Urban influence on changes in linear forest edge structure

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ABSTRACT

Urbanization has been a significant cause of deforestation throughout the latter half of the 20th century, and given global demographic trends, the conversion of forested land to urban uses will likely continue. California has had a long history of converting forests, and urbanization has been one of the principle drivers. While many studies have examined how urbanization alters forest landscape structure at landscape or regional scales, little is known about how urban development influences linear forest edge structure at local scales where individual homeowner decisions dominate. We studied how forest edges at two California coastal oak woodlands (Pacheco Valle (PV) and China Camp (CV)) in the San Francisco Bay Area in California changed in the decades following urbanization. Using remote sensing and object-based image analysis, we isolated 20 urban-forest edges per site and quantified each edge's complexity (measured by sinuosity) for three time points at each site. Edges exhibited low sinuosity immediately following development (PV = 1.584, CC = 1.5625), but grew significantly more complex (in 2003 PV = 1.8705, CC 1.906). Linear forest edge structure at both sites, despite different development dates, showed similar and statistically significant increases in sinuosity by 2003. We attribute the initial, more linear structure to mortality and trunk or canopy damage caused by construction, while ascribing the later, more complex structure to tree recruitment, canopy expansion, and homeowner actions that influence natural processes.

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1. Introduction

Forests are one of the most threatened land cover types in the world. Globally, more than nine million hectares of forested land was converted to other uses in the 1990s alone, representing the loss of 2.4% of all forest area (United Nations, 2002). Urbanization is one of the many processes converting forest land to developed uses, but is one that deserves special consideration. Urban areas have greatly expanded in the last 50 years, a trend that is expected to continue—the urban annual growth rate for 2010–2015 estimated to average 1.91% globally (United Nations, 2008). Not only does urbanization consume forested land, it increases habitat fragmentation at landscape scales (McKinney, 2002, 2006). Forest edges are one consequence of fragmentation, and their introduction can significantly alter forests through changes in species composition, overstory mortality, and recruitment (Harper et al., 2005). Our study investigated how linear forest edge structure is affected by urban development.

In California, the conversion from forests and rangelands to residential or agricultural uses in California began on a limited scale in the 16th and 17th centuries and has continued in recent decades. Losses, especially those in recent years, have been most evident in the San Francisco Bay Area, San Joaquin Valley, Sacramento Valley, South Coast, and Delta bioregions (California Department of Forestry and Fire Protection, 2003).

The San Francisco Bay Area has experienced massive urban development in the past 70 years, with 12% of the former forest and rangeland converted to housing (California Department of Forestry and Fire Protection, 2003). The region's population currently stands at 6.8 million people and is projected to rise to 10.2 million by 2050 (State of California, 2007). Oak woodlands have been a historically important land cover type in the California, covering around 25 percent of all forested land in the state. The original area covered by oak woodlands has been significantly reduced, from 4 to 4.85 million hectares before European settlement to around 2.83 million hectares today (Thomas, 1997). Urbanization further threatens woodlands, especially those managed as rangelands. The bulk of oak woodlands in California are owned in large holdings, but subdivision and other development has been driving the trend toward more owners of smaller parcels. Many large landholders sell their properties to developers, fragmenting the landscape while upending existing management practices (Huntsinger et al., 1997; Standiford and Barry, 2005).

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1.1. Quantifying landscape change

Quantifying the changes wrought by such development can help scientists understand how urban edges influence primary (e.g. mortality, canopy damage) and secondary (e.g. recruitment, canopy expansion) forest responses to disturbance (Harper et al., 2005). Quantifying geometrically complex landscape objects like coastlines, mountains, and fluvial systems has been difficult in the past (Andrle, 1996), but increases in computing power have made such analyses widespread. Many studies now seek to understand past changes by using landscape metrics in conjunction with historic and current aerial photography and satellite imagery (e.g. Coppin et al., 2004; Desclée et al., 2004; Lu et al., 2004; Lunetta et al., 2004). The observed changes are often quantifiable using landscape metrics like fractal dimension and its derivatives.

Since its introduction by Mandelbrot (1967), the fractal dimension (D) of a line or surface has become an accepted technique to describe irregular shapes in nature (Jiang and Plotnick, 1998). Landscape metrics have incorporated measures from both information theory and fractal geometry (Mandelbrot, 1983) based on a categorical, patch-based representation of a landscape (i.e. nonlinear surfaces of differing composition). Landscape metrics are often used to quantify the spatial heterogeneity of individual patches (Herold et al., 2005). In landscape ecology, they measure the shape and pattern of vegetation in natural landscapes (Gustafson, 1998; Hargis et al., 1998; Neel et al., 2004). Spatially explicit metrics are typically computed as patch-based indices (e.g. size, shape, edge length, patch density, fractal dimension) or as pixel-based indices (e.g. contagion, lacunarity) computed for all pixels in a patch (Gustafson, 1998). Fractal dimension and shape index are two patch-based metrics in landscape ecology that describe the complexity and fragmentation of a patch, typically as a function of its perimeter and area (Farina, 2007). In fractal dimension, for example, landscapes composed of simple geometric shapes will have a small fractal dimension, approaching 1.0. If the landscape contains patches with complex and convoluted shapes, the fractal dimension will be large (O'Neill et al., 1988).

The study of landscape changes is a major application of bulk (or area-based) fractal dimension in ecology (De Cola, 1989; Krummel et al., 1987; Lam, 2005; Peng et al., 2006). Fractal dimension has been applied to measure growth of urban areas (Shen, 2002; Zuo et al., 2007) and urban morphology (Thomas et al., 2008; Zhang et al., 2007) to better understand them as processes. While some studies show urbanization decreases the fractal dimension of a landscape at large scales (De Cola, 1989; Krummel et al., 1987; O'Neill et al., 1988; Turner et al., 1989), others have found different results on smaller scales. One study of urban development in Santa Barbara, California, documented changes in urban structure from historical air photos, calculating six different metrics for each point in the time series (Herold et al., 2002). Fractal dimension increased over time, reflecting greater spatial complexity as a function of urban growth and building density. Fractal dimension also increased in forest patches adjacent to afforesting old fields (Narumalani et al., 2004). Several other studies have used area-based fractal dimension to quantify deforestation (Ewers and Laurance, 2006), forest fragmentation (Kojima et al., 2006), and forest structure (Imre and Bogaert, 2004; Kostylev et al., 2005; Motisi et al., 2004).

1.2. Quantifying linear landscape features

Linear shape metrics can capture meaningful information from one dimensional features, and linear fractal dimension and sinuosity are two common ways to quantify the complexity of these shapes. The first, linear fractal dimension, stems from Mandelbrot's pioneering work with fractals (Mandelbrot, 1967). It has been widely used in studies measuring the complexity of various coastlines (e.g. D'Alessandro et al., 2006; Dai et al., 2004; De Pippo et al., 2004; Jiang and Plotnick, 1998; Tanner et al., 2006), but Klinkenberg (1994) has an extensive review of many other applications. The second, sinuosity, has seen wide application in the field of hydrology. Hydrologists typically use sinuosity to help quantify the degree to which a stream or river meanders (e.g. Constantine and Dunne, 2008; Langbein and Leopold, 1966; Mueller, 1968; Schumm, 1963; Stølum, 1996). It can also help infer details about processes at work within a riparian system. A meandering stream, for example, will have a high sinuosity index and infer certain patterns of sedimentation and erosion (Mueller, 1968). Sinuosity values can range from one to infinity, but realistic values range from around 1.0 to ≈3.5 (Schumm, 1963; Stølum, 1996).

While both fractal dimension and sinuosity describe the complexity of linear features, fractal dimension also measures the feature's degree of self-similarity. Self-similarity describes the degree to which an object (like a line or an edge) is exactly or approximately similar to a part of itself (i.e. the whole has the same shape as one or more of the parts) (Mandelbrot, 1967). Study systems without apparent self-similarity (or a reasonable range of scales over to test fractal geometry) are poorly described by fractal dimension (Halley et al., 2004). Sinuosity, on the other hand, does not quantify self-similarity, only the complexity of the shape.

Most studies measuring forest changes like fragmentation and deforestation have used a patch-based approach (e.g. Haines-Young and Chopping, 1996; Wickham et al., 2007). Such metrics are appropriate at large scales, but many microclimatic processes that dictate forest edge effects operate on smaller scales—typically 10–150 m deep measured perpendicular to the edge (Camargo and Kapos, 1995; Chen et al., 1992; Davies-Colley et al., 2000; Kapos, 1989; Matlack, 1993), but some studies have reported effects as deep as 240 m (Chen et al., 1995) and even 500 m (Laurence, 1991). (Harper et al., 2005 offers an excellent review of many studies related to depth of edge influence.) Since many forest patches are more than 150 m deep, area-based shape metrics may dilute important changes at one forest edge by including measurements from an unaffected edge.

1.3. Objectives and hypotheses

We were interested in how suburban development influenced small-scale changes in linear forest edge structure in two coast live oak woodlands in the San Francisco Bay Area. Specifically, we were interested in how post-development changes manifest themselves on the immediate forest edge—the contact zone between the forest and non-forest—at spatial scales meaningful to urban and suburban land uses (one city block, or 80 m parallel the edge as the crow flies) over long time periods (decades). We chose sinuosity to measure these responses based on the scale of our measurements and the lack of meaningful self-similarity at the city block scale (Halley et al., 2004). We investigated two main questions: Were the linear forest edges at each site similar immediately following suburban development? Did they exhibit similar changes in the decades that followed development? We hypothesized that the forest edges would have low sinuosity immediately following development to progressively higher sinuosity over the entire time frame of the study.

2. Materials and methods

2.1. Study site

We acquired imagery for three dates for each of two sites in Marin County, California—Pacheco Valle and China Camp—located 28 km and 22 km north of San Francisco, California, respectively (Fig. 1). The two sites were chosen for their well documented
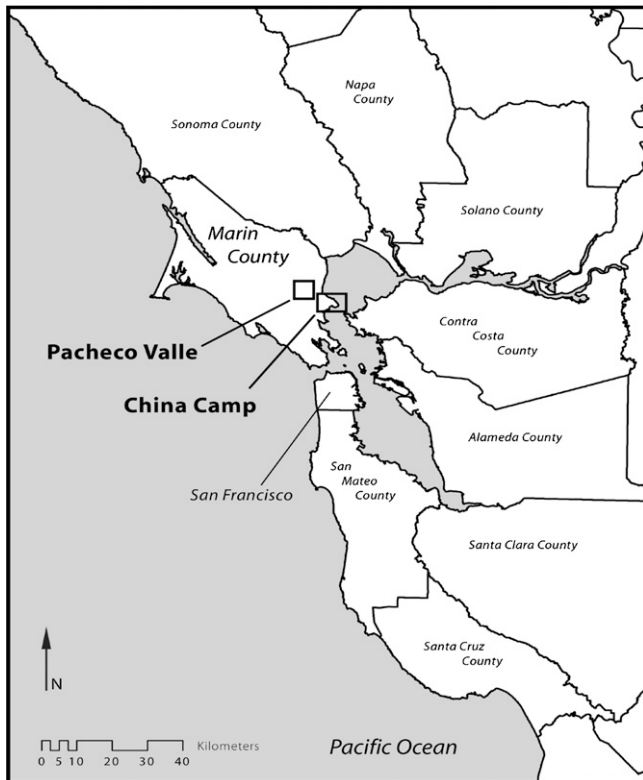
Fig. 1. The study sites, Pacheco Valle and China Camp, are located in Marin county 28 km and 22 km north of San Francisco, California.

housing developments and near continuous canopy coast live oak woodland. Both sites are characterized by *Q. agrifolia*, *Q. kelloggii*, and *Q. lobata* along with *Arbutus menziesii* and *Umbellularia californica*. Both sites feature moderate to steep topography, with Pacheco Valle ranging from 50 m to 350 m in elevation and China Camp rising from sea level to 300 m.

Pacheco Valle refers to both a residential subdivision in a canyon and the protected open space land that surrounds the development. The canyon bottom was developed in the late 1970s and early 1980s in a series of stages that began with condominiums built around a circular road with single-family housing built off a spur road heading north from the condominiums. According to the aerial photographs, the development process removed all vegetation from the house sites prior to construction.

China Camp State Park along with the adjacent Henry Barbier Park and San Pedro Ridge Reserve form continuous protected open space (hereafter "China Camp") bordered by the city of San Rafael, California, on the south and west sides. San Pablo Bay bounds the open space to the north and east. Two single family housing developments encroach on China Camp's boundaries. One is located in the western half of China Camp, and stretches up a canyon and its western slopes. The second is located in the eastern half and begins at the common opening of two canyons, and then extends up into the two canyons. The first subdivision was developed in the late 1950s and the second in the mid- to late-1960s. Construction followed the same approach as Pacheco Valle.

2.2. Imagery acquisition and registration

We acquired three images each for both Pacheco Valle and China Camp. The first image was taken from the early stages of housing construction (1975 for Pacheco Valle, 1968 for China Camp). The second and third images for each site were taken from the same years, 1982 and 2003. We used a mix of black-and-white (B&W)

Table 1
Summary of information on the aerial photographs used in this study. NASA Ames is the National Aeronautics and Space Association Ames Research Center, and the U.S.G.S is the United States Geological Survey.

	Date	Type	Scale	Agency
Pacheco Valle	May 28, 1975	Color-IR	1:30,000	NASA Ames
	January 6, 1982	Black & White	1:10,000	U.S.G.S.
China Camp	April 16, 1968	Black & White	1:30,000	U.S.G.S.
	January 7, 1982	Color-IR	1:48,001	NASA Ames

and color-infrared (CIR) aerial photographs for the 1968, 1975, and 1982 depending on availability (Table 1). For the 2003 images, we used IKONOS imagery from GeoEye (GeoEye, Inc., Dulles, VA). All aerial photographs were acquired from the United States Geological Survey EROS Data Center (U.S. Geological Survey, Sioux Falls, SD).

We orthorectified all images using ERDAS Imagine 9.2 software (ERDAS, Inc., Atlanta, GA) and its Image Geometric Correction tool with a minimum of 18 control points to tie the images to a 2 m digital elevation model of the San Francisco Bay Area from the National Geospatial-Intelligence Agency. We standardized all aerial photographs at 41 cm resolution and IKONOS images at 1 m resolution. The root mean square error (RMSE) for each orthorectified aerial photograph was below 5 cm based on a minimum of 5 check points.

2.3. Image segmentation and classification

Following orthorectification, we segmented all images using Definiens Professional 5. We segmented the aerial photographs at a scale factor of 100, shape of 0.2, and compactness of 0.5; and the IKONOS images at a scale factor of 50, shape of 0.2, and compactness of 0.5. We later corrected visually interpreted errors of over- or undersegmentation in ArcGIS through manual photointerpretation. Erroneous segments were defined as those that strayed from the photointerpreted forest edge by more than 1 m.

To classify the aerial photographs, we exported the object vectors to a shapefile and imported them into ArcGIS along with the orthorectified images. At that point, we manually labeled the object polygons into two classes, Woodland and Not Woodland.

Since the IKONOS images contained more consistent and reliable spectral information than the aerial photographs, we used Definiens Professional's rule-based fuzzy classification system (see Table 2 for a list of classes and features used). We later condensed the resulting classes into Woodland and Not Woodland and manually relabeled erroneous polygons (e.g. irrigated grasslands that were misclassified as trees).

2.4. Edge selection, extraction, and sinuosity calculation

Once we were satisfied with the land cover classifications, we dissolved the boundaries between polygons of the same class. Then we changed the polygon borders into lines and clipped the lines to 20 segments per site 80 m in straight-line length (the length of a city block).

We chose the 80 m segments based on the following five criteria: (1) The segment must be a continuous forest canopy bordering

Table 2
Classes (left) with the bands (Red, Minimum pixel value of NIR), enhancements (NDVI), and other spectral information (brightness).

Class	Features used
Woodland	NDVI
Irrigated grass	NDVI, Red, Minimum pixel value of NIR, Brightness
Not vegetation	NDVI
Shadows	Brightness

a residential development. (2) The segment must be on a straight forest edge (end- and midpoints can only deviate slightly from a straight line). (3) The edge must be present in all three images. (4) It must not include any substantial image warping or tearing introduced by the orthorectification process. (5) Residential development must have begun within the five years before the first image was taken. Twenty segments matched these criteria at Pacheco Valle and twenty at China Camp. Edge sections ranged from directly adjacent (<1 m) to distant (>250 m). To calculate sinuosity, we took the path-length of each segment and divided it by its straight-line length (80 m for each).

We also assessed which edges advanced or retreated from their previous time point. Edges where the forest encroached on non-forest land over 50% or more of their length were said to advance; those where the forest retreated from the previous time's position over 50% or more of their length were said to retreat.

2.5. Statistical tests

We imported the results of the sinuosity calculations into R, an open source statistical software package (R Development Core Team, 2009). The data were significantly non-normal, so we used the Wilcoxon rank sum test to test for differences between the different time points at each site. At Pacheco Valle, for example, we compared 1975 with 1982 and 2003, and 1982 and 2003 with each other. We also tested for differences between the common time points, 1982 and 2003, for both sites. Finally, we ran a linear regression to determine rates of change in sinuosity.

3. Results

We identified 20 forest edges at each site created or modified by suburban development that persisted through to 2003. Edges at both sites were relatively straight immediately following development. Sinuosity for Pacheco Valle and China Camp were statistically similar ($p = 0.72$, Wilcoxon rank sum) in the development phase (1968 at China Camp, 1975 at Pacheco Valle), and were again statistically similar ($p = 0.97$) in 2003.

There were differences in 1982, however (Table 3). The edges at Pacheco Valle were only seven years old, and the sinuosity was still relatively low (mean = 1.588 ± 0.077). China Camp's edges were 14 years old and more sinuous (mean = 1.754 ± 0.092). These differences are significant, but only with 90% confidence ($p = 0.083$).

3.1. Changes in sinuosity

Changes in sinuosity at each site took place over different time scales (Table 4). The first time period at Pacheco Valle began in 1975

Table 3
Mean sinuosity values for each year at each site (±1 S.E.).

	Development[a]	1982	2003
Pacheco Valle	1.584 ± 0.076	1.588 ± 0.077	1.8705 ± 0.093
China Camp	1.5625 ± 0.061	1.754 ± 0.092	1.906 ± 0.117

[a] Development occurred in 1975 at Pacheco Valle and in 1968 at China Camp.

Table 4
Median changes in sinuosity of the forest edge between three time points.

	Development[a]-1982	1982–2003	Development[a]-2003
Pacheco Valle	–	0.3225[*]	0.2725[*]
China Camp	0.1575[*]	–	0.265[*]

(–) No significant differences.

[*] $p < 0.05$.

[a] Development occurred in 1975 in Pacheco Valle and in 1968 in China Camp.
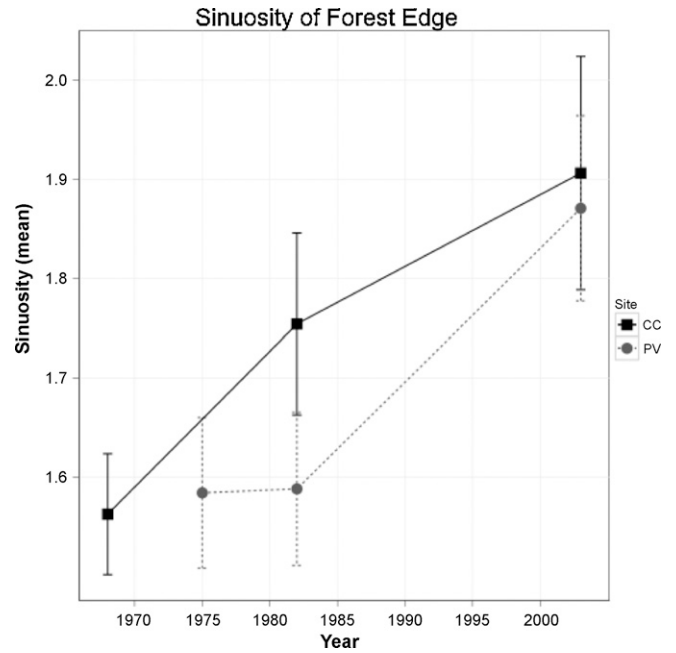

Fig. 2. Mean sinuosity of forest edges at Pacheco Valle (circles, dashed line) and China Camp (squares, solid line). Error bars represent one standard error.

was only seven years long, and thus no significant changes in sinuosity took place. In the following 21 years, sinuosity of Pacheco Valle's edges changed significantly and substantially. The median change over that time was 0.3225, by far the largest median change of the entire study. Over the entire 28 years at Pacheco Valle, the median change was 0.2725. The changes at China Camp reflect the different time scale over which we investigated those changes. Following development in 1968, sinuosity at China Camp increased over the next 14 years by a median change of 0.1575. Sinuosity continued to increase between 1982 and 2003 (Fig. 2), but not by a statistically significant amount. The median change at China Camp for the 35 years in this study was 0.2625. While both sites ended up with similar sinuosity measures, sinuosity at China Camp increased at a more measured pace than Pacheco Valle, which increased significantly between 1982 and 2003.

Linear regression of sinuosity changes over the years, while poor at explaining variation in the data, shows significant trends at both sites. At Pacheco Valle, sinuosity increased by 0.012 per year between 1975 and 2003 ($p = 0.0078$). At China Camp, it increased by 0.0085 per year between 1968 and 2003 ($p = 0.018$).

Sinuosity of the forest edges at Pacheco Valle remained nearly constant in the years immediately following development (1975–1982). After 1982, though, sinuosity increased. At China Camp, edge sinuosity increased quickly between 1968 and 1982, but that pace slowed between 1982 and 2003 (Fig. 2).

3.2. Advancing and retreating edges

The number of edges that advanced or retreated varied between sites and over the different time periods (Table 5). At Pacheco Valle, only four of the 20 edges advanced between 1975 and 1982, while 14 advanced between 1982 and 2003. Over the entire study (1975–2003), nine edges advanced at Pacheco Valle. China Camp's edges were very different. Between 1968 and 1982, advancing edges (10) matched declining edges (10). In the second period (1982–2003), 18 edges advanced. And over the entire study (1968–2003) at China Camp, 15 edges advanced—a sharp contrast to Pacheco Valle. There was no significant link between sinuosity and advancing or retreating edges except at China Camp

Table 5
Number of advancing edges vs. retreating edges over the three time spans.

		Development[a]-1982	1982–2003	Development[a]-2003
Pacheco Valle	Advancing	4	14	9
	Retreating	16	6	11
China Camp	Advancing	10	18	15
	Retreating	10	2	5

[a] Development occurred in 1975 in Pacheco Valle and in 1968 in China Camp.

between 1982 and 2003, where advancing edges were more sinuous. Advancing edges outnumbered retreating edges between 1982 and 2003 at both sites, but the retreating edges were more numerous at Pacheco Valle due to the large number of retreating edges in the first seven years following development.

4. Discussion

The linear forest edge structure at Pacheco Valle and China Camp changed significantly since suburban development in 1975 and 1968, respectively. Contrary to our hypothesis, sinuosity did not increase linearly over the time frame of the study. Rather, changes in sinuosity appear to change with age following the initial disturbance, with the greatest changes starting around seven years after development.

The brief time period following development at Pacheco Valle (1975) to 1982 was not enough time for significant changes in edge structure to occur. Following that initial window, though, edge structure changed more substantially (median change was 0.3225) and more significantly ($p = 0.019$) than any other change in this study. This burst also meant the changes over the entire study period were significant, albeit less so than 1982–2003 (median change was 0.2725, $p = 0.049$).

The longer first time period at China Camp offer a deeper story into what happened to the forest edges following suburban development. Contrary to what happened at Pacheco Valle, the edge sinuosity at China Camp increased significantly in the first window between 1968 and 1982 (median change was 0.1575, $p = 0.04$; see Fig. 3 for an example). This time period is twice as long as Pacheco Valle's first interval and is the likely explanation for why China Camp saw significant changes where Pacheco Valle did not. The differences between Pacheco Valle and China Camp hint at the processes behind edge structure development.

Linear forest edge structure is influenced by both primary and secondary responses (Harper et al., 2005). Early changes in edge structure at Pacheco Valle between 1975 and 1982, including the high number of retreating edges (16), were likely due to primary responses like tree mortality and canopy or trunk damage. Construction sites like those at Pacheco Valle in 1975 and China Camp in 1968 are associated with high tree mortality rates (Edberg and Berry, 1999; Nowak et al., 1990). Many contractors at building sites use heavy machinery that compacts the soil. They may also change the grade around the trees by adding or removing soil. In urban settings like Pacheco Valle and China Camp, grade changes and soil compaction are responsible for a large percentage of Q. agrifolia tree failures (Edberg and Berry, 1999). The primary responses' near term impacts may be evident at Pacheco Valle where sinuosity did not change significantly, but 16 of the 20 sampled edges retreated. We think two factors could have caused this pattern: First, development at the sites had only begun in 1975, and more trees could have been removed between then and 1982. Second, bare soil was visible at all Pacheco Valle sites in 1975, meaning soil compaction and mechanical injury may have affected the most exposed trees on the edges with equal probability. The first explanation is more likely, but we cannot discount the second given the susceptibility of Q. agrifolia to the disturbances present at construction sites.

Secondary responses affected edge structure after the construction and primary responses. Canopy expansion and tree recruitment, both secondary processes, operate on longer time scales, and thus are hypothesized to manifest themselves later than primary responses (Harper et al., 2005). The significant changes in sinuosity at China Camp between 1968 and 1982 fit the longer time scales of secondary effects, as do the significant changes at Pacheco Valle between 1982 and 2003. Tree recruitment, in particular, is likely the major driver of sinuosity changes in these time periods. Previous studies of forest expansion have found seedlings encroaching on grasslands in clumped distributions, especially in semi-arid environments where other individuals can create attenuating microclimates (Flores and Jurado, 2003; Kennedy and Sousa, 2006). Spatially contagious distributions like these could lead to more sinuous edges.

Homeowners are also another possible factor influencing edge structure at these sites. Some homeowners may choose to maintain their yard in an open lawn, removing any seedlings and saplings that appear along the new edge. Other individuals may actively

Fig. 3. An example of changing edge sinuosity from China Camp. The lines represent the maximum continuous canopy extent in 1968 (solid), 1982 (long and short dashes), and 2003 (short dashes). Note the new extension of the forest between the two houses in the top of the image that developed in 1982. By 2003, that extension had been reduced in size, likely due to the removal of a tree in the front yard of the second house from the top.

shape the forest edge by planting new trees. Still others may allow the edge develop on its own, doing little to influence the process.

Homeowners at Pacheco Valle and China Camp probably fall into the latter two categories given the significant increases in sinuosity, and past research helps support this theory. Many studies have uncovered people's preferences for forested landscapes (e.g. Ulrich, 1983, 1986), and still others found a link between forest patch complexity and neighborhood satisfaction (Lee et al., 2008). Homeowners attitudes toward landscaped trees may also be driven by economics. Anderson and Cordell (1988) found sale prices for homes with trees in the landscaping increased 3.5–4.5%, while trees contributed up to 12% of a property's value in another study (Morales et al., 1976). Landscaped trees may lower energy costs for homeowners by providing shade in the summer (Akbari et al., 1997, 2001), but it is likely that aesthetics play a larger role, given the San Francisco Bay Area's relatively mild summers. Anecdotally, there are many homeowners in the Bay Area who claim to have purchased their home for the oak trees in the yard rather than other qualities of the house (Miller, 2007).

Forest landscape structure in urban environments generally increases in complexity over time. Many existing studies that found similar results have focused on larger scale changes. In the eastern United States, forest patch shape based on a perimeter/area fractal dimension increased with population growth rate (Medley et al., 1995). Another study of villages within a protected area in India reported similar increases in shape complexity over 12 years (Nagendra et al., 2006). Closer to our area, a model of urban growth in southern California predicted a minimum 10% increase in habitat edge length when forecasting build-out at 30 m resolution (Swenson and Franklin, 2000). If this projection proves true, it would continue an existing trend—California's wildland-urban interface increased in area by 8.7% in the 1990s (Hammer et al., 2007).

5. Conclusions

Forest edges are dynamic ecological transition zones, and their structure changes substantially after urban development. Edge structure, as characterized by sinuosity, increased in complexity shortly, but not immediately, after urban development. The edges created by development remained relatively straight over the first seven years at Pacheco Valle, but most retreated from their initial position. In the 14 years following development at China Camp, though, the edges had both increased in sinuosity and advanced their positions. By 2003, edge structure at both sites had increased in sinuosity, likely from a combination of natural forest responses to edge creation and actions taken by homeowners to further develop the forest edge. While forest edges can change frequently and rapidly at the landscape level, they are also highly dynamic structures at small, physiologically relevant scales.

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