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Modeling the connection between viewscapes and home locations in a rapidly exurbanizing region

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ABSTRACT

Low-density exurban development represents a unique form of landscape change motivated by aesthetics and individual choice, whether driven by perceptions of beauty or more broadly as worldviews expressed through outward appearance and actions. However, little is known about how individual preferences for new home sites manifest in landscape patterns of exurbanization. In this study, we examine the extent to which viewscapes - the visible part of a landscape that creates connection between people and their surroundings - drive patterns of development in the Sonoita Plain of Arizona. We mapped the locations of over 2,000 homes built before and after the Great Recession (~2010) and calculated line-of-sight viewscapes of each home with four metrics: viewscape area, privacy (number of visible neighbors), greenness (NDVI), and terrain ruggedness. We found that exurban homes have significantly larger and more private viewscapes compared to suburban homes and what would be expected by chance. After 2010, exurban homes were built at locations with yet larger and more private viewscapes even as settlement density increased. An autologistic model of post-2010 settlement patterns showed that viewscape privacy is positively associated with the probability of exurban development after accounting for road proximity and the area and greenness of viewscapes. Application of the predictive model was made possible through a new open-source algorithm that computes spatially continuous, all-possible vantage points (1.3M). Our algorithm allows planners to visualize wall-to-wall spatial patterns of viewscape drivers across a large region and more comprehensively consider the roles that viewscapes play in landscape change.

1. Introduction

Regions across the United States with scenic beauty and other natural amenities are experiencing rapid population growth and residential development. Often described as "exurban", these regions are characterized by low-density residential settlement in rural areas appreciated for their aesthetic, recreational, and other consumption-oriented values (McCarthy, 2008; Taylor, 2011). A complex and varied picture of exurbanization drivers is emerging and the reasons that people move to scenic rural areas are as numerous as the communities that they form. For many exurbanites, natural amenities, such as scenic beauty (Gosnell and Abrams, 2011; Waltert and Schläpfer, 2010), expansive vistas (Nasar et al., 1983; Vukomanovic and Orr, 2014), wilderness (Rudzitis and Johansen, 1991), recreational opportunities (Hansen et al., 2005; Marcoullier et al., 2002), and climate (McGranahan, 2008; Mueser and Graves, 1995) play an important role in the decision to migrate. Attractive natural amenities in some exurban areas have been reported by new residents as even more important reasons for relocation than cost of living or job opportunities (Hansen et al., 2005; Rudzitis, 1999). Social and cultural connections to small-town rural life (Hines, 2007) and a desire for a sense of community (Vogt, 2011) can also be a draw for some amenity migrants. But, privacy and solitude, often described as being unaware of other people when at home (Kondo et al., 2012), are also highly valued by many exurbanites who seek seclusion or a "frontier living" experience (Hines, 2007; Hines, 2011). As many as 46% of amenity migrants in Washington state described finding "privacy" or "peace-and-quiet" as a primary real estate purchase goal (Kondo et al., 2012). Taken together, these drivers of relocation suggest that exurban development represents a unique form of land use change motivated by aesthetics - whether strictly related to perceptions of beauty or more broadly as principles or worldview expressed through outward appearance and actions - and largely driven by individual choice.

Exurban density areas have grown 27.9%, or approximately

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340,000 km^2, between 1990 and 2010 (1990, 2000, 2010 US Census; summarized from block groups, excluding publicly owned protected open spaces). Exurban areas now occupy 26.8% (about 1.6 M km^2) of the conterminous United States, compared to 2.5% in suburban and 0.3% in urban density classes (housing density definitions sensu Leinwand et al., 2010). Approximately 6.6% of 1990 rural density lands transitioned to exurban density by 2010. Per capita land consumption[1] in exurban areas is particularly high, averaging 0.14 acres/person of impervious surface compared to 0.08 acres/person in suburban areas and 0.03 acres/person in urban areas (2011 NLCD; 2010 US Census). The rapid growth and dispersed nature of exurban development raises numerous environmental concerns, including changes to water quality and quantity (Bolin et al., 2008; Houlahan and Findlay, 2003), altered fuel loads and fire regimes (Schoennagel et al., 2009), habitat fragmentation (Forman and Deblinger, 2000), and the spread of invasive species (Joly et al., 2011). Rapid in-migration can also impact nearby towns and communities by creating conflict between long-term residents and newcomers (Walker and Fortmann, 2003) or between growing local communities and broader regional interests (Steinberg and Clark, 1999). For example, new investments in infrastructure, such as roads and other public services, may be built to accommodate exurbanization, which may in turn cause various types of landscape change (Forman and Alexander, 1998; Langen et al., 2009; Vukomanovic et al., 2013). And those changes depend on multiple drivers of exurbanization, where different preferences lead to different outcomes.

While a general understanding of the drivers of exurbanization is emerging (e.g. Gosnell and Abrams, 2011; Kondo et al., 2012; Mueser and Graves, 1995; Nelson, 1992; Rudzitis, 1999), little is known about how individual preferences for new home sites are manifested in the spatial distribution of landscape change. Interviews, surveys, focus groups, and other narratives have provided valuable place-based information and context, though these studies by design have not been able to translate their findings to explain spatially explicit patterns of exurban development (Walker, 2011). Whether by norms of disciplinary practice or protocols designed to protect participant identity, location information is seldomly reported from narrative and survey data in exurban studies. And geographical and demographic analyses of exurbanization thus far have relied largely on Census data aggregated to the county level (Hansen et al., 2005; McGranahan, 2008; Rudzitis et al., 2011). Aggregated analyses are valuable for understanding broader-scale regional trends, but miss individual perspectives and the specific features of the natural and built environment that attract amenity migrants. For example, amenity migrants who are looking for a sense of community and rural small-town life likely want to increase their interactions with other members of the community, potentially leading to some clustering of homes and businesses and/or greater home visibility. Alternatively, those searching for privacy and solitude likely want to minimize their local interactions with others and seek some measure of “invisibility” in the landscape more likely found through dispersed development. In summary, new approaches are needed to understand how the individual preferences of amenity migrants are spatially distributed at landscape scales, to assess the relative importance of built and natural landscape drivers, and to anticipate future patterns of exurbanization and accompanying landscape changes.

Viewscapes are the visible portions of a landscape that create a visual connection between people and their surroundings (Vukomanovic et al., 2018). Studies of visual quality and landscape amenity drivers, which inform both the theory and practice of landscape and urban planning, rest on the premise that people form important visual connections with their environment and that these connections inform choices, such as house location. These choices are complex and many factors related to both visual quality preferences and other constraints (zoning, home price, well/water availability, etc.) will inform a single house location decision. Among visual quality preferences, trade-offs may exist between desired features. For example, the desire for expansive, vista views (Nasar et al., 1983; Ulrich, 1986) may stand in juxtaposition to the yearning for privacy and solitude (Kondo et al., 2012), because seeing a large viewscape area might also mean that the observer is similarly visible to surrounding neighbors. Similarly, in mountainous or semi-arid regions, the common and widespread preference for greenness (Ode et al., 2009; van den Berg et al., 2003) may be met in low-lying riparian areas, however views of complex terrains - those with more variation and richness of landscape elements which are generally considered more appealing (McGranahan, 2008) - may require a home to be located at a less green, higher elevation location. To gain a spatial understanding of visual quality drivers, what is needed are viewscape perspectives that consider the revealed preferences underlying the locations of many homes (e.g. hundreds to thousands).

Exurban development, a unique form of land change motivated by aesthetics, is increasing rapidly and viewscape perspectives can provide important insights about privacy and other visual quality drivers of growth. In this study, we model spatially-explicit connections between viewscape characteristics and home locations in a rapidly exurbanizing region. We ask three questions to understand the extent to which viewscape privacy drives the spatial distribution of exurban houses compared to other elements of visual quality and other types of housing density: 1) Are exurban homes located in the most secluded, private locations with little visibility of neighbors?; 2) Which metrics of visual quality (viewscape privacy, visual scale, greenness, and ruggedness) best explain the probability of exurban development?; and 3) Does the privacy of exurban viewscapes change as a region's population grows? Our goal was not to develop a comprehensive land change model that attempts to explain all drivers of exurbanization, but rather to examine the role of viewscape privacy in the siting of exurban homes - never before considered at landscape to regional scales.

We study the Sonoita Plain of Arizona as an example of a scenic, mountainous region experiencing low-density population growth. Numerous scenic vistas combined with local land-use policies that allow development of low-density housing and private roads make this region well suited to studying drivers of exurban housing. To answer these questions, we mapped the historical and current distribution of 20th and 21st century homes before and after the Great Recession (prior to 2010), compared the roles that viewscape privacy and other elements of visual quality play in the distribution of homes, and modeled the connections between viewscapes and exurban land change post 2010. Application of the model was made possible through a new open-source algorithm that computes spatially continuous, all-possible vantage points (in this study, 1.3 M). Our approach allows planners to visualize wall-to-wall spatial patterns of viewscape drivers across an entire study area.

2. Methods

2.1. Study region

The Sonoita Plain covers 700 km^2 of southeastern Arizona, with rolling hills ranging from 1100 to 1600 m in elevation in the Plain and steep terrain reaching 3000 m in the surrounding Santa Rita and Huachuca Mountains (Fig. 1). The natural landscape includes plant communities of desert grassland, plains grassland and desert scrub vegetation (Bock and Bock, 2000). Residential development is concentrated on private lands in the central Plain where groundwater extraction from a single large aquifer is more available (Vukomanovic et al., 2013). The population of surrounding Santa Cruz County increased 46.5%, 45.1%, 29.3%, and 23.6% each decade from 1970 to 2010 (U.S. Census, 2010), as ranches and rangeland were converted to

[1] Acres of impervious surface (2011 NLCD “Developed Imperviousness” data) per person summarized at the block group level (2010 US Census).

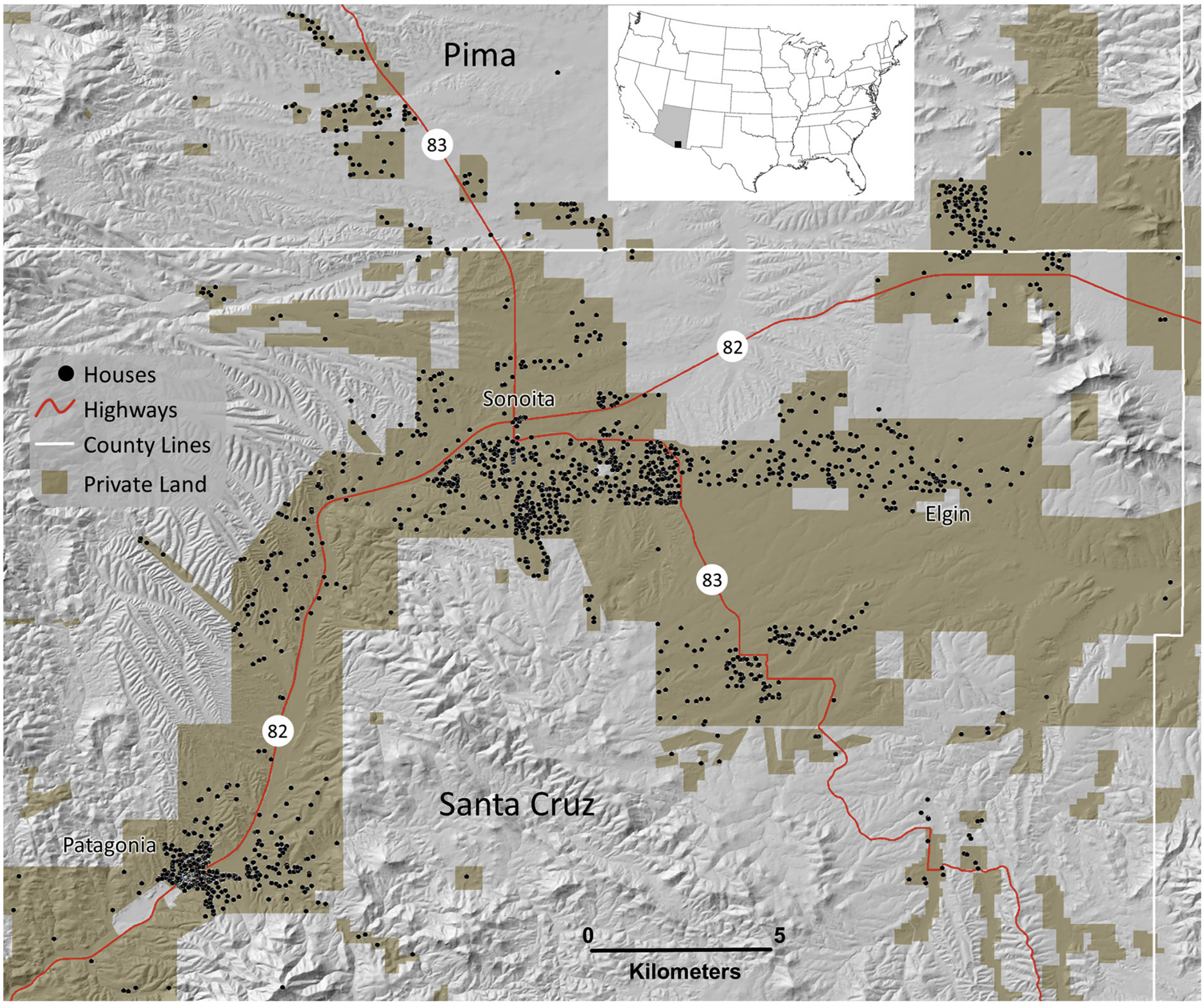

Fig. 1. The Sonoita Plain (700 km^2) in southeastern Arizona is a high plains desert completely ringed by mountains. Removed from urban centers and industry, the Sonoita Plain provides a unique opportunity to study amenity-driven residential development.

residential and limited commercial developments. The region rebounded quickly following the Great Recession housing crash (Ziegler, 2017). Housing prices in the town of Patagonia, for example, increased 9% each year post-2010 (Wood, 2018). With low cost of living, great scenic beauty, and plenty of developable land, the Sonoita Plain has emerged as a booming housing market and destination for amenity migrants seeking new low-density residences and vacation homes. Local real estate companies highlight the region's rural lifestyle, emerging winery/vineyard attractions, and variety of recreational opportunities on public lands (Sonoita Realty, 2016; Wildhorse Realty, 2016).

The region is well suited to the study of exurban drivers as the rugged topography and low-height desert vegetation provide scenic beauty, including numerous scenic vistas, opportunities for recreation, and rural lifestyle amenities (Fig. 2a). The topography of the region allows houses to be nestled between rolling hills, restricting the visibility of neighboring homes and creating perceptions of privacy (Fig. 2b). Further, local land-use policy does not restrict the development of low-density housing and private roads (SCCBD, 2011). Land ownership is roughly 50% public (US Forest Service, Bureau of Land Management, State Lands) and 50% private (ASLD, 2011), with almost all private land zoned for residential development (SCCBD, 2011). Sonoita Plain residents are generally older and wealthier compared to the state of Arizona (US Census, 2010), giving them greater mobility and freedom in their housing decisions. Combined, these factors point to patterns of residential development driven more by individual choice than local or regional planning. These individual choices are reflected in both the spatial distribution of homes (Fig. 1) and in the variety of housing styles found in the Plain (Fig. 2c).

2.2. Housing data and line-of-sight viewscape modeling

We heads-up digitized the historical distribution of suburban, exurban, and rural houses built on private land prior to 2010 using high-resolution (1-m) NAIP aerial imagery. Ownership data was used to delineate the public-private boundary (ASLD, 2011). It is possible for both private and public lands and their respective visual qualities to be a part of exurban viewscapes in the study area. We cross-referenced the digitized houses with 2010 US Census data to match the number of houses mapped to the number reported in each Census block. Using the same digitizing methods, we mapped the distribution of new homes, built between 2010 and 2016, for the statistical modeling described in section 2.3.

We applied open-source GRASS GIS module r.viewshed (Haverkort et al., 2009) to calculate line-of-sight viewsheds for all digitized houses on a 10-m DEM (USGS National Elevation Dataset). Module r.viewshed uses a computationally efficient line-sweeping algorithm and can be run in a high-performance computing environment. We set the observer height at 3-m above the surface to simulate a typical household viewpoint (Fig. 2) and we restricted the maximum visibility distance to 10 km in all directions (Marsh and Schreiber, 2015). Though digital surface models (DSM) derived from lidar data can more accurately measure forested viewscapes (Vukomanovic et al., 2018), this region is

Fig. 2. (A) The amenity-rich Sonoita Plain is characterized by rolling hills, scenic vistas, and abundant recreational opportunities. (B) The rolling topography means that homes are nestled in the hills, creating possibilities for privacy and solitude. The white circle reveals the location of an exurban homesite. (C) Development is driven by individual choice, rather than developers, as reflected in the many different housing styles.

dominated by low-stature desert plant communities that do not significantly impede scenic vistas. Lidar elevation data are not publicly available in this region.

Viewscapes describe the visible portions of the landscape *and* the features therein valued by people (Vukomanovic et al., 2018). We characterized each home's viewscape by calculating the area, greenness (average maximum NDVI), terrain ruggedness (mean TRI), and privacy (number of visible neighbors) as metrics of landscape visual quality important to amenity migrants based on recommendations by Vukomanovic and Orr, 2014. New with this study, we measured the number of visible neighboring homes as a metric of privacy. With the line-of-sight viewscapes approach, the number of (neighboring) homes visible from a given home (vantage point) is the same as the number of homes that can see that vantage point, making this a robust metric for privacy. We calculated viewscape greenness using a composite of maximum NDVI values derived from two decades (1996–2017) of Landsat imagery acquired during annual precipitation and green-up windows, including winter rains (Dec - Feb) and the summer monsoon (July - Sept). At the pixel-level, greenness represents the highest NDVI values (pixel max) and viewscape greenness is the average of the pixel max. TRI quantifies terrain heterogeneity by measuring the sum change in elevation between a cell and the mean of its 8-cell neighborhood (Riley et al., 1999). Mean TRI values for the viewscapes ranged from 0 ("level") to 337 ("moderately rugged").

2.3. Statistical analysis and model development

We used two approaches to quantify the extent to which home locations are spatially clustered at different densities. First, we used Ripley's K-function to quantify spatial clustering over a range of 100 measurement distances (0.1–8 km) (Bailey and Gatrell, 1995). The spatial extent of analysis was limited to areas of private land (Fig. 1). Next, we categorized homes into one of three housing-density classes following recommendations described by Leinwand et al., 2010: rural (0–0.0618 units/ha), exurban (0.0618–1.47 units/ha), and suburban (1.47–10 units/ha).

We compared differences in the area and privacy of viewscapes between exurban, suburban, rural, and randomly located homes (built through 2010) using pairwise Wilcoxon rank-sum tests (non-parametric alternative to the two-sample *t*-test). Using analysis of variance, we compared viewscape privacy, area, greenness, and ruggedness of exurban homes built prior to 2010 to new exurban homes built between

2010 and 2016. Next, we used autologistic regression to assess the combination of visual qualities (privacy, area, greenness, and ruggedness) that best explained the probability of exurban development between 2010 and 2016 based on differences between observed new houses and a matching number of randomly located houses within the privately owned portions of the study region. We also considered the significance of a home's proximity to a primary road to account for the potential importance of accessibility in remote locations. We used an information-theoretic approach to model selection, testing all 21 combinations of variables, and identified the best model based on the set of variables that minimize Akaike Information Criterion (AIC) (*sensu* Quinn and Keough, 2002; Burnham and Anderson, 2002). We only applied the model with lowest AIC score to the spatially-continuous viewscape maps described in section 2.4 below. The autologistic form of ordinary logistic regression allowed our model to simultaneously account for expected spatial dependence in the housing data and avoid autocorrelated residuals (Besag, 1974; Gumpertz et al., 1997).

2.4. Model application with spatially-continuous all-possible viewscapes

Traditional methods for calculating viewscapes use compute-intensive raster algebra techniques which handle each individual viewscape one at a time. This computational challenge limits the practical number of viewpoints that can be calculated (Llobera et al., 2010). We developed an approach to computing spatially-continuous grids of all-possible viewscapes that reduced computational processing times by multiple orders of magnitude. First, we created a regular grid of viewpoints (n = 1,323,696) at 30-m spacing over the 1,188 km^2 study region. Next, we computed all-possible lines-of-sight from each viewpoint using the r.viewshed algorithm and stored the number of visible cells from each viewpoint. We further sped up the process by calculating individual viewscapes and visual quality metrics in parallel in a high-performance computing environment (GNU Parallel; Tange, 2011). Maximum visibility distance was set to 10 km in all directions, and we increased the extent of the DEM to avoid any edge effects. Our open source GIS code and workflows may be found at: https://github.com/petrasovaa/continuous-viewscape-modeling.

3. Results

3.1. Differences among exurban, suburban, and rural viewscapes

Our heads-up digitizing identified a total of 1843 homes in 2010. The Ripley's K-function showed that home locations were significantly clustered across the range of distances (0.1–8.0 km, $p < .001$) with the strongest clustering at 1.9 km (Kdiff = 4801.2). Based on housing density definitions of Leinwand et al., 2010, exurban homes were the most common density type (53.8%), followed by suburban (27%) and rural (19.2%). Exurban homes built prior to 2010 have significantly larger viewscapes than randomly-distributed, suburban, and rural homes (Fig. 3a). Despite having larger area viewscapes, exurban homes were also more private (i.e. fewer visible neighbors) compared to suburban homes or what would be expected by chance (Fig. 3b). Proximity to roads, greenness, and ruggedness did not significantly differ between the two time periods ($p > .05$).

An additional 165 homes were built between 2010 and 2016 with 90.2% located in low-density exurban and rural settings. Analysis of variance shows that the new exurban homes had significantly larger viewscapes ($p = .028$) and possessed greater privacy ($p = .0002$) compared to homes built prior to 2010 (Fig. 4).

3.2. Auto-logistic model of exurban land change

The best multivariable auto-logistic model (lowest AIC) showed that the probability of exurban development between 2010 and 2016 was negatively associated with the number of visible neighbors (viewscape privacy; std. coeff = −1.205) and distance to roads (std coeff = −6.071) and positively associated with viewscape area (std coeff = 0.774) and greenness (std coeff = 0.592) ($r^2 = 0.40$, AIC = 287.9; spatial autocovariate std. coeff = 1.946). This lowest AIC model did not include terrain ruggedness of exurban viewscapes. Application of the lowest AIC model to the spatially continuous grids of viewscape metrics and road proximity (Fig. 5) produced a map of the probability (or suitability) of exurban development across the study region. 43% of private land (177 km^2) has a predicted probability greater than 50 percent. Fig. 6 plots relationships between each individual variable and the probability of exurban development.

4. Discussion

More than simply lower-density suburbia (Davis et al., 1994), exurban development is a unique, yet growing trend driven by individual choice and shifting land-use incentives (Gosnell and Abrams, 2011; Kondo et al., 2012; Mueser and Graves, 1995; Rudzitis, 1999). But the manner in which individual preferences manifest in landscape patterns of exurbanization has received little attention. In this study, we examined the roles played by viewscape privacy and other elements of visual quality and found that i) exurban homes in the Sonoita Plain of Arizona have both larger and more private viewscapes compared to those in suburban settings or what could be expected by chance, ii) the size and privacy of exurban viewscapes increased over time, and iii) viewscape privacy was more strongly associated with the probability of exurban home locations than other metrics of visual quality. Finally, using efficient data processing and parallelization, we developed a new open-source approach to computing spatially continuous, all-possible viewscapes in a region. Overcoming the computational challenge of calculating numerous viewscapes allowed us to apply our model to every pixel in the study region and more thoroughly evaluate relationships between viewscapes and land change through measurement and visualization of large-area patterns.

Exurban homes have larger and more private viewscapes compared to other residences and what would be expected by chance (Fig. 3), suggesting that exurbanites are carefully selecting the location of their home to optimize aesthetics and expression of their individual choices. This is consistent with exurban literature that natural amenities in some areas are more important reasons for relocation than cost of living or job opportunities (Hansen et al., 2005; Rudzitis, 1999). For example, occupying the undeveloped exurban frontier requires significant infrastructure, including construction of new roads and drinking water systems (Naeser and St. John, 1998). Our finding that exurban homes are located in the most secluded, private locations (Fig. 3b) further underscores the importance of aesthetics and individual choice in exurbanization. This result is not due to lower housing density alone; the average density of exurban homes is almost five times the density of what would be expected by chance. If exurban homes were located without consideration of visual scale, it would be reasonable to expect no difference between the size of exurban viewscapes and randomly-located homes. By comparison, rural homes in the Sonoita Plain occupy the largest properties, lowest density settings, but not the largest viewscapes. Most rural homes were built in the 20th century for agricultural operations and as such consideration of visual quality was likely dwarfed by needs for land productivity and access to water (Bahre, 1991; Bock and Bock, 2000).

Our finding that the newest exurban homes are being built at locations with yet larger viewscapes suggests an enduring preference for expansive, scenic views in the American Southwest. Even in the aftermath of the Great Recession, exurbanites are motivated to seek the aesthetic amenities afforded by expansive vistas. In recent decades prior to 2010, growth of low-density housing reflected a mix of amenity-driven residential development and homes associated with agricultural operations, primarily ranching (Bock and Bock, 2000). Newly-arrived amenity migrants, on the other hand, are solely constructing primary

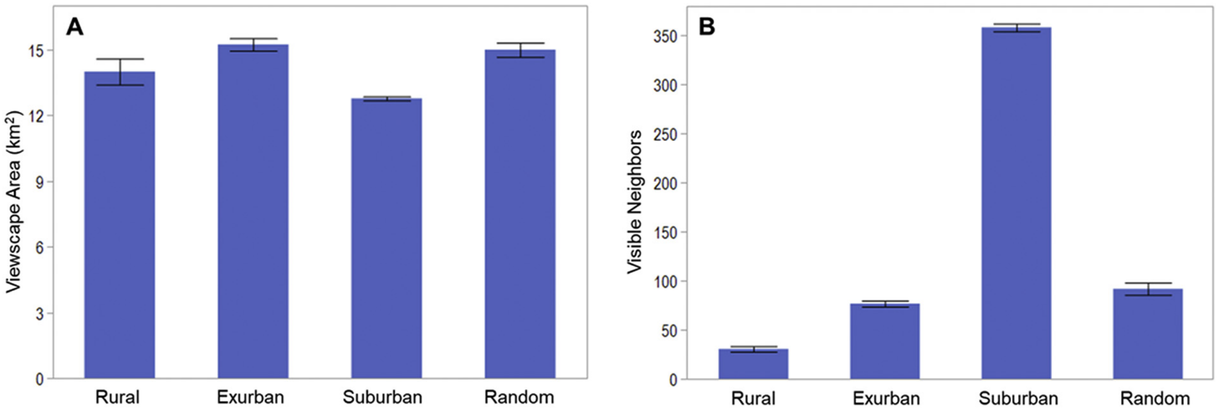

Fig. 3. (A) Mean viewscape size by housing density (Wilcoxon rank sum test: $p = .0007$), and (B) mean number of visible neighbors by housing density (Wilcoxon rank sum test: $p < .0001$) of homes built prior to 2010. Bars represent standard error of means.

and secondary residences that reflect their personal and aesthetic preferences. These new homes have both more expansive vistas and more privacy than earlier exurban homes. Even as the population and the number of houses grows, the trend that exurbanites are finding ways to be more secluded speaks to the importance and endurance of privacy as an amenity driver. While there are still large amounts of private developable land, exurban privacy may be less obtainable in the future as the region grows. Continued desire for viewscape privacy in new home construction suggests that future in-migrants may need to look deeper into rural working lands for more seclusion, pushing the extent of exurban land use into undeveloped, natural or agricultural landscapes. With 177 km^2 (43%) of the private lands mapped by the probability model as high *suitability* (i.e. prob > 0.5), the region could accommodate substantial landscape change in coming decades in the absence of alternative planning.

Viewscapes have been considered in a range of landscape assessment applications, from the visual impacts of clear-cut timber harvests (Chamberlain et al., 2015) and wind turbines (Maslov et al., 2017) to understanding willingness-to-pay for scenic preferences in a mountain region (Grêt-Regamey et al., 2007). To our knowledge, this is the first broad-scale viewscape study with many replicate observations of the role privacy plays in landscape change. For example, through surveys Kondo et al. (2012) and Hines (2007) found that privacy was a motivation for western amenity migrants to migrate or purchase real estate, but they did not correlate the responses to models of viewscape conditions. Though we have no data on stated preferences, our auto-logistic model considers several commonly studied metrics of visual quality across a landscape. Even after accounting for these well-established variables, viewscape privacy was the most important visual quality driver. To date, viewscape calculations have rarely been incorporated into spatially-explicit land change models (e.g. Meentemeyer et al., 2013; Terando et al., 2014), possibly because of the computational challenge of calculating all-possible viewscapes across every pixel in a region. Our approach moves exurbanization and viewscape studies toward a better understanding of the way individual preferences of amenity migrants are spatially exhibited on a landscape.

Privacy, viewscape area, greenness, and proximity to primary roads are the most significant drivers of new exurban development, while terrain ruggedness is not significant after accounting for other variables (Fig. 5). In the Sonoita Plain, greener viewscapes include low-lying riparian areas and mountain tops, two areas that are spatially separated by grasslands and foothills. However, the homes that see the greenest portions of the landscape are themselves most commonly located on the central Plain, which is less green (Fig. 5). Metrics that commonly aggregate measures of greenness to a whole county (e.g. % forest, McGranahan, 2008) would thus likely miss the importance of this amenity at a particular location. As we learn more about emerging preferences from all avenues of amenity migration scholarship, our approach to all-possible viewscape calculations could be used to test where on the landscape those preferences are visible. In turn, model results could help prioritize areas for future infrastructure or accelerate planning of conservation/land protection mechanisms. The visual

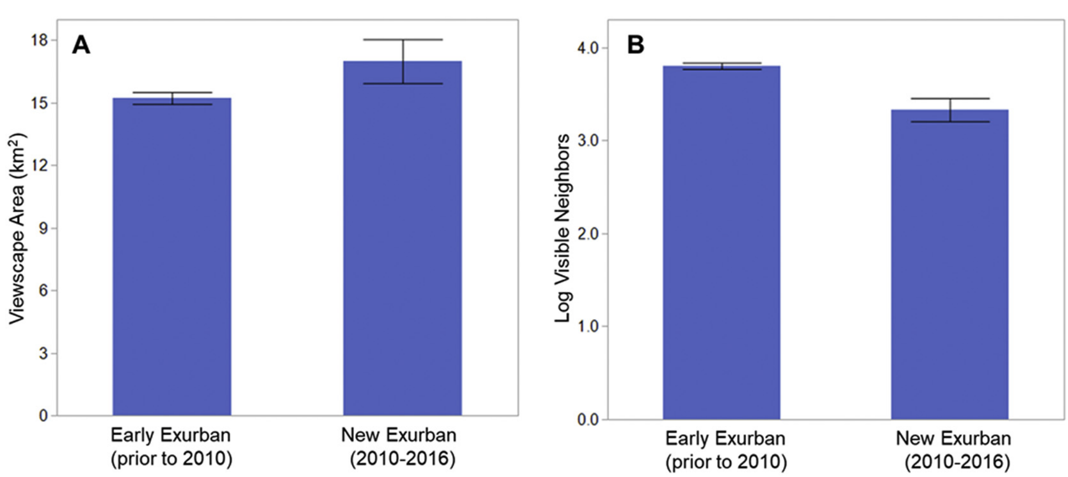

Fig. 4. (A) Mean viewscape area and (B) log mean number of visible neighbors of early exurban homes (built prior to 2010) compared to new exurban homes (built 2010–2016). Privacy increases as the number of visible neighbors decreases. Bars represent standard error of means. Number of visible neighbors was log-transformed to meet parametric assumptions of ANOVA.

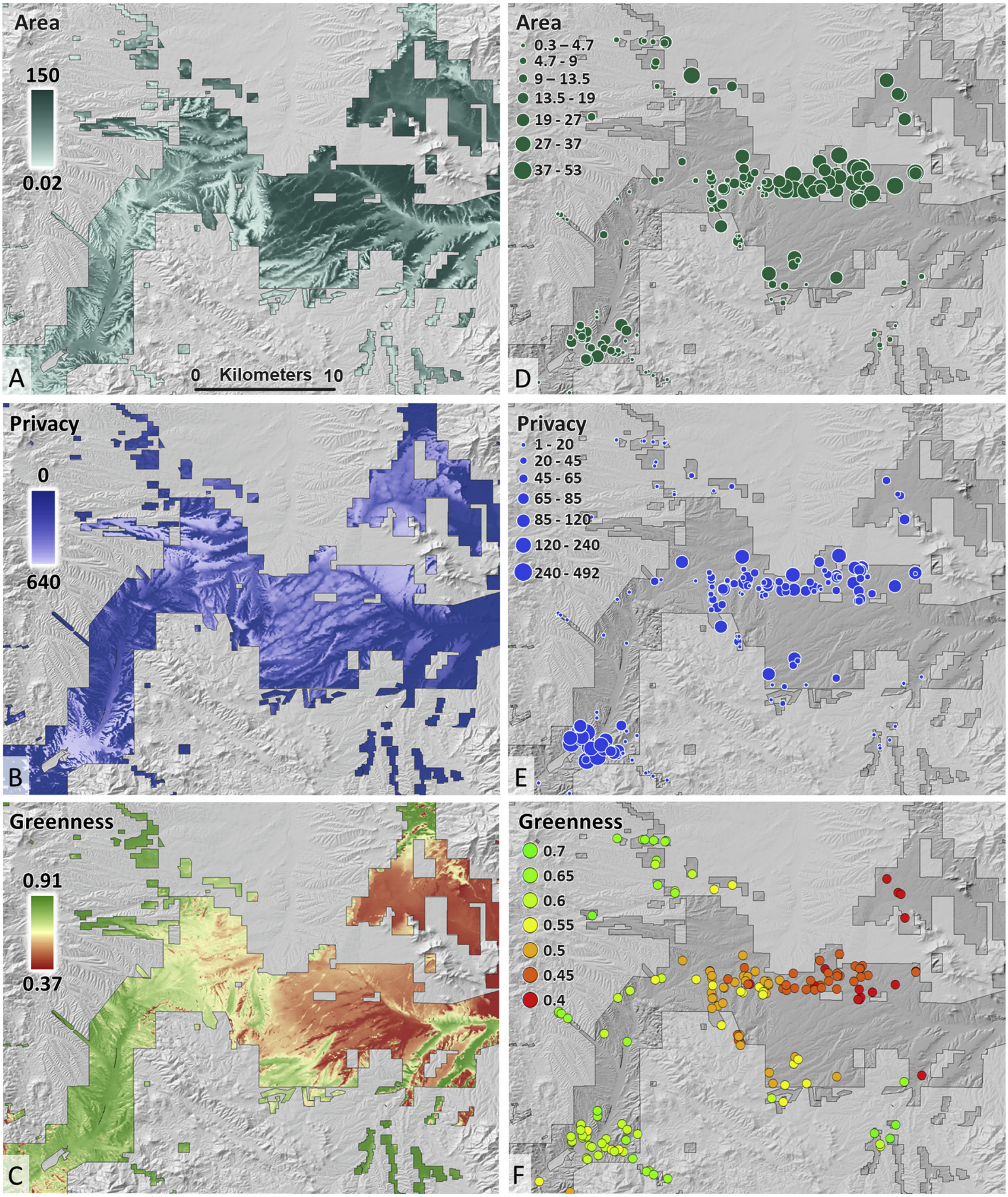

Fig. 5. Continuous, all-possible viewscapes of (A) area (km^2), (B) privacy (number of visible neighbors), and (C) greenness (average maximum NDVI) on developable land. The all-possible viewscape coverage computes viewscapes at 30-m intervals for continuous study area coverage and model application. Proportional circles illustrate the area (D) and privacy (E) of individual viewscapes seen from exurban homes built between 2010 and 2016. Graduated colors (F) illustrate the greenness of those individual viewscapes.

quality metrics applied here are well established and performed well in an arid, exurbanizing environment. The metrics selected provide direct measures of visual quality within the 2000+ viewscapes evaluated. Vukomanovic and Orr (2014) provide extensive review of the visual quality literature and selected visual scale (area), greenness (NDVI) and complexity (terrain ruggedness) as important metrics that could be tested at landscape scales for 1000s of vantage points. In this research, we add privacy as a fourth metric of visual quality. In other environments, additional factors such as landscape mosaic or the visibility of hedges and tree lines (van Zanten et al., 2016) may be important metrics of visual quality. Regions where exurbanization is well characterized, such as the US Sierra Nevada (e.g. Loeffler and Steinicke, 2007) or Yellowstone/Montana (e.g. Hines, 2007), may provide opportunities to incorporate understandings of new types of visual quality drivers gleaned from local perspectives into spatially-continuous viewscape models.

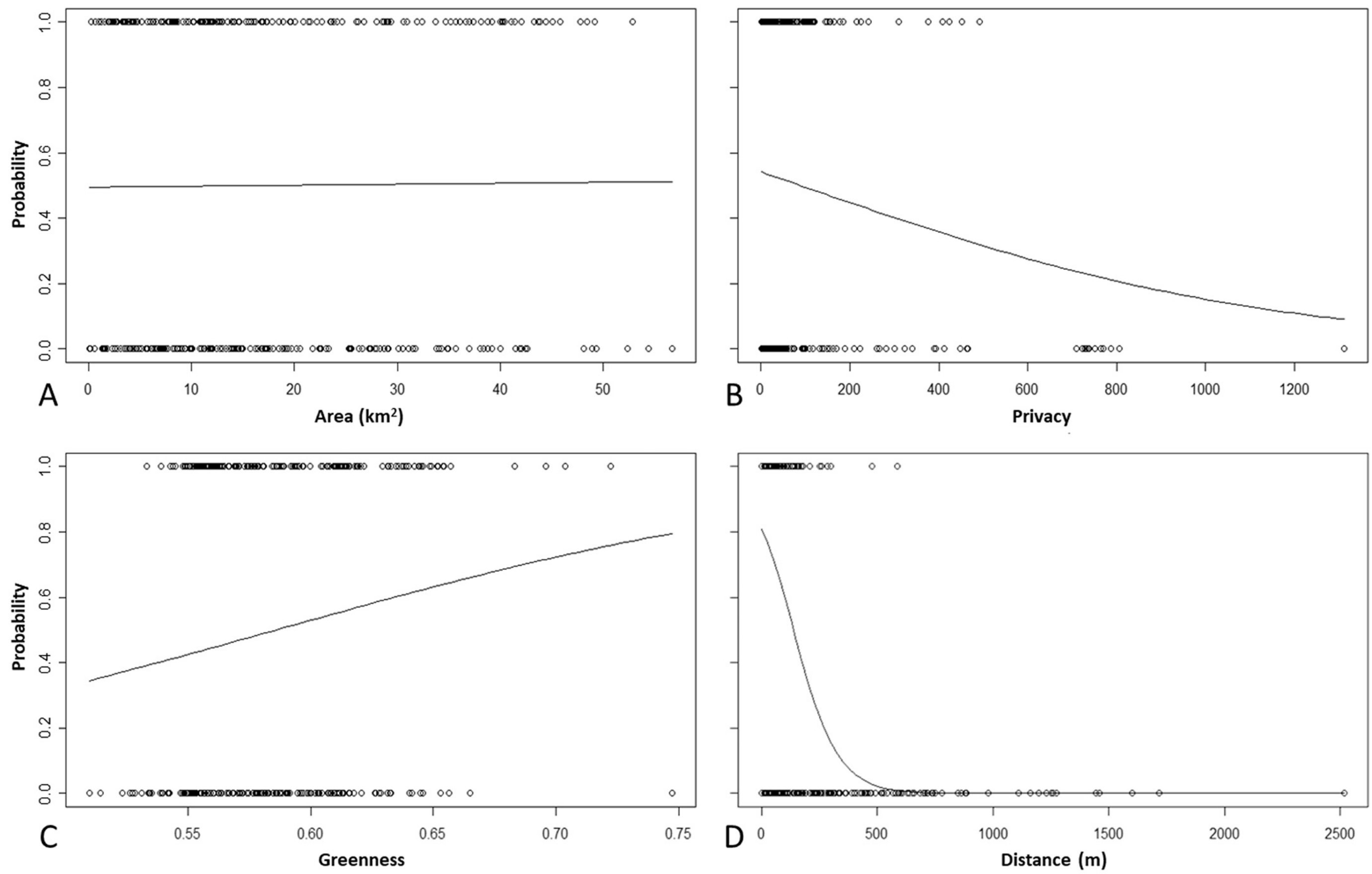

Fig. 6. Relationships between probability of exurban development between 2010 and 2016 and viewscape (A) area (km^2), (B) privacy (number of visible neighbors), (C) greenness (average maximum NDVI), and (D) distance (m) to nearest road (1 s = distribution of observed new houses; 0 s = distribution of randomly located houses).

Application of the model shows high probability of exurban development in a) northeastern Sonoita Plain, b) the central east portion of the Plain (near the town of Elgin), and c) pockets of the northeast Sonoita Plain (Fig. 1). Other pockets of high(er) development probability occur throughout the study area where steep topography creates privacy or verdant canyons form part of the viewscapes. The protected lands of the Coronado National Forest surround the Sonoita Plain to the east and south and the Las Cienagas National Conservation Area forms a development boundary to the northeast. Areas with the highest probabilities of development abutt Las Cienagas in the northeast and the Coronado in the southwest portions of the Sonoita Plain. The "sky islands" of the Sonoita Plain range in elevation from 915 to 3300 m and support plant communities as biologically diverse as those encountered along a latitudinal gradient of Canada to Mexico. This diversity of plants and animals (> 7000 species) includes many rare and endemic species (Sky Island Alliance, 2018). Demand on scarce water resources (Bahre, 1991; Glennon and Maddock, 1994) and the direct impacts of houses and roads on wildlife (Forman and Alexander, 1998) raise concerns about the impacts of projected development. The natural and scenic amenities of these protected areas increase the desirability and the probability of continued exurban development, putting those same amenities and values at risk.

Our finding of higher development probabilities near protected areas augments earlier work describing the amenity draws of public lands for housing development (Joppa et al., 2008; Radeloff et al., 2010) by explicitly considering visual quality. It also suggests opportunities for future research on the importance of public lands within viewscapes. As public lands are not created equal—National Parks and wilderness areas have permanent protection from conversion of natural land cover and mandated plans to maintain a natural state, while extractive activities and grazing are allowed on some US Forest Service and Bureau of Land Management lands (USGS GAP, 2016)—future work could explore how to weigh these different types of public lands. The importance of public lands within viewscapes will likely depend on the environment, where complementary regional perspectives could strengthen our overall understanding of viewscape preferences.

Location matters in exurbanization where the spatial configuration of houses, roads, and associated infrastructure greatly depend on the drivers of in-migration preferences. Different patterns of exurban growth have different impacts on both ecosystems and rural communities. Spatially-explicit information about landscape drivers and exurban preference could prove helpful for infrastructure planning and growth management efforts. Over time, more densely populated exurban areas may start to attract different amenity migrants, such as those searching for community and small-town life. Questions about trade-offs and tipping points are a fascinating frontier in the growing body of amenity migration research. We believe that a viewscapes approach to understanding land change, guided by the meteoric increase in computing power and new geospatial modeling techniques, hold great promise to not only shed light on individual drivers but to help anticipate trade-offs between the positive and negative outcomes of amenity migration and landscape change. If people have to choose, what is more important?

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