; Theobald 2004; Hansen et al. 2005; Clark et al. 2009). The per capita land conversion in exurban areas is much greater than in urban locations (Hasse and Lathrop 2003; Vias and Carruthers 2005). Theobald (2005) found that development patterns that are contiguous, of high density, and less dispersed have reduced overall effects on natural resources. The reduced effect on natural resources comes from smaller footprints or “disturbance zones”, lower percentage of impervious surfaces, and reduced pollution because fewer vehicle miles were generated. Exurban growth displays the opposite development pattern, suggesting a greater impact on natural resources. Those same natural-resource amenities that attracted an influx of migrants are often degraded by the growing number of homes and associated development.

Houses, roads, and other infrastructure have impacts of ecological processes beyond their physical boundaries. Some modifications, such as mowing grass around houses, are immediately obvious, whereas others may manifest far off-site and substantially lagged in time, such as the slow transport of road-related pollutants into ground water systems (Forman et al. 2003). Findlay and Bourdages (2000) found that the full effects of road construction (restricted movements, increased mortality, habitat fragmentation, edge effects, invasion by exotic species, and increased human access to wildlife habitats) on wetland biodiversity may be undetectable in some taxa for decades. Where road networks are dense, the disturbance effects of traffic on bird populations may be compounded and traffic noise constitutes a serious problem for some birds (Peris and Pescador 2004). Populations of many species of large wildlife, including wolves (Mech et al. 1988; Mladenoff et al. 1995) and mountain lions (van Dyke et al. 1986) only thrive where road density is less than 0.6 km/km2. The spatial arrangement of houses, and their associated infrastructure, therefore has important implications for ecosystem function.

Amenity-driven exurbanization can also have dramatic impacts on rural economies and the social fabric of communities. The change from historic natural-resource production to amenity-based experience-production can create deep and divisive conflicts between long-term residents and newcomers. Control and ownership of the landscape has important economic consequences for both groups, as either livelihood production or investment (Nelson 2001; Shumway and Otterstrom 2001; Hurley and Walker 2004). Walker and Fortmann (2003) describe one such conflict in a former mining and ranching community in the Sierra Nevada that has experienced rapid exurban in-migration. Newcomers in this community, with their ideals of landscape aesthetic and experience consumption, came to dominate county government and attempted to incorporate landscape-scale aesthetic and environmental principles into county planning. Long-term residents saw such actions as a threat and a political firestorm ignited over the proposed changes. The authors noted that acrimonious rhetoric emerged on a daily basis in meetings and editorials and that key proponents and their families were threatened with violence. This conflict involved multiple issues, including competition between different forms of economic production, class conflict and social control, and cultural friction (Walker and Fortmann 2003).

The drivers of exurbanization are numerous, and people move to rural areas for a variety of economic and non-economic reasons. Drivers include both push- (crime, crowding, poor education systems, etc.) and pull- (affordable or desirable housing, privacy, better schools, etc.) factors (Marans et al. 2001). These drivers have been augmented by technological advancements and increases in tele-commuting (Green 2002), and transportation and road-network improvements (Stewart and Johnston 2006). In the case of amenity migrants, studies have shown that non-economic pull-factors are often most important (Marcouiller et al. 2002). For many exurbanites, natural amenities, such as scenic beauty, expansive vistas, wilderness, recreational opportunities, and climate, play an important role in the decision to migrate (McCarthy 2008; McGranahan 2008; Gosnell and Abrams 2011). Social and cultural connections to small-town rural life can also be a draw for some amenity-migrants (Hines 2007). As shown above, work has been done to identify the drivers of exurbanization, but very little is known about the spatial distribution of these preferences or the relative importance of some drivers over others. Different drivers could mean very different spatial arrangements of homes and therefore different impacts on both social systems and ecosystem function. Understanding the factors which drive exurbanization can help set the stage for research that explores the spatial patterns of exurban development.

A. Privacy and Social Environment as Drivers

A central component of the idealization of frontier or rural life is the desire for privacy and solitude. In a study of amenity migrants in San Juan and Okanogan counties in Washington State, Kondo et al. (2012) report that forty-six percent of participants described finding privacy or peace-and-quiet as a primary purchase goal. For most participants, privacy meant that they could be unaware of other people when at home. As one Okanagan County home-owner noted, “We wanted a fair amount of land. So that you have a lot of privacy” (Kondo et al. 2012).

Similarly, in his ethnographic study of Park County, Montana – the region immediately north of Yellowstone National Park, which boasts dramatic scenic features and extensive opportunities for recreation and wildlife viewing – Hines (2007) found that the frontier idyll was a powerful driver of amenity-migration. The West is especially amenable to ideas of the frontier and there is a powerful connection between the Rocky Mountain West and the search for experiences of a by-gone era (Riebsame 1997; Hines 2011). In this scenic and rapidly growing area, the percentage of the population who are newcomers in the last 15 years is close to one-third. In addition to the scenic natural features, privacy and solitude are important to exurbanites in Park County. As one newcomer described it, “There is a sublimity to it I can’t describe…with the sky filled (I mean filled) with stars, and not another light visible. It makes you feel like you have gone back to a time before humans” (Hines 2007). In the same vein, those who sought an agricultural environment based on the historical model of the homesteader experience, also valued privacy. Hines (2007) describes speaking to one exurbanite who was quite distraught by the new houses appearing around his home. This amenity-migrant was also resentful that affluent exurbanites were building in the open spaces for the views – to see and be seen; he had come as a homesteader and he wants his frontier to remain a frontier.

The ideals of the frontier and the search for "a more authentic existence" based on the homesteader experience (Hines 2007) are not the only drivers of amenity migration. Other groups, described as "social-environment" migrants by Hines (2007), are looking for a place where they can become part of a community. Seeking an idealized bucolic vision of rural/small-town U.S.A. (the "real America"), social-environment migrants are not only looking for a sense of community, but also the physical space of a small-town. Hines (2007) found that these amenity-migrants often choose to live close to neighbors and like being able to walk to local commerce, the post office, and public meetings in town. Importantly, social-environment migrants are looking to increase their interactions with other members of their community. A sense of community and neighborhood can be a key factor in household decisions to purchase homes in rural areas (Vogt and Marans 2001 (reported in Vogt 2011).

Although the perceptions of idyllic small-town life are just as idealized as notions of the frontier, the attachment to the built environment of community stands in sharp contrast with the ideals of solitude and privacy. It seems that both "frontier" migrants and "social environment" migrants are seeking a connection to by-gone eras and it is likely that both the privacy of the frontier and the social environment of rural small towns are appealing to at least some amenity-migrants. However, there are trade-offs between these two choices and in examining the actual location of exurban homes, a clearer idea of the stronger preference should emerge. Although costs, zoning and management plans, access to infrastructure, and other constraints may modify choice, study of the trade-offs that people make reveals what is most important to them (Rapoport 1985; Day 2000). The trade-off between privacy and social-environment drivers of exurbanization is important, and could be better understood by looking at the problem from the perspective of where exurbanites actually chose to live. Surveys and ethnographic studies have great value in that they provide a sense of what people value and the potential behaviors of respondents. There is an additional value in measuring actual behavior.

There have been limited attempts to integrate what has been learned directly from exurbanites about their reasons for moving to rural landscape and the spatial pattern of actual exurban development (Walker 2011). This study explores this problem by documenting the physical manifestations of exurban home site locations relative to the sites of other homes through a viewshed-based geographical representation and analysis. By looking at where people actually chose to build and live, it is possible to examine which drivers are optimized and which are compromised. In terms of physical distribution across the landscape, the desire for privacy stands juxtaposed against the desire for social-environment with its strong attachment to the built environment.

Although these desires are not mutually exclusive and are probably present, to some extent, in both “frontier” and “social environment” migrants, they do result in different spatial distributions of development.

In this research, we hypothesize that privacy influences the spatial pattern of exurban development, supporting the idea that privacy is a primary driver of exurbanization as a whole. Our objective is to examine whether privacy is manifest in the home locations actually selected by exurbanites. The results will shed light on the importance of privacy as a driver of exurbanization, furthering our understanding of the actual physical distribution of low-density development.

We begin by describing the Sonoita Plain, southeastern Arizona, USA, a study area that provides a buffered region of exurbanization, ideal for understanding spatial patterns with limited external influences. This is followed by a description of the spatial viewshed analysis used to assess the influence of privacy on the spatial pattern of exurban development. We finish with an analysis of results and their broader implications.

III. Study Area

The Sonoita Plain (696 km^2) lies in a predominantly semiarid grassland located in northwestern Santa Cruz County, Arizona, USA (31° 32-44’ N/110° 28-44’ W). The Sonoita Plain is surrounded by the Santa Rita Mountains to the west, the Huachuca Mountains to the south-east, the Empire Mountains to the north, the Whetstone

Mountains to the north-east and the Canelo Hills to the south (Figure 1). Elevations range from about 1,100 to 1,600 m in the central Plain, while elevations of upland areas, especially the Canelo Hills in the south part of the study area, approach 2,900 m (USGS National Geospatial Program 2011). This constrained geographic area is entirely ringed by mountains that provide vertical visual boundaries. The unique topography makes this area especially well-suited to viewshed analysis since the mountains effectively constrain what is visible to those living in the Sonoita Plain to the interior Plain and the sides of the mountains facing the Plain. Land ownership is roughly 50% public (US Forest Service, Bureau of Land Management, State Lands) and 50% private (ASLD 2011).

The Sonoita Plain is acknowledged to be a prime example of high plain southwestern grassland (Bock and Bock 2000). The area is characterized by the desert grassland, plains grassland and desert scrub vegetation communities (501 km^2 / 72% of study area), with some riparian forest and riparian woodland communities along Cienega Creek in the northern part of the study area (22 km^2 / 3% of study area) (Arizona Game and Fish Department Natural Vegetation 1976). Upland regions ringing the central Plain are dominated by oak communities (172 km^2 / 25% of study area) (Arizona Game and Fish Department Natural Vegetation 1976), while agricultural and developed areas (3 km^2 / 0.4% study area) are located near towns (USGS National Gap Analysis Program 2004).). Mean temperatures range from a January minimum of -2^oC to a June maximum of 33^oC (1971–2000), and average annual rainfall is 460 mm, with more than 50% occurring during the summer (July to September) monsoon (Kupfer and Miller 2005).

The study area was delineated using an impervious surface layer developed by the Water Resources Research Center, University of Arizona for the state of Arizona. The imperviousness of the substrate was selected as the defining study area characteristic because it has important consequences for the availability of water. Wells are mostly limited to the unconsolidated material of the Plain, with a handful of wells drawing water from shallow aquifers in the mountains. Given that ground water is the sole source of potable water in the area, the pervious substrate corresponds well to human settlement in the area. The Sonoita Plain was classified as either pervious (unconsolidated material/soil) or impervious (rock) and the area within the delineated “study area” outlined in Figure 1 corresponds to unconsolidated material/soil. As the Sonoita Plain is entirely ringed by mountains, this study area classification delineates the interior of the Plain and separates the study area from communities on the other sides of the mountains. Here “Sonoita Plain” and “study area” are used interchangeably to describe the interior of the Plain, as shown in Figure 1. This delineation was primarily used to constrain the locations of simulated housing distributions.

In recent years, residential developments have sprung up on land historically used for cattle ranching. People are relocating to the Sonoita Plain in increasing numbers and houses are being constructed as vacation homes, retirement homes, and primary residences for those who commute to jobs in the relatively nearby municipalities of

Tucson, Nogales and Sierra Vista, Arizona. Santa Cruz County grew by 46.5%, 45.1%, 29.3%, and 23.6% each decade from 1980 to 2010 (U.S. Decennial Census 2010).

The towns of Sonoita, Patagonia, and Elgin, and surrounding census blocks within the study area, had a median household income of $62,984 in 2010, compared to a median household income of $35,707 for Santa Cruz County and $48,745 for all of Arizona. The median 2010 house value for the study area is $368,421, whereas the median house value for Santa Cruz County was $125,907 and $187,700 for the entire state of Arizona. While 24.5% of residents of Santa Cruz County had incomes below the poverty level in 2010 (13.9% for Arizona), only 6.1% of the residents of the Sonoita Plain had incomes below the poverty level. In 2010, the median age of residents in the Sonoita Plain was 58.0 years, while the median age of residents in Santa Cruz County was 31.8 years and 34.2 years for the entire state of Arizona (US Bureau of the Census 2010). Overall, the residents of the Sonoita Plain are older and wealthier than residents in the rest of Santa Cruz County or the state Arizona overall. These trends are in keeping with those observed for amenity-migrants elsewhere (Smith and Kannich 2000; reviewed in Rudzitis et al. 2011) and suggest the ability or freedom on the part of Sonoita Plain exurbanites to select housing location.

With 1,867 households and approximately 2,930 residents (U.S. Bureau of the Census 2010), the Sonoita Plain currently supports three different housing densities. Following Theobald (2005) and Leinwand et al. (2010), the area contains rural housing densities (0-

0.0618 units/ha), exurban housing densities (0.0618-1.47 units/ha), and suburban housing densities (1.47-10 units/ha). These housing densities are shown in Figure 2. The 69,519 ha study area is 91.5% (63,607 ha) rural, 8.3% (5,762 ha) exurban, and 0.2% (150 ha) suburban.

IV. Methods

Spatial analysis and modeling was conducted using ArcGIS v. 10.0 (ESRI, Redlands, CA, USA). All maps are displayed in geographic-coordinate system GCS North American 1983, datum D North American 1983; all analysis layers were projected to NAD 1983 UTM Zone 12N.

A. Deriving Contextual Variables

A.1 House Locations

It is common practice to measure and express the pattern and extent of development through population or population density. However, population data from the US Bureau of the Census are tied to the primary residences and such measures underestimate landscape changes because vacation and second homes are not represented. Therefore, housing density is a more complete and consistent measure of landscape change than population density (Theobald 2005). In lightly-settled landscapes, houses are not evenly distributed across census blocks and simple housing-density measures do not capture real location distribution or settlement patterns. To address this, locations of all houses in the Sonoita Plain study area were manually digitized from 2010 high resolution (1 m) aerial imagery obtained from the USDA Farm Service Agency, National Agricultural Imagery Program (NAIP). These locations were cross-checked against 2010 U.S. Bureau of the Census data to ensure that the number of homes digitized in each census block matched the number of homes reported in the 2010 US Census. By digitizing the location of each house, a representation of how houses are distributed across the landscape emerges.

The Sonoita Plain currently has 1,867 homes (U.S. Bureau of the Census) and supports three different housing-density classes. Following Theobald (2005) and Leinwand et al. (2010), the study area was divided into the following housing-density classes: rural (0-0.0618 units/ha), exurban (0.0618-1.47 units/ha), and suburban (1.47-10 units/ha). This study focuses on those houses classified as exurban; of the 1,867 total houses in the study area, 998 are exurban.

A.2 Roads, Towns, Elevation

Road information came from 2010 census data (U.S. Bureau of the Census) for Santa Cruz, Cochise, and Pima counties in Arizona. The locations of the three towns within the study area, Sonoita, Elgin, and Patagonia, came from the Arizona State Land Department (2006). The elevation model used was the 1/3 arcsecond digital elevation model provided by the U.S. Geological Survey (USGS National Geospatial Program 2011).

B. Viewshed Analysis

A viewshed is composed of the areas of land, water, and other environmental elements that can be seen from a fixed vantage point (Gimblett 2013). The most common uses of viewshed analysis include visual exposure, archeological research, and photo-elicitation/landscape-classification. Examples of visual exposure research include study of the visual pollution from mines and how it should be considered in impact assessments (Zhou et al. 2011) or assessing alternatives for the distribution of clear-cut areas to minimize visual impact the work of (Domingo-Santos et al. 2011). Viewshed analysis has been used in archeological research to detect settlements and other infrastructure for some time; recent work by Alexakis et al. (2011) integrates viewshed analysis with remote sensing and geomorphology to reconstruct Neolithic landscapes in Thessaly and detect settlements. Mark and Brabyn (2011) used viewshed analysis to tag photos, which were then used in landscape classification, while Sheeran et al. (2011) used viewshed analysis of photo-elicitation to ascertain how farmers valued trees on their pastures. To our knowledge, viewshed analysis has not been used previously to assess housing location choice.

Viewshed analysis identifies the cells in an input raster that can be seen from an observation point. Starting with the cells closest to the observation point, a line-of-sight process calculates and maps whether the cell can or cannot be seen. As long as the tangent increases in the line-of-sight from the observation point, the cell is visible; if the tangent decreases, the cell is not visible (Gimblett 2013). Using elevation data as the input, each cell in the output raster that can be seen from the observation point is given a value of one, while all of the cells that cannot be seen from the observer point are given a value of zero. In our viewshed analysis, each exurban house served as an observation point and the viewshed for each house represents the portions of the landscape visible from that location. We calculated the viewshed for each of the 998 exurban homes in the Sonoita Plain and tabulated the number of neighboring houses that fell within each viewshed. The vantage-point was not restricted, meaning that we considered the view in all directions around each home.

C. Visibility Buffers

Visual acuity, or resolving power, is the ability to distinguish fine details and provides a measure of how much an eye can differentiate one object from another (Russ 2006). It is often expressed as cycles per degree (CPD); this is a measure of angular resolution, or the ability to differentiate objects in terms of visual angles. For a human eye, with excellent acuity, the maximum resolution (for a black/white bar or stripe) is 50 CPD or 1.2 arcminute per line pair (0.35 mm per line pair at 1 m) (Russ 2006).

In order to buffer the viewshed to the limits of human vision (i.e., calculate from how far away a house could actually be seen by a person), we used the angular diameter of the house to compute visibility distance. The angular diameter can be expressed as $r = g/(2 \times \tan(\alpha/2))$, where g is the actual size, r is the distance, and α is the angular diameter or apparent size. The Santa Cruz county zoning and development code sets a 35-foot maximum building height to homes in all zones (Santa Cruz County 2011). This maximum height was used as the actual size and 1.2 arcminutes (0.02 degrees) was used as the angular diameter. The visibility distance was calculated to be 30.56 kilometers in each direction.

A visibility buffer of 30.56 km corresponds almost exactly to the maximum width of the study area (31.71 km) and exceeds the length of any of the computed viewsheds. Therefore even houses at the very edge of the study area potentially have the entire study area within their visibility buffers. The mountains surrounding the Sonoita Plain provide vertical visual boundaries and all viewsheds were contained within the central Plain. Since the visibility buffer exceeded the width of any of the calculated viewsheds, it proved unnecessary to clip any of the viewsheds.

D. Validation

The rolling topography of the Sonoita Plain presents the possibility that the ability to see (or not see) neighbors may be a feature of the landscape, rather than the outcome of house-location choice. Is the ability to see (or not see) neighbors just a coincidence of geography, where the gentle hills of the Sonoita Plain effectively hide neighbors regardless of location? In order to test whether the privacy findings for exurban homes (number of visible neighbors) reflect location choice on the part of homeowners, we tested the actual exurban distribution against simulated, random house location distributions.

Following Theobald (2005), the study area was divided into "developable" and "undevelopable" areas, with Bureau of Land Management (BLM), State, US Forest Service, and Nature Conservancy lands classified as "undevelopable", while private lands were deemed "developable". Land ownership data came from the Arizona State Land Department (ASLD 2011), which covers the entire state of Arizona. The ASLD land ownership data was cross-checked against hardcopy maps from the Santa Cruz County Assessor's Office (SCC 2011). One discrepancy was found and a single parcel was changed from "private" to "BLM" ownership to match the finer-scale information from the Santa Cruz County Assessor's Office. We simulated ten random house location distributions on portions of the study area deemed "developable". Each simulated distribution included 998 houses, which matched the number of actual exurban houses in the study area. We calculated the viewshed for each house in each of the ten simulated distributions and then tabulated the number of neighboring houses that fell within each viewshed. Although the viewsheds of 998 houses were examined in each simulation, 1,867 houses (total number in the study area) were used in tabulated the visible neighbors.

We performed two-sample Kolmogorov-Smirnov (K-S) tests to compare cumulative distribution functions (CDFs) of the two data sets (actual exurban homes and simulated house distribution). The two-sample K-S test was used to test whether two probability distributions differ. The Kolmogorov-Smirnov statistic is defined as $D_{n,n'} = \underset{x}{sup} \left|F_{1,n}(x) - F_{2,n'}(x)\right|$, where $F_{1,n}$ and $F_{2,n'}$ are the distribution functions of the first and second sample respectively (Massey 1951). The K-S test was run ten times in order to compare the actual distribution of exurban homes to each of the ten simulated distributions. The null hypothesis is that the actual homes and the simulated homes are from the same continuous distribution. The alternative hypothesis is that they are from different continuous distributions (Sager 2010). The result h is 1 if the test rejects the null hypothesis at the 5% significance level; otherwise it is 0. The test statistic k is the maximum difference between the curves (Massey 1951). The two-sample K-S test is distribution free and valid for testing data against any continuous distribution (Sager 2010).

V. Results

A. Exurban Viewsheds

We performed a viewshed analysis for each of the 998 exurban homes in the Sonoita Plain and tabulated the number of neighboring houses that fell within each viewshed. All of the houses in the study area (exurban, suburban, and rural) were considered as potentially visible and were included in the calculation of the number of neighboring houses that fell within each viewshed. Table 1 summarizes the results of the exurban viewshed analysis.

Figure 3 shows a frequency distribution of the number neighboring houses visible from each exurban viewshed. In the first column, for example, 218 exurban houses had ten or fewer neighboring houses fall within their viewsheds, while an additional 163 exurban houses had 10-20 neighboring houses within their viewsheds. The distribution displays a strong positive (right) skew, where the mass of the distribution is concentrated on the left and there are relatively few high values. The great majority of houses see few, if any, neighbors. A logarithmic regression ($y = -62.53\ln(x) + 184.19$) yielded a coefficient of determination (R^2) value of 0.9321. The R^2 value provides a measure of how well future outcomes are likely to be predicted by the model (Lehmann and Romano 2005).

B. Validation

Table 2 shows the results of the validation comparison between the number of neighbors visible from the exurban homes in the Sonoita Plain and those visible in each of ten simulated, random house distributions. Two-sample Kolmogorov-Smirnov tests were used to compare the cumulative distribution functions (CDFs) of the two data-sets. The result h is 1 if the test rejects the null hypothesis that the actual exurban houses and the simulated houses are from the same continuous distribution.

In each comparison, more neighboring houses fell in the viewsheds of the simulated houses than the actual exurban houses. As shown in Table 2, the differences were statistically significant in each of the comparisons without exception. The p-value gives the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis (that the actual exurban houses and the simulated houses are from the same continuous distribution) is true (Lehmann and Romano 2005). The predetermined significance level was set at 0.05 ($h = 1$ if $p<0.05$)

and the p-values obtained were far lower than the specified significance level (1.41E-10 to 9.44E-22), indicating that the observed results are highly unlikely under the null hypothesis. The exurban households see significantly fewer neighbors than would be expected if the houses were placed randomly and without consideration for the visibility of neighbors.

VI. Discussion

The objective of this study was to examine whether exurban amenity-migrants were selecting housing sites that afforded privacy and where few, if any, neighbors were visible. This work responds to calls (Walker 2011) to integrate ethnographic descriptions of preference with geospatial representations of exurban development. Both small-town rural life and the frontier experience hark to by-gone eras and have been idealized by amenity-migrants. In terms of the spatial distribution of development, however, the desire for privacy stands juxtaposed to the desire for social-environment and its strong attachment to the built environment. In examining the physical distribution of actual exurban homes, we hoped to determine which preference is optimized and plays a larger role in house selection choice in the Sonoita Plain.

Viewshed analysis of the 998 exurban homes in the Sonoita Plain sheds light on the actual spatial distribution of exurban development, providing insight on the proposed primary drivers of exurbanization, in particular, privacy. We found that the great majority of exurban homes in the Sonoita Plain see few, if any, neighbors (median of 34.00 and mean of 48.51, with a strong positive (right) skew due to relatively few high values). The logarithmic regression R^2 of 0.932 suggests that exurbanites are more likely to select house locations with fewer visible neighbors. The comparison of these results with each of ten simulated house distributions showed that the actual exurban households see significantly fewer neighbors than would be expected if the houses were placed randomly on potentially developable land without consideration for the visibility of neighbors.

Validation comparisons were performed between the number of neighbors visible from the exurban homes in the Sonoita Plain and those visible in each of ten simulated house distributions. Without exception, the number of neighboring houses that fell in the viewsheds of the simulated houses was higher than for the actual exurban houses. The differences were statistically significant in each comparison. The exurban households see significantly fewer neighbors than would be expected if the houses were placed randomly and without consideration for the visibility of neighbors.

These results are even more substantive when we consider the conservative approach used to limit viewsheds to what might be potentially visible to a human observer.. We assumed exceptional vision (physical limits of human vision), under perfect weather conditions (no reduced visibility), and with maximum contrast between the houses and the surrounding landscape (black/white contrast). We know that these conditions rarely, if ever occur, and certainly not for all viewsheds or all homeowners. Weather conditions are variable and can greatly alter visibility and relatively few people have exceptional vision. Personal observations in the study area reveal that many homeowners choose to paint their homes in muted earth tones that blend into the landscape rather than provide great contrast. This means that in all likelihood, the actual visibility buffers are much smaller and each household can see fewer neighbors than the numbers here report. With even fewer visible neighbors, this suggests that privacy is even more important than the values reported here indicate.

Viewsheds with few, if any, visible neighbors are preferred by amenity-migrants in the Sonoita Plain. Our results suggest that in this region, the desire for privacy supersedes the desire for social-environment and its attachment to the built environment. The ideals of the frontier and the search for “a more authentic existence” based on the homesteader experience, of which a central component is the desire for privacy and solitude (Hines 2007; Kondo et al. 2012), appear to be important drivers of amenity migration in this area. Although it is likely that both the privacy of the frontier and the social environment of rural small towns are appealing to at least some amenity-migrants, in the case of the Sonoita Plain, privacy appears to be a more important driver.

This study builds on earlier work in the Sonoita Plain that focused on threats to ecosystem function and examined the effects, as well as the potential for long-term biophysical degradation, of exurban development in a semiarid grassland (Vukomanovic et al. 2013). These studies found that although exurban areas support lower population densities than do suburban areas, they appear to have comparable impacts on ecological processes. Not only do the dispersed settlement patterns characteristic of exurbanization create practical complications for natural resource management and planning, but the impact zones around homes and road networks affect ecosystem function across much of the landscape (Vukomanovic et al. 2013). The results of the of the development hazards research in the Sonoita Plain were especially striking because development in the area is not readily visible. This study provides some evidence that the development in this region may be masked, at least in part, by the desire for privacy. The widespread selection of housing sites where few neighbors are visible means that the effects of exurbanization are largely hidden from most inhabitants of the Sonoita Plain.

Healthy grasslands provide many ecosystem services, most of which currently have no market value. Grasslands contribute to maintaining the composition of the atmosphere by sequestering carbon, absorbing methane, and reducing emissions of nitrous oxide. Native grasslands maintain a large genetic library, ameliorate regional climate, and preserve soil from devastating erosion (Sala and Paruelo 1997). The Sonoita Plain is widely considered a prime example of a healthy high-plain southwestern grassland (Bock and Bock 2000), with high ecological value. The “social environment” migrant’s connection to the built environment could mean that those exurbanites would be content with – or even prefer - to live at higher housing densities. The privacy requirements of “frontier” migrants, on the other hand are less conducive to communities with higher housing densities. Given the impacts on ecosystem function from exurbanization, the communities of the Sonoita Plain might consider actively targeting “social-environment” migrants. If the same number of amenity-migrants can be accommodated in a smaller area, the ecological impacts are minimized.

In addition to the profound ecological impacts, very low-density exurban development imposes a high cost on county fiscal resources. In Santa Cruz County, Arizona, a substantial proportion of population growth is accommodated though unregulated development (Santa Cruz County 2011). The lack of infrastructure keeps the tax base benefits of low-density development very low, and so exurban development often creates service demands that exceed revenues available through property tax (Pima County Board of Supervisors 2001). In neighboring Pima County, Arizona, it is estimated that there is an annual deficit of $35-55 million between revenue from property taxes and the costs to bring in roads, utilities and sewers to new exurban developments (Pima County Board of Supervisors 2001). From an economic perspective, it appears to be to Santa Cruz County's advantage to actively court "social environment" amenity-migrants, as service and infrastructure needs would be constrained to a smaller area. However, such an approach would also have to address the demand for privacy demonstrated in the current spatial distribution of exurban development.

Much of the work on the impacts and drivers of exurbanization has been done on the county-scale, relying largely on census data (Mueser and Graves 1995; McGranahan 2008; Rudzitis et al. 2011). This type of research is valuable for the study of broad trends and for identifying common drivers of exurbanization, such as climate (McGranahan

1999) or proximity to water bodies (Mueser and Graves 1995). The study described here was conducted at a much finer scale. We found that the spatial distribution of exurban homes corresponds with higher privacy from neighboring homes, shedding light on the potential trade-offs between the desire for privacy and the desire for social environment. Finer-scale efforts make it possible to untangle preferences and to study migration drivers that may at times be contradictory. This work responds to calls to integrate ethnographic descriptions of preference with geospatial representations of exurban development (Walker 2011), which requires a fine scale of analysis. It would be interesting to look at exurban viewsheds even more closely, specifically the orientation of houses and any modification near the house that might alter view. Such fine-scale information would provide information on what people can actually see (as opposed to potentially see), which would further our understanding of exurban preference. It would also be interesting to distinguish between primary and secondary residences and assess if there are differences in the preferences of these two groups of homeowners. For example, it may be that privacy is more valued by secondary homeowners, as social-environment/community desires are met at their primary residences. This information could then be fed back into regional-scale models of exurban development.

Residents in very high amenity areas, displaying “last settler syndrome” and seeing further in-migration as a threat to the very landscape qualities that drew them initially, may adopt regulations to constrain further growth (McGranahan 2008; Hines 2010; Kondo et al. 2012). Housing prices are inordinately high in the most scenic rural counties and they no longer have the highest rates of migration (Rudzitis 2011). This suggests that in rural areas that have long experienced amenity migration (Aspen, Sun Valley, Park City, the Hamptons, etc.), further in-migration will increasingly be shaped by efforts to preserve valued landscape aesthetics rather than by the landscape preferences of potential new in-migrants. However, in areas that have more recently started to experience amenity migration, and where land availability and price still allow at least some choice, information about landscape drivers and exurban preference could prove helpful to planning and management efforts.

The post-productivist transformation of rural economies from resource extraction to amenity-based industries, such as residential development and recreation (Hines 2007; McCarthy 2008) reflects not only changing economic forces, but also societal concerns about extractive uses in threatened landscapes. Many amenity-migrants view dispersed, low-density residential development as a conservation-compatible land use and certainly preferable to material production. Despite this pervasive view, Radeloff et al. (2010) have argued that it is not material extraction/production but housing growth that poses the main threat to protected areas in the United States. It is important to understand the drivers of amenity migration and the preferences of exurbanites, because migration choices have important implications for the distribution of development. The spatial arrangement of exurban houses, roads and associated infrastructure will depend on the primary driver of migration, and different spatial distributions will have different impacts on both social systems and ecosystem function. Information about landscape drivers may be of interest to county administrators and policy makers. However, much more work is needed to fully understand what factors are driving exurbanization regionally and landscape drivers certainly warrant further study.

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Table 1: Exurban viewsheds in the Sonoita Plain.

Summary of Descriptive Statistics	Value
Houses in the Sonoita Plain	
Total (Suburban + Exurban + Rural)	1,867
Exurban	998
Number of Visible Neighbors (Exurban Viewsheds)	
Minimum	0
Maximum	238
Mean	48.51
Median	34
Standard Deviation	46.40

Table 2: Comparison of actual exurban house distribution to each of ten simulated house distributions (Two-sample Kolmogorov-Smirnov test).

Simulated Distributions Compared to Exurban Houses	**h**[a]	**p-value**	**k**[b]
1	1	1.27E-11	0.1403
2	1	8.41E-14	0.1533
3	1	1.41E-10	0.1335
4	1	9.44E-22	0.1935
5	1	8.45E-08	0.1138
6	1	9.41E-15	0.1586
7	1	1.17E-12	0.1466
8	1	4.14E-12	0.1433
9	1	3.90E-11	0.1372
10	1	1.76E-11	0.1394

[a] The result h is 1 if the two data sets are from different distributions at the 5% significance level. [b] The test statistic k is the maximum difference between the curves.

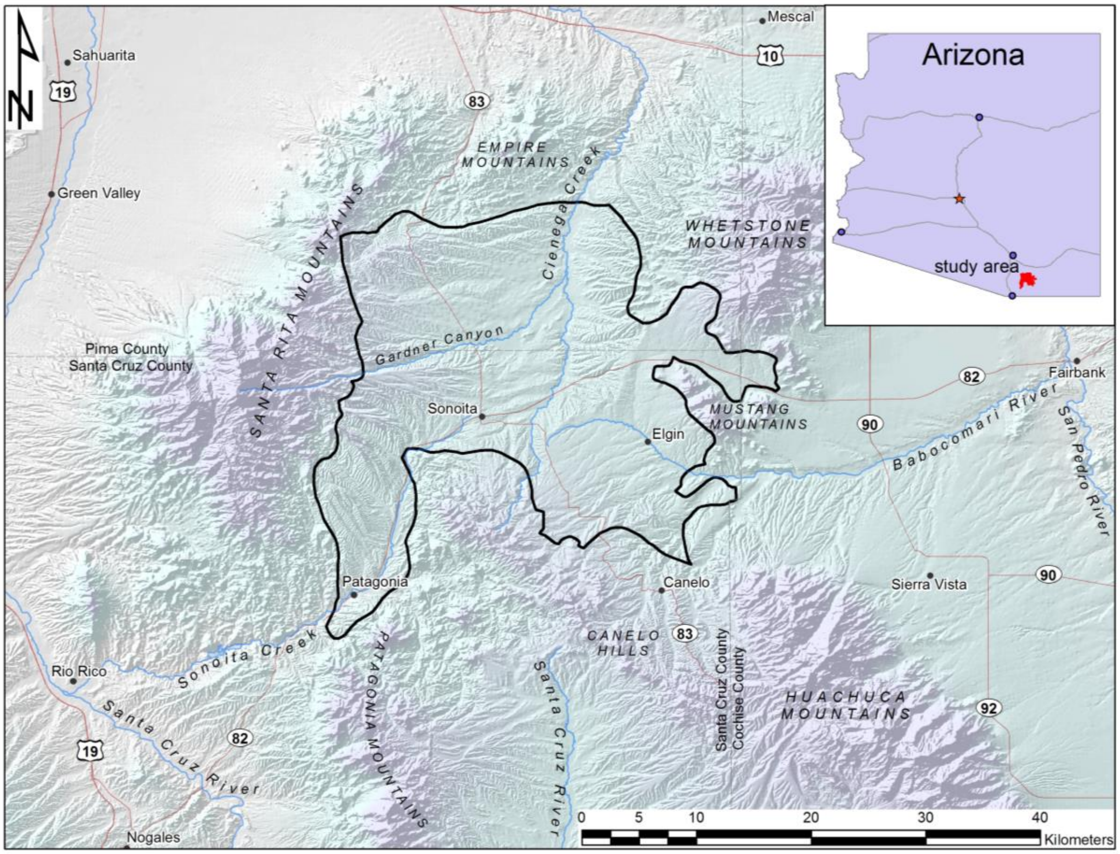

Figure 1: Map of the Sonoita Plain, highlighting the mountains surrounding the study area.

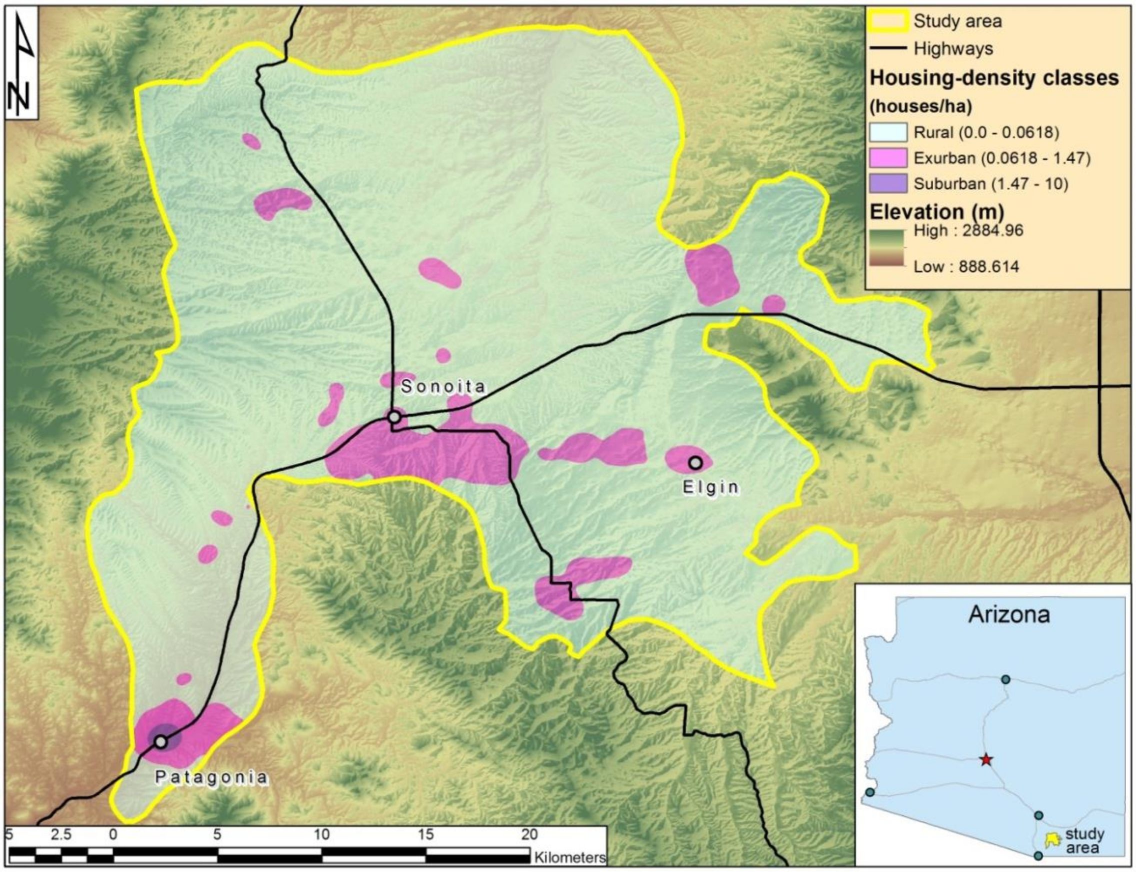

Figure 2: Housing-density classes in the Sonoita Plain, southeastern Arizona

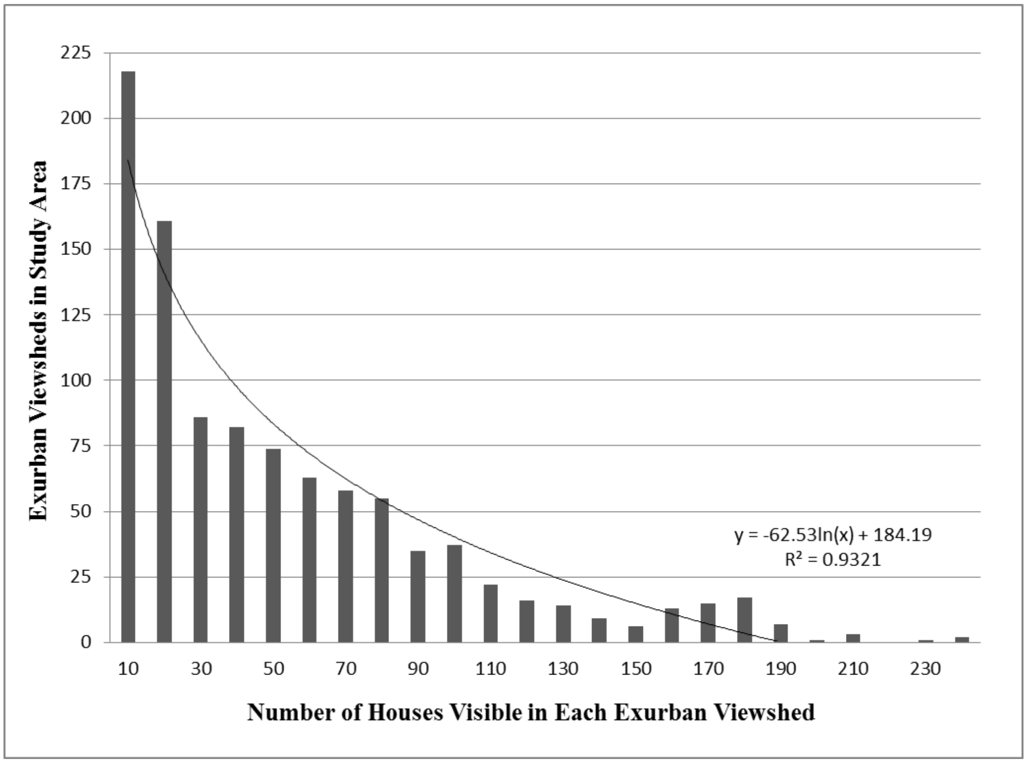

Figure 3: Plot of the number of study area houses visible in each exurban viewshed. The number of houses visible includes all potentially visible houses (exurban, suburban and rural) in the study area.

APPENDIX C

LANDSCAPE AESTHETICS AND THE SCENIC DRIVERS OF AMENITY MIGRATION IN THE NEW WEST: NATURALNESS, VISUAL SCALE, AND COMPLEXITY

To be submitted to *Landscape and Urban Planning*

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I. Abstract

The American West, once characterized by open spaces, low population densities, and the dominance of primary sector activities, such as mining, logging, and ranching, is experiencing high rates of population growth related to amenity migration. Values associated with landscape aesthetics and scenic beauty are common "pull factors" for amenity migrants, however the specific features of the environment that attract amenity migration are poorly understood and the relative contributions of different visual quality elements to the appeal of an area are unclear. In this study we focused on three visual quality metrics that are important in a semi-arid grassland system in the intermountain West (USA), with the objective of exploring the relationship between the location of exurban homes and aesthetic landscape preference, as exemplified through greenness, viewshed size, and terrain ruggedness. Using viewshed analysis and the three visual quality metrics we compared the viewsheds of actual exurban houses to the viewsheds of randomly-distributed simulated (validation) houses. We found that the actual exurban households can see significantly more vegetation (higher average Normalized Difference

Vegetation Index (NDVI) values) and a more rugged terrain (higher mean Terrain Ruggedness Index (TRI) values) than simulated houses. The actual exurban viewsheds have a higher mean TRI value, but a lower maximum TRI value than the simulated viewsheds, suggesting that the actual exurban homes see a more rugged terrain, but don’t necessarily see the highest peaks. This provides some evidence that visual complexity throughout the viewshed may be more important than seeing the very highest peaks. The viewsheds visible from the actual exurban houses were significantly larger than those visible from the simulated houses, indicating that visual scale is important to the general aesthetic experiences of exurbanites. The differences in visual quality metric values between actual exurban viewsheds and simulated viewsheds call into question the use of county-level scales of analysis for the study of landscape preferences, which may miss key landscape aesthetic drivers of preference. Information about landscape drivers may be of interest to county administrators and policy makers as it can inform growth strategies designed to minimize negative ecological impacts and, by protecting visual quality, perhaps even help to sustain economic growth in the New West.

II. Introduction

Rural regions throughout North America and Europe are progressing through a striking and sustained post-industrial/post-productivist transition (Smith and Kannich 2000; Rudzitiz et al. 2011; Taylor 2011). The emphasis has changed from material production and extractive industries to the production and consumption of experiences (Taylor 2011; Hines 2011). Across the United States, amenity-rich regions are experiencing rapid land-use change in the form of low-density residential development or exurbanization. Exurbia, as both physical space and social phenomenon, describes very-low-density, amenity-seeking, post-productivist residential settlement in rural areas (Taylor 2011). This settlement is often spurred by amenity migration, which refers to "the purchasing of primary or secondary residences in rural areas valued for their aesthetic, recreational, and other consumption-oriented use values" (McCarthy 2008). In the United States, exurban land use occupies five to seven times more area than land with urban and suburban densities, and has increased at a rate of about 10 to 15% per year (Theobald 2001; 2005).

The American West, long characterized by open spaces, low population densities, and the dominance of primary sector activities, such as mining, logging, and ranching, is experiencing high rates of population growth related to amenity migration (Rudzitis 1999; Shumway and Otterstrom 2001; Vias and Carruthers 2005; Travis 2007). Extractive and manufacturing activities that were once at the center of western economics are now overshadowed by service-sector and high-tech industries (Power and Barrett 2001; Vias and Carruthers 2005; Gosnell and Abrams 2011). In the New West, scenic landscapes are increasingly valued more for the aesthetic and recreational amenities they provide than for mineral resources, forage or timber (Riebsame 1997; Power 1996; Rasker and Hansen 2000; Power and Barrett 2001; Hansen et al. 2002; Winkler et al. 2007). Amenity migration to the ranching landscapes of the American West has largely driven the transformation of rangelands from low-value productive lands to high-value positional goods (Travis 2007). A study of ranching activities in southern Arizona points to a combination of low-density residential development, specific tax policies, and the commodification of the ranching lifestyle idyll in the transformation of rural landscapes (Sayre 2002).

The post-productivist transformation of rural economies reflects both economic forces and societal concerns about extractive uses in threatened landscapes. However, it is not clear to what extent amenity-based communities and the environmental conditions and aesthetics that they have come to enjoy can be sustained. As residential development drives the growth of infrastructure and nearby commercial developments, the number and complexity of land-use transitions tend to increase, and with them, the potential for detrimental impacts (Vogt 2011). Despite its large spatial extent, exurbanization is seldom guided by growth management plans (Kondo et al. 2012) and has received much less study than land-use change in suburban or urban areas (Hansen et al. 2005).

The rapid and dispersed nature of exurban development raises numerous ecological concerns, including reduction of water availability to biota, habitat fragmentation, disrupted fire regime, alteration of the food network, and change in vegetation owing to invasive species (Ewing 1994; Theobald 2004; Hansen et al. 2005; Clark et al. 2009). Houses, roads, and other infrastructure have impacts on ecological processes beyond their physical boundaries. Some modifications, such as mowing grass around houses, are immediately obvious, whereas others may manifest far off-site and substantially lagged in time, such as the slow transport of road-related pollutants into ground water systems

(Forman et al. 2003). Findlay and Bourdages (2000) found that the full effects of road construction (restricted movements, increased mortality, habitat fragmentation, edge effects, invasion by exotic species, and increased human access to wildlife habitats) on wetland biodiversity may be undetectable in some taxa for decades. Populations of many species of large wildlife, including wolves (Mech et al. 1988; Mladenoff et al. 1995) and mountain lions (van Dyke et al. 1986) only thrive where road density is less than 0.6 km/km2. The spatial arrangement of houses, and their associated infrastructure, therefore has important implications for ecosystem function.

The drivers of exurbanization are numerous, and people move to rural areas for a variety of economic and non-economic reasons. Drivers include both push- (crime, crowding, poor education systems, etc.) and pull- (affordable or desirable housing, privacy, better schools, etc.) factors (Marans et al. 2001). These drivers have been augmented by technological advancements and increases in tele-commuting (Green 2002), and transportation and road-network improvements (Stewart and Johnston 2006). In the case of amenity migrants, studies have shown that non-economic pull-factors are often most important (Marcouiller et al. 2002). Social and cultural connections to small-town rural life can be a draw for some amenity-migrants (Walker and Fortmann 2003; Hines 2007). For many exurbanites, natural amenities, such as scenic beauty, expansive vistas, wilderness, recreational opportunities, and climate, play an important role in the decision to migrate (McCarthy 2008; McGranahan 2008; Gosnell and Abrams 2011).

A. Natural Amenities and Visual Quality

A variety of factors contribute to making the movement of affluent urban populations to scenic rural areas desirable. Values associated with quality of life, proximity to nature, and recreation are the common “pull factors” described in the amenity migration literature (Riebsame 1997; Marcoullier et al. 2002; Hansen et al. 2002; Kendra and Hull 2005). Wilderness areas, in particular, have proven to be a major draw for in-migrants (Rudzitis and Johansen 1989; Rudzitis and Johnson 2000; Rasker 2005), many of whom speak of the “one-hour rule” – they want to work within an hour’s drive of good fishing, skiing, and hiking (Hansen et al. 2002). Surveys of new residents and businesses in rural counties with high levels of natural amenities found that factors such as scenery, environmental quality, climate, recreational opportunities, and climate were more important reasons for relocation than job opportunities or cost of living (Johnson and Rasker 1995; Rudzitis 1999; Hansen et al. 2002).

Work has been done to identify the drivers of exurbanization, but very little is known about the spatial distribution of these preferences. The specific features of the environment that attract amenity migration are poorly understood and the relative contributions of different visual quality elements to the appeal of an area are unclear. The visual quality literature is vast and many visual quality concepts or indicators have been identified (reviewed in Tveit et al. 2006). Here we focused on three landscape visual-quality concepts that are likely important in a semi-arid grassland system in the intermountain West (USA), with the objective of exploring the relationship between house location preference and these indicators of visual quality. The three visual quality concepts are naturalness, visual scale, and complexity; respectively, these concepts were assessed by the following metrics: greenness, viewshed size, and terrain ruggedness. Different drivers could mean different spatial arrangements of homes and therefore different impacts on both social systems and ecosystem function. A better understanding of the factors that drive amenity-migration can help set the stage for research that explores the spatial patterns of exurban development.

A.1 Naturalness: Greenness

The wide-spread aesthetic preference for natural elements and settings is a well-documented phenomenon that is covered by a vast literature and substantiated by well-controlled research (Hartig 1993; Tviet et al. 2006; Ode et al. 2009). As a concept, naturalness is generally used to describe how close a landscape is to a perceived natural state. Perceived naturalness can thus be different from quantitative ecological definitions of naturalness (Purcell and Lamb 1998; Lindhagen and Hörnsten 2000). Vegetation or greenness is an important element of naturalness and has been found to enhance landscape preference (Real et al. 2000; Hands and Brown 2002; Hägerhäll et al. 2004)

One of the important draws of natural settings is that they offer excellent opportunities for relaxation and restoration from stress (Purcell et al. 2001; Van den Berg et al. 2003; Hartig and Staats 2005). Studies have also found that greenness is positively associated with self-reported health (Maas et al. 2006; Maas et al. 2009), physical activity (Rodriguez et al. 2005; McGinn et al. 2007; Cohen et al. 2007; Bell et al. 2008) and mental health (Kawachi and Berkman 2003; Macintyre et al. 2008; Maas et al. 2009). Nature also plays an important role in the vision of the rural idyll and exurbanites often have the cultural, political, and economic capital to force this vision to the top of the public agenda (Walker and Fortmann 2003; Hines 2007; Kondo et al. 2012). Increased greenness raised the sale prices of ranchettes in Yavapai County, Arizona (Sengupta and Osgood 2003). The concept of "greenification" has been introduced to the study of rural gentrification (Smith 1998), drawing attention to the importance of ideals of nature to rural in-migrants and highlighting the way that natural rural spaces have become high-end consumptive commodities.

A.2 Visual Scale: Viewshed Size

Theories relating to visual quality and landscape preference strongly emphasize the concept of visual scale. Visual scale is related to the degree of openness in the landscape (Tveit et al. 2006) and is affected by line-of-sight and viewable area. Research on landscape preference has consistently found that people like traversable foregrounds and open vistas (Ulrich 1986) and the degree of openness is directly related to landscape preference (Nasar et al. 1983; Hanyu 2000; Clay and Smidt 2004). In prospect-and-refuge theory (Appelton 1975), prospect is used to describe the degree to which the environment provides opportunity, and is claimed to be important in landscape preferences. The prospect element predicts that humans should be attracted to broad, unoccluded vistas and the degree of prospect has been described as the depth and aerial extent of the view (Germino et al. 2001). Other studies have used openness as an indicator and have defined it as the ease with which an observer can obtain an extensive view over the landscape (Weinstoerffer and Girardin 2000). Viewshed size measures the extent of the view, providing a method to compare visual scale and openness.

A.3 Complexity: Terrain Ruggedness

Complexity has been identified as a key concept of visual quality and is defined as the diversity and richness of landscape elements and features (Litton 1972; Kaplan and Kaplan 1989). Complexity can be thought of as the number of different visual elements in a scene or the intricateness of the scene (Kaplan and Kaplan 1989) and is important for landscape preference (Stamps 2004). Although few studies have focused on what actually constitutes complexity with regard to landscape elements and how these elements relate to preferences (Tveit et al. 2006), complexity is a visual concept for which there has been an active development of indicators, both in relation to landscape ecology and visual indicators (Hunziker and Kienast 1999; Dramstad et al. 2001; Fjellstad et al. 2001; Palmer 2004). One such indicator is topographic heterogeneity or terrain ruggedness, which was selected by the US Department of Agriculture Economic Research Service (USDA-ERS) as one of three of physical factors that represent the base ingredients of natural amenities (Cromartie and Wardell 1999). In general, more varied or rugged terrains are considered more appealing (Kaplan and Kaplan 1989; McGranahan 1999; Stamps 2004; McGranahan 2008). Population growth has been shown to be positively correlated with mountainous topography in the rural counties of Idaho, Montana, and Wyoming, USA (Hansen et al. 2002).

B. Preference Scale and Viewshed Analysis

Much of the work on the impacts and drivers of exurbanization has been done on the county-scale, relying largely on census data (Mueser and Graves 1995; Hansen et al. 2002; McGranahan 2008; Rudzitis et al. 2011). The USDA-ERS has proposed a county-scale “natural amenities index” based on three classes of physical factors: climate, topography, and water area (Cromartie and Wardell 1999). These factors were selected as representing the base ingredients of natural amenities, and population growth in rural counties in the United States was strongly correlated with this natural amenities index from 1970 to 1996 (McGranahan 1999). Any given area is bound to have numerous settings and viewpoints of varying scenic quality (Dramstad et al. 2006). When counties are the units of analysis in landscape preference, individual viewpoints or scenes are not assessed, but rather the interest is in the general capacity of each county to yield scenic beauty. This approach is supported by the finding that regional landscape features are important for housing value independently of the particular setting of a housing unit (Luttik 1999).

Although informative of broad trends, county-level scales of analysis are too coarse to study the specific features of the environment that attract amenity migration. For example, previous studies that included topography as a preference metric divided the entire United States into five topographic categories, with a four-category scale of relief within each general topography type (McGranahan 1999; Cromartie and Wardell 1999; McGranahan 2008). At this scale of analysis, entire counties fall within a single topographic category. In order to study the relative importance of visual quality drivers, the spatial distribution of exurban development requires analysis on a finer scale. By exploring the relationships between house location and visual quality metrics, we get more information about landscape preference. Analysis at the viewshed scale allows us to tease apart visual quality metrics and study the relative contributions of different visual quality elements to the desirability of an area.

A viewshed is composed of the areas of land, water, and other environmental elements that can be seen from a fixed vantage point (Gimblett 2013). The most common uses of viewshed analysis include visual exposure, archeological research, and photo-elicitation/landscape-classification. Examples of visual exposure research include study of the visual pollution from mines and how it should be considered in impact assessments (Zhou et al. 2011) or assessing alternatives for the distribution of clear-cut areas to minimize visual impact the work of (Domingo-Santos et al. 2011). Viewshed analysis has been used in archeological research to detect settlements and other infrastructure for some time; recent work integrates viewshed analysis with remote sensing and geomorphology to reconstruct Neolithic landscapes in Thessaly and detect settlements (Alexakis et al. 2011). Mark and Brabyn (2011) used viewshed analysis to tag photos, which were then used in landscape classification, while Sheeran et al. (2011) used viewshed analysis in a photo-elicitation study that looked at how farmers valued trees on their pastures. To our knowledge, viewshed analysis has not been used previously to assess housing location choice. Viewshed analysis allows assessment of what is visible from where people actually chose to live, allowing for a much finer-scale study of preference.

There have been limited attempts to integrate what has been learned directly from exurbanites about their reasons for moving to rural landscape and the spatial pattern of actual exurban development (Walker 2011). There is also a lack of systemic studies which examine the relationships between visual indicators and house location. By looking at where people actually chose to build and live, it is possible to examine which drivers are optimized and which are compromised. The objective of this paper is to explore the relationship between the location of exurban homes and aesthetic landscape preference, as exemplified through three visual quality metrics, using viewshed-based geographical representation and analysis.

We begin by describing the Sonoita Plain, southeastern Arizona, USA, a study area that provides a buffered region of exurbanization, ideal for understanding spatial patterns with limited external influences. This is followed by a description of the spatial viewshed analysis used to assess the influence of greenness, viewshed size, and terrain ruggedness on the spatial pattern of exurban development. We finish with an analysis of results and their broader implications.

III. Study Area

The Sonoita Plain (696 km^2) lies in a predominantly semiarid grassland located in northwestern Santa Cruz County, Arizona, USA (31° 32-44’ N/110° 28-44’ W). The Sonoita Plain is surrounded by the Santa Rita Mountains to the west, the Huachuca Mountains to the south-east, the Empire Mountains to the north, the Whetstone Mountains to the northeast and the Canelo Hills to the south (Figure 1). Elevations range from about 1,100 to 1,600 m in the central Plain, while elevations of upland areas approach 2,900 m (USGS National Geospatial Program 2011). This constrained geographic area is entirely ringed by mountains that provide vertical visual boundaries. The unique topography makes this area especially well-suited to viewshed analysis since the mountains effectively constrain what is visible to those living in the Sonoita Plain to the interior Plain and the sides of the mountains facing the Plain, reducing the risk of potentially confounding influences beyond the mountains.

The Sonoita Plain is acknowledged to be a prime example of high plain southwestern grassland (Bock and Bock 2000). This is largely characterized by the desert grassland, plains grassland and desert scrub communities (501 km^2 / 72% of study area), with some riparian forest and riparian woodland communities along Cienega Creek in the northern part of the study area (22 km^2 / 3% of study area) (Arizona Game and Fish Department Natural Vegetation 1976). Upland regions ringing the central Plain are dominated by oak communities (172 km^2 / 25% of study area) (Arizona Game and Fish Department Natural

Vegetation 1976), while agricultural and developed areas (3 km^2 / 0.4% study area) are located near towns (USGS National Gap Analysis Program 2004). Mean temperatures range from a January minimum of -2^{o}C to a June maximum of 33^{o}C (1971–2000), and average annual rainfall is 460 mm, with more than 50% occurring during the summer (July to September) monsoon (Kupfer and Miller 2005). Much of the Sonoita Plain has not burned within historic fire return intervals, suggesting an accumulation of organic fuels (Vukomanovic et al. 2013).

The study area was delineated using an impervious surface layer developed by the Water Resources Research Center, University of Arizona for the state of Arizona. The imperviousness of the substrate was selected as the defining study area characteristic because it has important consequences for the availability of water. Wells are mostly limited to the unconsolidated material of the Plain, with a handful of wells drawing water from shallow aquifers in the mountains. Given that ground water is the sole source of potable water in the area, the pervious substrate corresponds well to human settlement in the area. The Sonoita Plain was classified as either pervious (unconsolidated material/soil) or impervious (rock) and the area within the delineated “study area” outlined in Figure 1 corresponds to unconsolidated material/soil. As the Sonoita Plain is entirely ringed by mountains, this study area classification delineates the interior of the Plain and separates the study area from communities on the other sides of the mountains. Here “Sonoita Plain” and “study area” are used interchangeably to describe the interior of the Plain (Figure 1). This delineation was primarily used to constrain the locations of simulated housing distributions.

In recent years, residential developments have sprung up on land historically used for cattle ranching. People are relocating to the Sonoita Plain in increasing numbers and houses are being constructed as vacation homes, retirement homes, and primary residences for those who commute to jobs in the relatively nearby municipalities of Tucson, Nogales and Sierra Vista, Arizona. The median income, median house value, percent of residents with incomes below the poverty line, and median age in 2010 for the Sonoita Plain (towns of Sonoita, Elgin, and Patagonia, and surrounding census blocks), Santa Cruz County, Arizona and the entire state of Arizona ((US Bureau of the Census 2010) are shown in Table 1. Overall, the residents of the Sonoita Plain are older and wealthier than residents in the rest of Santa Cruz County or the state Arizona overall. These trends are in keeping with those observed for amenity-migrants elsewhere (Smith and Kannich 2000; reviewed in Rudzitis et al. 2011) and suggest the ability or freedom on the part of Sonoita Plain exurbanites to make choices about housing location.

IV. Methods

Spatial analysis and modeling was conducted using ArcGIS v. 10.0 (ESRI, Redlands, CA, USA). All maps are displayed in geographic-coordinate system GCS North American 1983, datum D North American 1983; all analysis layers were projected to

NAD 1983 UTM Zone 12N. Validation tests were performed and output figures created (Figures 5-8) using MATLAB 7.12.0 (The MathWorks Inc., Natick, Massachusetts).

A. Deriving Contextual Variables

A.1 House Locations

It is common practice to measure and express the pattern and extent of development through population or population density. However, population data from the US Bureau of the Census are tied to primary residences and such measures underestimate landscape changes because vacation and second homes are not represented. Therefore, housing density is a more complete and consistent measure of landscape change than population density (Theobald 2005). In lightly-settled landscapes, houses are not evenly distributed across census blocks and simple housing-density measures do not capture real location distribution or settlement patterns. To address this, locations of all houses in the Sonoita Plain study area were manually digitized from 2010 high resolution (1 m) aerial imagery obtained from the USDA Farm Service Agency, National Agricultural Imagery Program (NAIP). These locations were cross-checked against 2010 U.S. Bureau of the Census data to ensure that the number of homes digitized in each census block matched the number of homes reported in the 2010 US Census. By digitizing the location of each house, a representation of how houses are distributed across the landscape emerges.

In 2010, the Sonoita Plain had 1,867 homes (U.S. Bureau of the Census) and supported three different housing-density classes (Figure 4). Following Theobald (2005) and

Leinwand et al. (2010), the study area was divided into the following housing-density classes: rural (0-0.0618 units/ha), exurban (0.0618-1.47 units/ha), and suburban (1.47-10 units/ha). This study focuses on those houses classified as exurban; of the 1,867 total houses in the study area, 998 are exurban.

A.2 Roads, Towns, Elevation

Road information came from 2010 census data (U.S. Bureau of the Census) for Santa Cruz, Cochise, and Pima counties in Arizona. The locations of the three towns within the study area, Sonoita, Elgin, and Patagonia, came from the Arizona State Land Department (2006). The elevation model used was the 1/3 arcsecond digital elevation model provided by the U.S. Geological Survey (USGS National Geospatial Program 2011).

B. Viewshed Analysis

Viewshed analysis identifies the cells in an input raster that can be seen from an observation point. Starting with the cells closest to the observation point, a line-of-sight process calculates and maps whether the cell can or cannot be seen. As long as the tangent increases in the line-of-sight from the observation point, the cell is visible; if the tangent decreases, the cell is not visible (Fisher 1991; Gimblett 2013). Using elevation data as the input, each cell in the output raster that can be seen from the observation point is given a value of one, while all of the cells that cannot be seen from the observer point are given a value of zero. In our viewshed analysis, each exurban house served as an observation point and the viewshed for each house represents the portions of the landscape visible from that location. We calculated the viewshed for each of the 998 exurban homes in the Sonoita Plain. The vantage-point was not restricted, meaning that we considered the view in all directions around each home. When combined with additional metrics, such as greenness, viewshed size, and terrain ruggedness, viewshed analysis allows comparison of the landscape characteristics visible from each vantage point.

C. Greenness

The Normalized Difference Vegetation Index (NDVI) provides a measure of greenness that can be summarized and applied across different areas of interest for comparison (Tucker 1979). The principle underlying NDVI is that healthy green vegetation reflects more infrared radiation and absorbs more energy in the red wavelength than unhealthy vegetation or sparsely- and non-vegetated surfaces. NDVI is calculated according to the following algorithm: $NDVI = (NIR - RED) / (NIR + RED)$, where NIR is the amount of near-infrared wavelength reflectance and RED is the amount of red wavelength reflectance detected. Scores range from -1 to 1, where -1 indicates that no vegetation is present and 1 indicates dense levels of healthy vegetation (Tucker 1979).

NDVI has been widely used to assess levels of vegetation in agriculture and land-use/land-cover change research (e.g., Lenney et al. 1996; Lunetta et al. 2006; Brown et al. 2013). Recent studies have also used NDVI to look at the relationships between neighborhood greenness and health (Liu et al. 2007; Tilt et al. 2007; Bell et al. 2008). The correlation between NDVI scores and the observed residential greenness ratings of environmental psychology experts is high, indicating that NDVI is a useful measure of perceived greenness (Rhew et al. 2011).

We used the Version 5 NDVI product collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra platform (horizontal 8; vertical 5) at a 250 meter resolution. The NDVI product is multiplied by a scale factor of 0.0001 for a range of -10,000 to 10,000. A decadal average value for each pixel was calculated by summing all of the NDVI values from 2000 to 2010 and dividing by the number of images (249) (Figure 3). The viewshed for each exurban house, as well as for each simulated (validation) house, was overlaid on the NDVI surface. The NDVI values that fell within each viewshed (i.e., are visible from that house) were averaged to calculate a mean viewshed NDVI value.

D. Viewshed Size

Viewshed size provides a measure of how constrained or expansive the view is from each vantage point. The number of 30 x 30-meter pixels (DEM layer resolution) in each viewshed was tabulated to calculate the size of the viewshed.

E. Terrain Ruggedness

The Terrain Ruggedness Index (TRI) provides a quantitative measure of terrain heterogeneity and allows for terrain comparisons between areas (Riley et al. 1999).

Originally developed to assess the effects of terrain heterogeneity on wildlife abundance, the TRI is derived from digital elevation models (DEM) using a terrain analysis function implemented in a geographic information system. The TRI index has since been used for animal habitat mapping and analysis (Wilson et al, 2007; Sappington et al. 2007; Martinuzzi et al. 2009), connectivity analysis (Murphy et al. 2010; Habib et al. 2011), and movement ecology (Skarin et al. 2008; Mandel et al. 2008).

The TRI is computed for each grid cell of a DEM by calculating the sum change in elevation between the central grid cell and the mean of an 8-cell neighborhood of surrounding cells. The equation is TRI = $\sqrt{|(maxDEM)^2 - (minDEM)^2|}$ (Riley et al. 1998). Two 3x3 neighborhood rasters were created from the DEM: maximum value (*maxDEM*) and minimum value (*minDEM*). A raster calculator was then used to compute the TRI for each cell of the study area using the two neighborhood inputs (Figure 4). The viewshed for each exurban house, as well as for each simulated (validation) house, was overlaid on the TRI surface. The grid cell-level TRI values that fell within each viewshed (i.e., are visible from that house) were then averaged for a total TRI. We also calculated the maximum TRI value in each viewshed.

The TRI was originally developed for state-level analysis in Montana (USA); this area includes the Rocky Mountains, and the TRI classification categories reflect the extreme ruggedness of that terrain (Table 2). The TRI categories were assigned using the equal area classification method to group continuous ranges of TRI values into seven classes of unequal range, but equal area (Riley et al. 1999). Our study area does not yield the full range of values possible. Terrain ruggedness in the Sonoita Plain ranges from “level” to “highly rugged”, with the highest TRI values at 678.5 meters (Figure 2). Although the TRI categories are informative, the continuous distribution of values, rather than the categories were used to compare the actual exurban houses and the simulated (validation) houses.

F. Validation

In order to test whether the findings for each of the three visual quality metrics (greenness, viewshed size, and ruggedness) reflect location choice on the part of homeowners, we tested the actual exurban distribution against a simulated, random house location distribution. Following Theobald (2005), the study area was divided into “developable” and “undevelopable” areas, with Bureau of Land Management (BLM), State, US Forest Service, and Nature Conservancy lands classified as “undevelopable”, while private lands were deemed “developable”. Land ownership data came from the Arizona State Land Department (ASLD 2011), which covers the entire state of Arizona; land ownership in the study area is roughly 50% public and 50% private. The ASLD land ownership data was cross-checked against hardcopy maps from the Santa Cruz County Assessor’s Office (SCC 2011). One discrepancy was found and a single parcel was changed from “private” to “BLM” ownership to match the finer-scale information from the Santa Cruz County Assessor’s Office. We simulated a random house location distribution on portions of the study area deemed “developable”. The simulated distribution included 998 houses, which matched the number of actual exurban houses in the study area. We calculated the viewshed for each house in the simulated distribution and performed the calculations outlined above for each of the visual quality metrics.

We performed two-sample Kolmogorov-Smirnov (K-S) tests to compare the cumulative distribution functions (CDFs) of the two data sets (actual exurban homes and simulated house distribution). The two-sample K-S test was used to test whether the two probability distributions differ. The Kolmogorov-Smirnov statistic is defined as $D_{n,n'} = \underset{x}{sup} \left| F_{1,n}(x) - F_{2,n'}(x) \right|$, where $F_{1,n}$ and $F_{2,n'}$ are the distribution functions of the first and second sample respectively (Massey 1951). In total, four tests were performed: average NDVI, viewshed size, total (average) TRI, and maximum TRI. The null hypothesis is that the actual homes and the simulated homes are from the same continuous distribution. The alternative hypothesis is that they are from different continuous distributions (Sager 2010). The result h is 1 if the test rejects the null hypothesis at the 5% significance level; otherwise it is 0. The test statistic k is the maximum difference between the curves (Massey 1951). The two-sample K-S test is distribution free and valid for testing data against any continuous distribution (Sager 2010)

V. Results

A. Greenness

We performed a two-sample Kolmogorov-Smirnov (K-S) test to compare the cumulative distribution functions (CDFs) for average NDVI of the actual exurban houses and the simulated houses (Figure 5). The CDF describes the probability that a real-value variable *X*, in this case average NDVI, with a given probability distribution will be found at a value less than or equal to *x* (Hatke 1949). It can be thought of as the "area so far" function of the probability distribution. For example, 10% of the simulated houses are accounted for by the time the distribution reaches an average NDVI value of 3640.26, while 10% of simulated houses have average NDVI values below 3824.70. The exurban houses have viewsheds with higher average NDVI values than do the simulated (validation) houses. A p-value of 3.0299e-006 indicates that the results are significantly different at the predetermined significance level of 0.05 ($h = 1$ if $p<0.05$) (Table 3). The p-value gives the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis (that the actual exurban houses and the simulated houses are from the same continuous distribution) is true (Lehmann and Romano 2005). The actual exurban households can see significantly more vegetation than would be expected if the houses were placed randomly and without consideration for greenness. The sigmoid shape of the curve indicates a normal distribution for both the actual exurban and simulated distributions.

B. Viewshed Size

A two-sample Kolmogorov-Smirnov (K-S) test was used to compare the cumulative distribution functions (CDFs) for viewshed sizes of the actual exurban houses and the simulated houses (Figure 6). A p-value of 0.0105 indicates that the results are significantly different at the predetermined significance level of 0.05 ($h = 1$ if $p<0.05$) (Table 3). The viewshed sizes of exurban homes are larger than would be expected if the houses were placed randomly and without consideration for viewshed size. The steep slope at the low values indicates that both the actual exurban and the simulated distributions display a positive (right) skew, where the mass of the distribution is concentrated on the left and there are relatively few high values.

C. Terrain Ruggedness

C.1 Total Terrain Ruggedness Index (TRI)

We performed a two-sample Kolmogorov-Smirnov (K-S) test to compare the cumulative distribution functions (CDFs) for total (mean) TRI of the actual exurban houses and the simulated houses (Figure 7). The exurban houses have viewsheds with higher total TRI values than do the simulated (validation) houses. A p-value of 7.5723e-006 indicates that the results are significantly different at the predetermined significance level of 0.05 ($h = 1$ if $p<0.05$) (Table 3). The actual exurban households can see a significantly more rugged terrain than would be expected if the houses were placed randomly and without consideration for terrain ruggedness. The sigmoid shape of the curve indicates a normal distribution for both the actual exurban and simulated distributions.

C.2 Maximum TRI

A two-sample Kolmogorov-Smirnov (K-S) test was performed to compare the cumulative distribution functions (CDFs) for maximum TRI value of the actual exurban houses and the simulated houses (Figure 8). A p-value of 2.8987e-029 indicates that the results are significantly different at the predetermined significance level of 0.05 ($h = 1$ if $p<0.05$) and we can reject the null hypothesis that the actual exurban houses and the simulated houses are from the same continuous distribution (Table 3). The distribution functions cross at a TRI value of 556.4. At values below 556.4, the actual exurban houses have higher maximum TRI values than do the simulated distributions; this accounts for approximately 20% of the distribution. Almost two-thirds (64.6%) of the actual exurban viewsheds have a maximum TRI value of 556.4, while about one-third (36.0%) of simulated viewsheds have a maximum TRI value of 556.4. The highest 30% of maximum TRI values are significantly higher for the simulated viewsheds than for the actual exurban viewsheds.

VI. Discussion

The specific elements of visual quality that attract amenity migration are poorly understood and the relative contributions of different elements to the appeal of an area are unclear. The objective of this paper was to explore the relationship between the location of exurban homes and aesthetic landscape preference, as exemplified through three visual quality concepts (naturalness, visual scale, and complexity) represented by three corresponding metrics (greenness, viewshed size, and terrain ruggedness). We used viewshed-analysis to analyze these metrics for actual exurban houses and compared these distributions to a randomly-distributed simulated (validation) distribution. In examining the physical distribution of actual exurban homes, we hoped to gain a better understanding of the aesthetic preferences that drove house location selection in the Sonoita Plain.

We found that the actual exurban households can see significantly more vegetation than would be expected if the houses were placed randomly and without consideration for greenness. The actual exurban viewsheds had significantly higher average NDVI values than the simulated (validation) houses (p-value =3.0299e-006). Similarly, actual exurban viewsheds have significantly higher total (mean) Terrain Ruggedness Index (TRI) values than simulated houses (p-value=7.5723e-006). The exurban households see more-rugged or more-heterogeneous topography than would be expected is the houses were randomly placed. These two metrics are correlated as higher TRI values are found in the mountains that ring the Sonoita Plain and the mountains are also where we find oak and pine vegetation communities, which have higher NDVI values than the grasslands of the Sonoita Plain.

It is not clear which of these two metrics, greenness or terrain ruggedness, is the primary driver of aesthetic preference in this study area. In addition to mountains, the other landscape type that supports a lot of woody vegetation and has higher NDVI values in southeastern Arizona is riparian areas (Arizona Game and Fish Department Natural

Vegetation 1976). The boom of residential development along riparian areas in Arizona (Germaine et al. 1998) lends support to the importance of greenness in exurban house location selection, but terrain ruggedness is also important for landscape preference (Stamps 2004; McGranahan 2008). It could be that where there are trade-offs between greenness and ruggedness, we find different groups of amenity migrants. Birding enthusiasts, for example, may be drawn to areas that have more vegetation and can support a greater number and diversity of birds, such as riparian corridors, while avid hikers might be drawn to more mountainous terrain. Further study could help to tease apart these landscape preferences.

The step-wise maximum Terrain Ruggedness Index (TRI) value distributions of both the actual exurban and the simulated (validation) houses reflect the fact that there are a handful of high peaks that are visible from many parts of the central Plain. The distribution functions cross at a TRI value of 556.4. At values below 556.4, the exurban houses have a higher maximum TRI values than the simulated distributions. Almost two-thirds (64.6%) of the actual exurban viewsheds have a maximum TRI value of 556.4, while about one-third (36.0%) of simulated viewsheds have a maximum TRI value of 556.4. This value likely represents a single peak. The highest 30% of maximum TRI values are significantly higher for the simulated viewsheds than for the actual exurban viewsheds. The higher maximum TRI values for the simulated houses likely mean that they can see peaks in the Santa Rita Mountains to the northwest, which are the highest peaks in the region. Although significantly different, when we consider the range of potential TRI index values (0-4367), the difference between where the majority of values fall (556.4) and the highest maximum TRI value for the simulated distribution (606.3) isn’t very large.

It is interesting to note that the actual exurban viewsheds have a higher mean TRI value, but a lower maximum TRI value than the simulated (validation) viewsheds. The actual exurban homes see a more rugged terrain, but don’t necessarily see the highest peaks. This provides some evidence that visual complexity throughout the viewshed may be more important than seeing the very highest peaks. It also suggests that the viewsheds with the highest peaks may not necessarily have the most visually complex views, which may be an important consideration when evaluating the desirability of a location.

Viewshed size measures the extent of the view, providing a method to compare visual scale and openness. Visual scale is related to the degree of openness in the landscape (Tveit et al. 2006), which is directly related to landscape preference (Clay and Smidt 2004). The viewsheds visible from the actual exurban houses were significantly larger than those visible from the simulated houses. The distributions of both the exurban and the simulated viewsheds are positively (right) skewed, where the mass of the distributions is concentrated on the left and there are relatively few high values. This may suggest that the number of very large viewsheds is limited. Exurbanites in the Sonoita Plain favor extensive views over the landscape and it appears that visual scale is important to the general aesthetic experience.

To date, most studies that have examined the spatial distribution of exurbanization in the context of amenity drivers have been at the county-level scale (Mueser and Graves 1995; Hansen et al. 2002; McGranahan 2008; Rudzitis et al. 2011). The findings of this study challenge the idea that regional landscape features are important independently of the particular setting of a housing unit (Luttik 1999; McGranahan 2008) and calls into question the use of county-level scales of analysis for the study of landscape preferences. The fact that there are differences in the visual quality metric values between actual exurban viewsheds and simulated viewsheds indicate that county-level comparisons may miss key landscape aesthetic drivers of preference. Although informative of broad trends, county-level scales of analysis may miss the specific features of a region that attract amenity migration. It is not just the general characteristics of the area that are important, but also the visual quality from each vantage point. County-level metrics may be especially problematic for counties in the Western US, which tend to be large and where aggregate measures may mean the loss of valuable information. The Sonoita Plain itself is a wealthy island of exurban development in a county where 24.5% of the population has incomes below the poverty level and the median household income in 2010 was $13,038 lower than for the state of Arizona (Table 1). County-level analysis of amenity-migration drivers would have missed this area entirely.

The three visual quality metrics used to represent naturalness, visual scale, and complexity that were evaluated in this paper were selected because they were deemed important for this landscape, but they are by no means exhaustive and other visual quality metrics may be just as important in this and other similar landscapes. The concept of historicity, for example, may be especially relevant for areas of the American West where the ranching lifestyle has been idealized. Cultural landscape elements, such as historical agricultural buildings, traditional agricultural structures, and historical roads can be important reminders of heritage in some landscapes and can provide residents with feelings of community integrity and richness. This historic continuity can give landscapes depth of meaning and a sense of time, thus enhancing landscape aesthetics (Lowenthal 1979; Yahner and Nadenicek 1997; Hooke 2000). Furthermore, some visual quality metrics may be more important than others, while other metrics may differ in importance depending on distance from the observer. Foreground vegetation, for example, has been found to be much more important than distant vegetation (Appleton and Lovett 2003). A weighted metric, such as a cost surface, could be used to place greater emphasis on the foreground and could help to further untangle aesthetic preferences. Which additional elements of the view contribute to aesthetic preference and to what extent are some of the questions that would benefit from further study.

Residents in very high amenity areas, displaying “last settler syndrome” and seeing further in-migration as a threat to the very landscape qualities that drew them initially, may adopt regulations to constrain further growth (McGranahan 2008; Hines 2010; Kondo et al. 2012). Housing prices are inordinately high in the most scenic rural counties and they no longer have the highest rates of migration (Rudzitis 2011). This suggests that in rural areas that have long experienced amenity migration (US examples include Aspen, Sun Valley, Park City, and the Hamptons), further in-migration will increasingly be shaped by efforts to preserve valued landscape aesthetics rather than by the landscape preferences of potential new in-migrants. However, in areas that have more recently started to experience amenity migration, and where land availability and price still allow at least some choice, information about landscape drivers and exurban preference could prove helpful to planning and management efforts.

The post-productivist economic shift from traditional resource industries to a New West economy based on a mix of the traditional industries and new sectors such as real estate and recreation (Hines 2007; McCarthy 2008) reflects not only changing economic forces, but also societal concerns about extractive uses in threatened landscapes. Many amenity-migrants view dispersed, low-density residential development as a conservation-compatible land use and certainly preferable to material production. Despite this pervasive view, Radeloff et al. (2010) have argued that it is not material extraction/production but housing growth that poses the main threat to protected areas in the United States. The spatial arrangement of exurban houses, roads and associated infrastructure will depend on the primary drivers of migration, and different spatial distributions will have different impacts on both social systems and ecosystem function. Information about landscape drivers may be of interest to local government officials, planners, and policy makers, as it may enable growth strategies designed to minimize negative ecological impacts on private and public lands. Beyond their value for conservation, strategies to protect visual quality may also be vital to sustaining economic growth in the New West.

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Table 1: Comparison of income, house value and age in the Sonoita Plain, Santa Cruz County and Arizona

2010 Census Figures	Median Household Income ($)	Median House Value ($)	Income Below Poverty Level (% Population)	Median Age (Years)
Sonoita Plain, AZ	62,984	368,421	6.1	58.0
Santa Cruz County, AZ	35,707	125,907	24.5	31.8
Arizona	48,745	187,700	13.9	34.2

Table 2. Terrain Ruggedness Index (TRI) Categories (from Riley et al. 1999).

Category	Elevation Difference (m)
Level	0-80
Nearly Level	81-116
Slightly Rugged	117-161
Intermediately Rugged	162-239
Moderately Rugged	240-497
Highly Rugged	498-958
Extremely Rugged	959-4367

Table 3: Comparison of the actual exurban house distribution to the simulated distribution for each visual quality metric: greenness, viewshed size, and ruggedness (Two-sample Kolmogorov-Smirnov test).

Comparison between Actual Exurban Distribution and Simulated Distribution	h[a]	p-value	k[b]
Mean NDVI Value	1	3.0299e-006	0.1152
Size	1	0.0105	0.0721
Total (Mean) TRI Value	1	7.5723e-006	0.1112
Maximum TRI Value	1	2.8987e-029	0.2565

[a] The result h is 1 if the two data sets are from different distributions at the 5% significance level. [b] The test statistic k is the maximum difference between the curves.

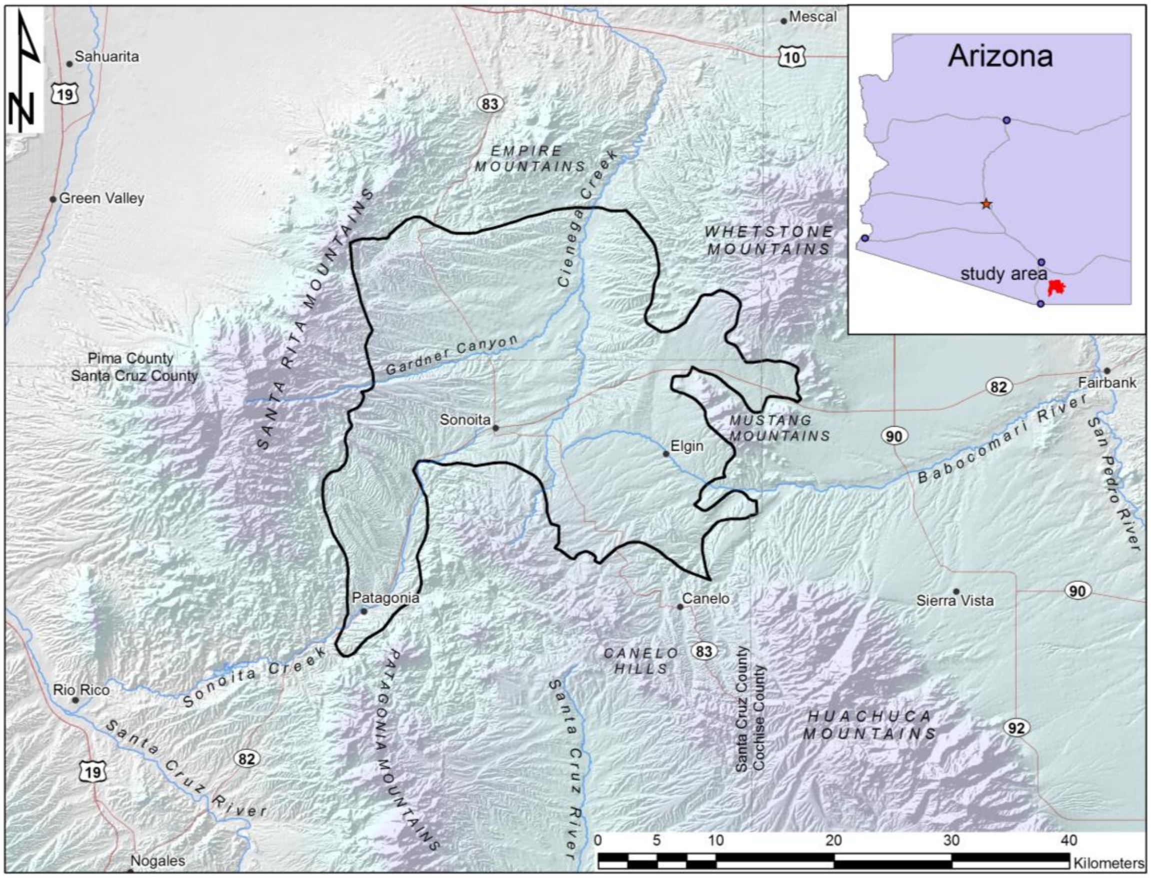

Figure 1: Map of the Sonoita Plain, highlighting the mountains surrounding the study area.

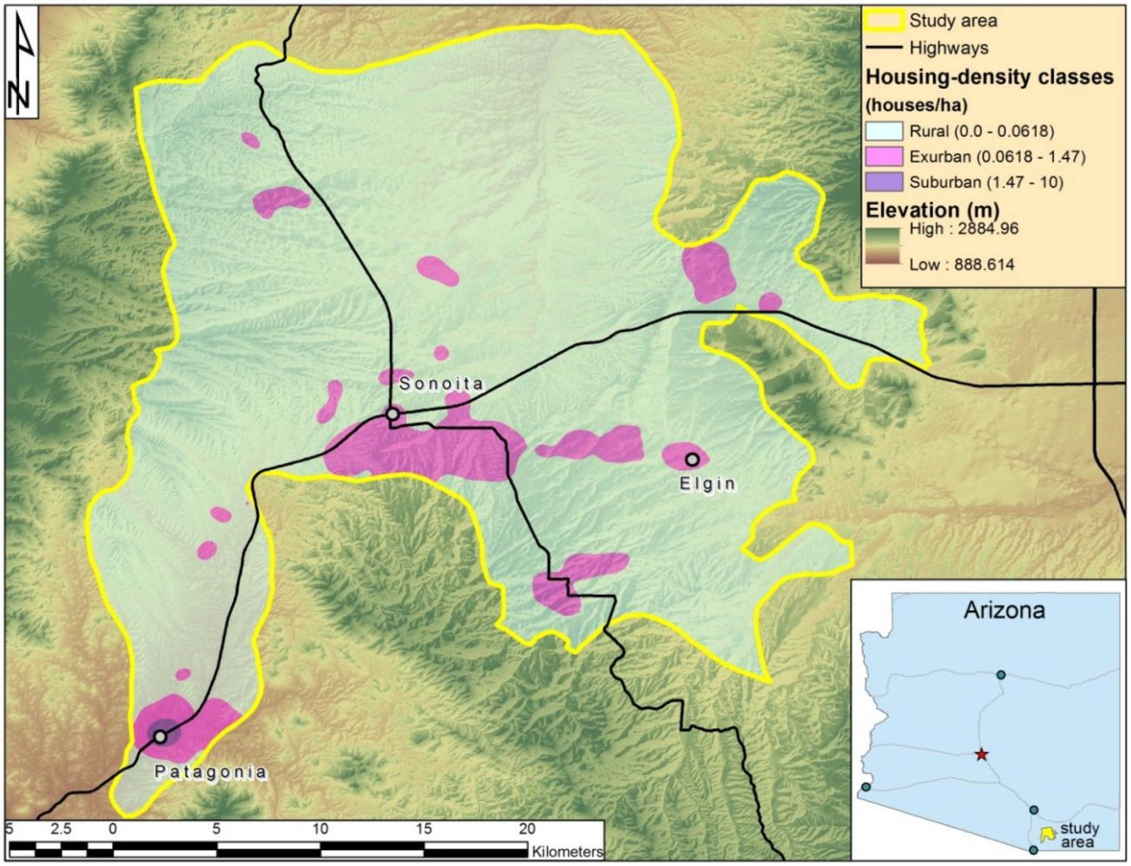

Figure 2: Housing-density classes in the Sonoita Plain, southeastern Arizona

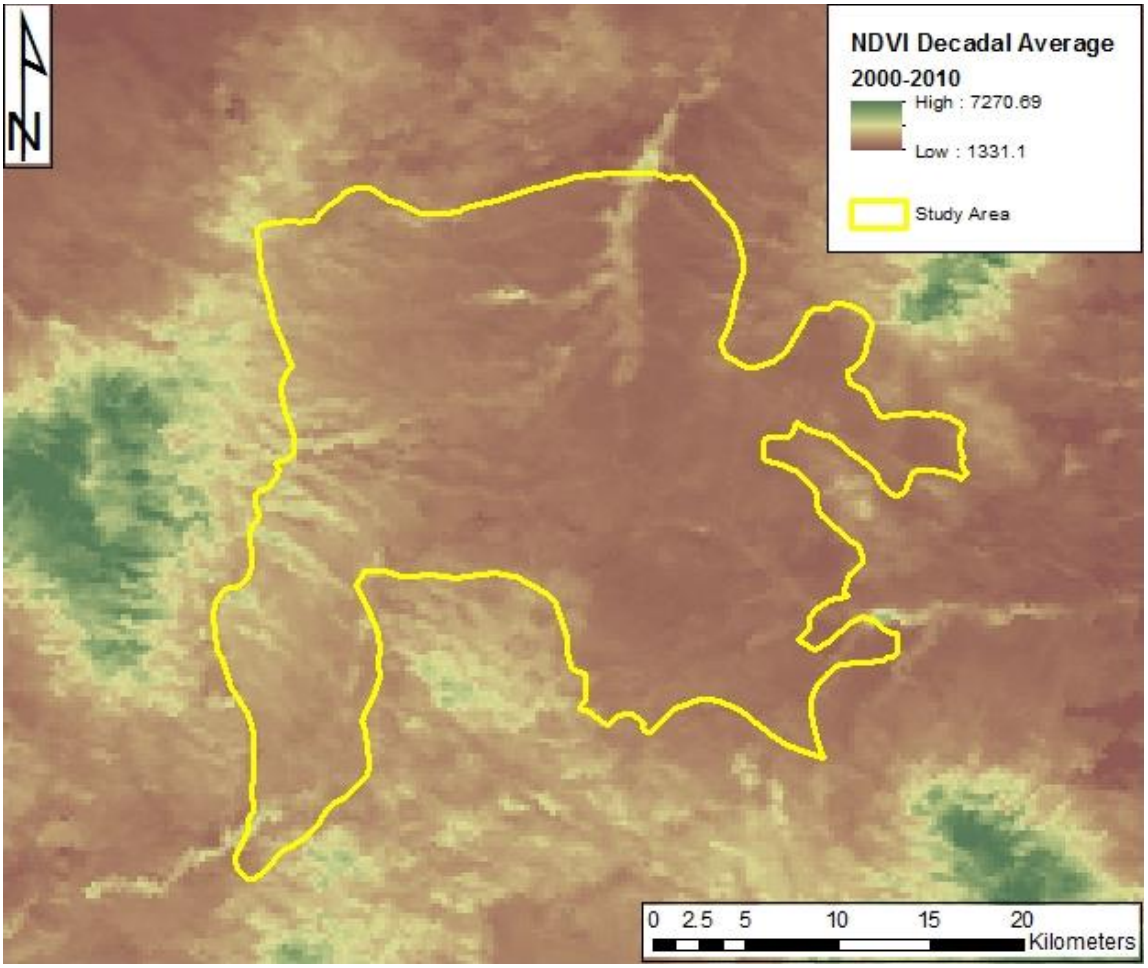

Figure 3: 2000-2010 decadal average NDVI values for the Sonoita Plain.

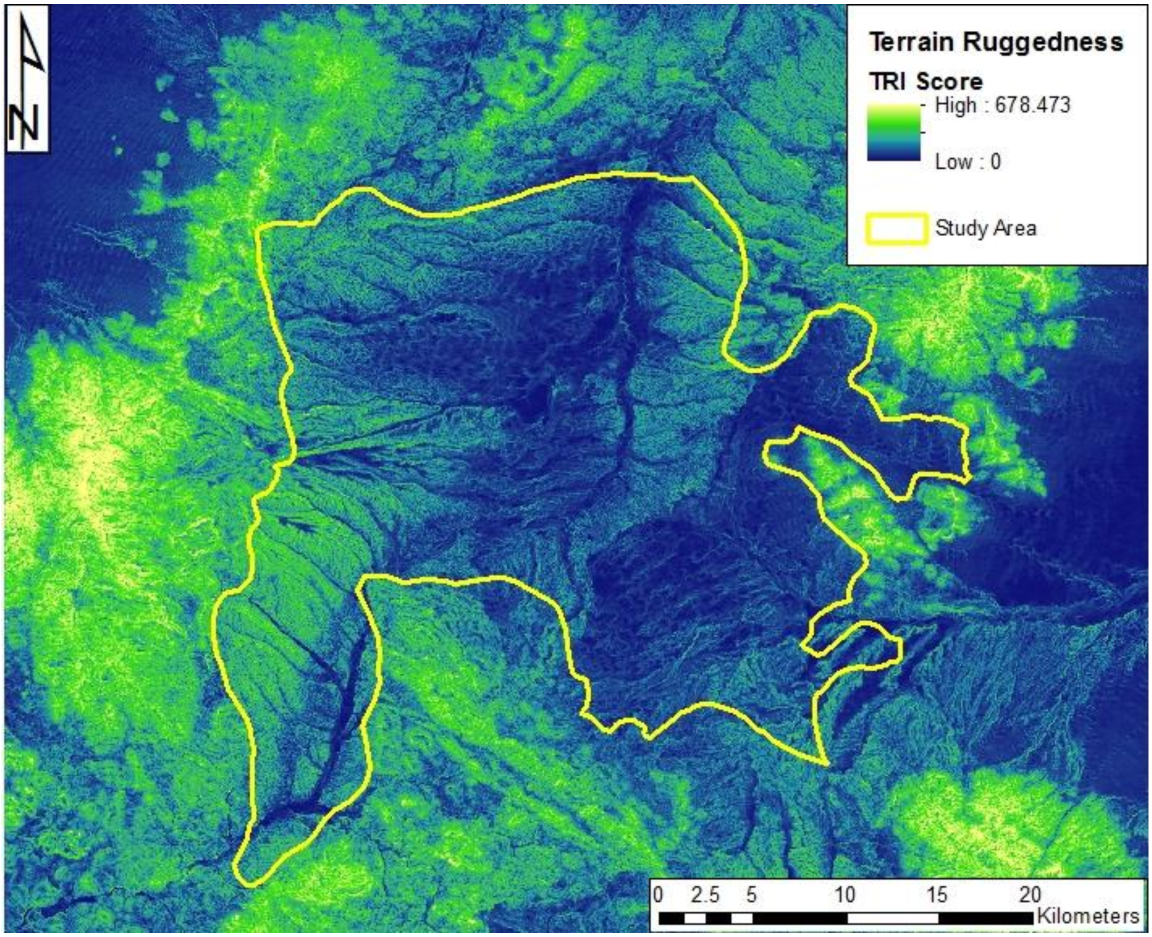

Figure 4: The Terrain Ruggedness Index (TRI) represents terrain heterogeneity in the Sonoita Plain (Index range is 0 to 4367 meters).

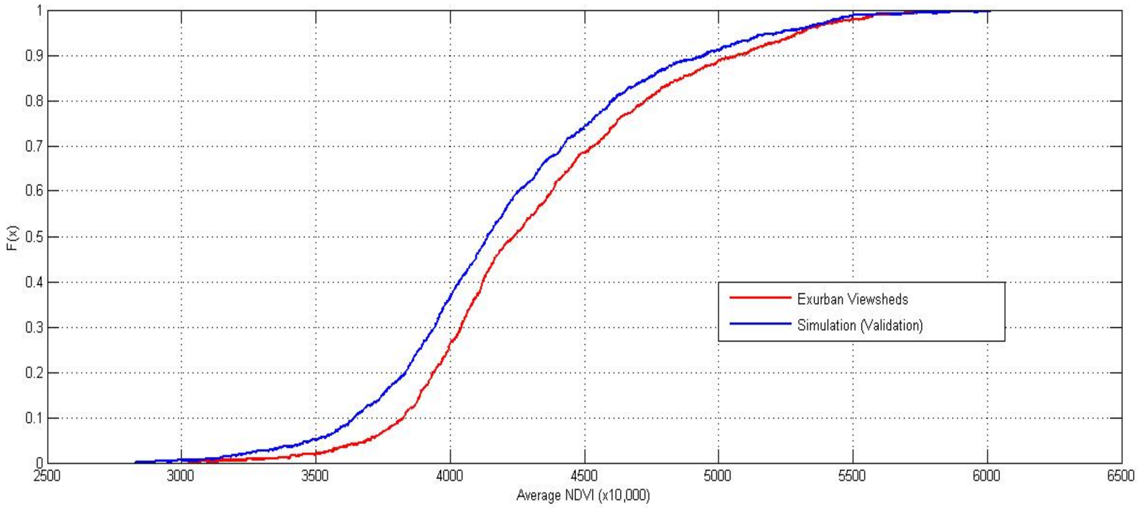

Figure 5: Cumulative distribution functions of average NDVI values for actual exurban and simulated (validation) houses.

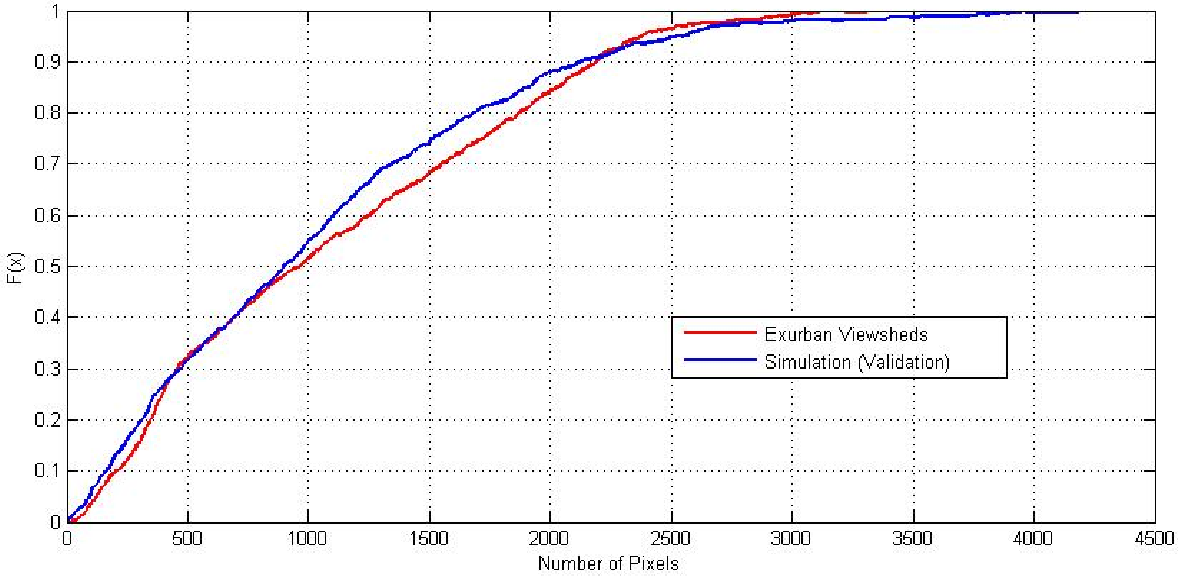

Figure 6: Cumulative distribution functions of viewshed size for actual exurban and simulated (validation) houses.

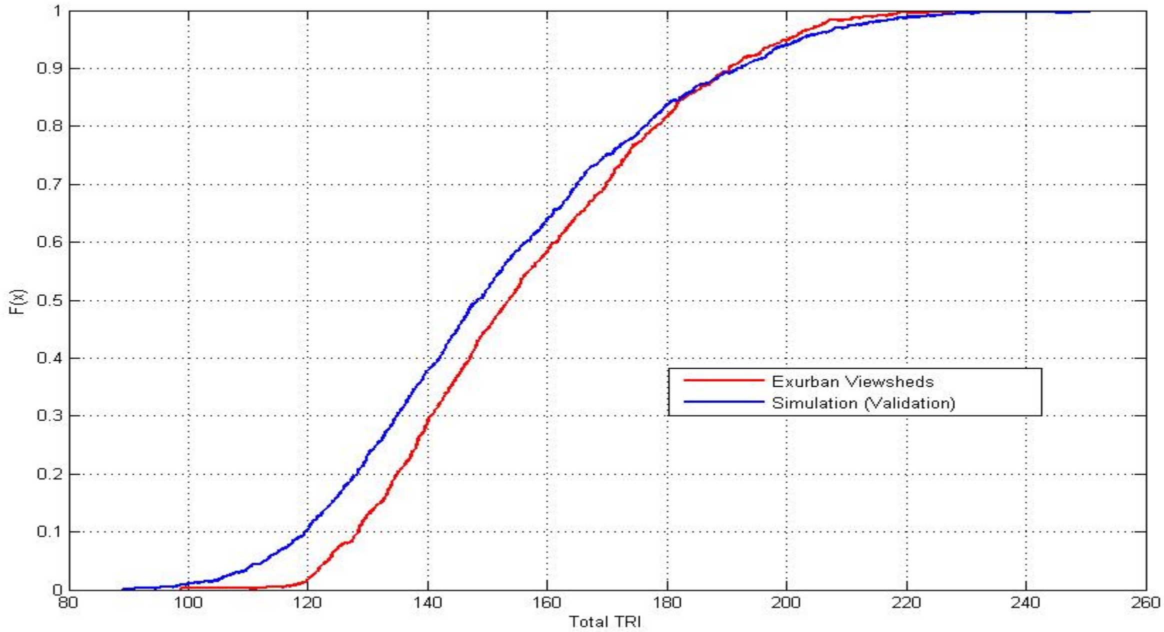

Figure 7: Cumulative distribution functions of total (mean) TRI values for actual exurban and simulated (validation) houses.

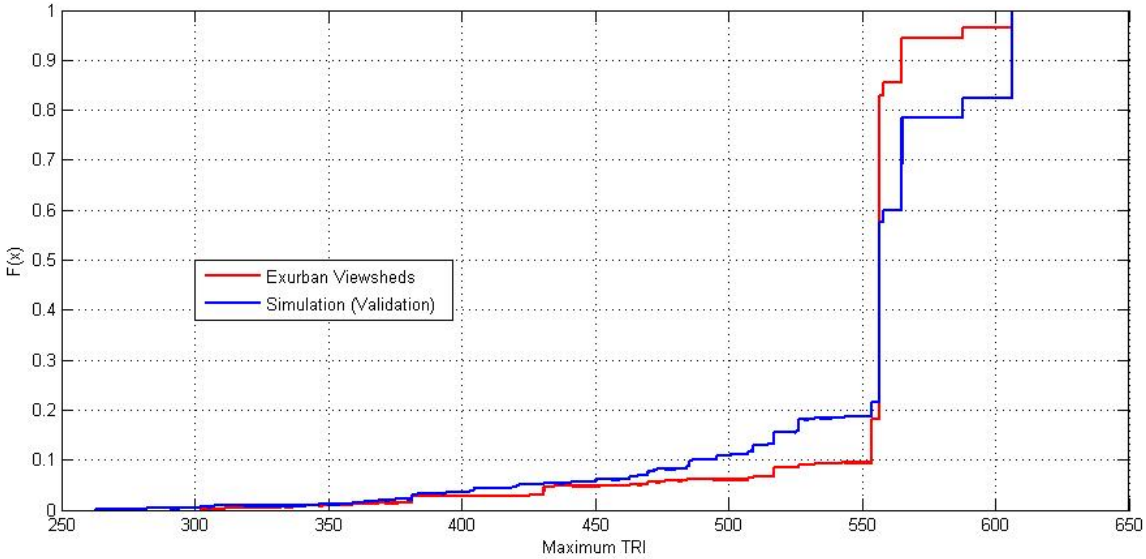

Figure 8: Cumulative distribution functions of maximum TRI values for actual exurban and simulated (validation) houses.