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Shifting Baselines in a California Oak Savanna: Nineteenth Century Data to Inform Restoration Scenarios

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Abstract

For centuries humans have reduced and transformed Mediterranean-climate oak woodland and savanna ecosystems, making it difficult to establish credible baselines for ecosystem structure and composition that can guide ecological restoration efforts. We combined historical data sources, with particular attention to mid-1800s General Land Office witness tree records and maps and twentieth century air photos, to reconstruct 150 years of decline in extent and stand density of Valley oak (*Quercus lobata* Neé) woodlands and savannas in the Santa Clara Valley of central coastal California. Nineteenth century Valley oak woodlands here were far more extensive and densely stocked than early twentieth century air photos would suggest, although reconstructed basal areas (7.5 m^2/ha) and densities (48.9 trees/ha) were not outside the modern range reported for this ecosystem type. Tree densities and size distribution varied across the landscape in relation to soil and topography, and trees in open savannas were systematically larger than those in denser woodlands. For the largest woodland stand, we estimated a 99% decline in population from the mid-1800s to the 1930s. Although most

of the study area is now intensely developed, Valley oaks could be reintroduced in urban and residential areas as well as in surrounding rangelands at densities comparable to the native oak woodlands and savannas, thereby restoring aspects of ecologically and culturally significant ecosystems, including wildlife habitat and genetic connectivity within the landscape.

Key words: bearing tree data, ecological baseline, GLO survey, historical landscape reconstruction, *Quercus lobata,* urban forestry

Introduction

Historical reconstruction of long-term land use history and associated ecological change is essential to understanding modern ecological patterns and processes (Foster et al. 2003; MacDougall et al. 2004) and for developing realistic conservation and restoration targets (Swetnam et al. 1999; Eberhardt et al. 2003; Grossinger et al. 2007). Historical information provides insight into how ecosystem composition and structure vary in relation to physical factors and disturbance regimes prior to the dramatic ecological transformations of the past century. Such data can suggest restoration opportunities and strategies within the context of contemporary land use restrictions and twenty-first century climate change (Harris et al. 2006; Hobbs 2007).

Long-term historical evidence can lead us to re-think the potential distribution and abundance of focal species. Restoration efforts are susceptible to the dangers of a shifting baseline when only recent population data, that may reflect highly altered population sizes and age/size structure, are used to set management targets. This shifting baseline affects interpretation of contemporary ecosystems and can result in arbitrarily low or otherwise ill-designed recovery targets (Pauly 1995; Jackson et al. 2001). Our study addresses this issue by using historical information to understand baseline conditions and long-term trajectories.

Given their long history of human exploitation, oak woodland and savanna ecosystems of the Mediterranean Region and California are vulnerable to shifting baselines (Plieninger et al. 2003; Carmel & Flather 2004; Plieninger et al. 2004; Pons & Pausas 2006). These ecosystems have been greatly diminished and fragmented by conversion to urban and agricultural land uses, and most remaining stands are degraded due to persistently low oak recruitment, disease, invasive exotic species, and altered fire regimes (Bolsinger 1988; Sork et al. 2002; Plieninger et al. 2003; Giusti et al. 2004; Kelly et al. 2005; Plieninger 2006; Tyler et al. 2006; Acacio et al. 2007; Zavaleta et al. 2007). Because of these transformations it is difficult to establish credible baselines for the structural and compositional properties and spatial distribution of these ecosystems.

In California, the need for historical perspective is particularly acute for the endemic Valley oak (*Quercus lobata* Née), a large, long-lived deciduous white oak that has been disproportionately impacted since early Euro-American settlement because of its association with productive agricultural soils and development-prone valley and foothill environments (Griffin 1973; Bartolome 1989). Valley oak woodlands and savannas can be found in inland valleys and foothills throughout California, providing critical habitat for a diverse range of native plants and vertebrate species. Valley oak savannas are estimated to cover 2.7% of the state (Allen-Diaz et al. 1999) and Valley oak woodlands 0.2% (Davis et al. 1998). Statewide trends show a steady decline in Valley oak density and regeneration rates over the last century, which raises concerns of reproductive isolation, reduced fecundity due to habitat fragmentation, loss of resiliency to ongoing climate change, and elimination of habitat for Valley oak associated species (Brown & Davis 1991; Pavlik et al. 1993; Davis et al. 2000; Sork et al. 2002; Mahall et al. 2005).

Because of their ecological and cultural significance, California's Valley oak woodlands and savannas are now being protected and restored at many sites within the species' historic range, but mitigation and restoration targets are often set without critical information on stand structure and variability under local environmental conditions. Instead, targets are typically based on remnant oak patterns and densities. The species can live 300 years or more, whereas historical studies have mainly documented change since the second quarter of the twentieth century, the earliest period for which aerial photography is available (Tyler et al. 2006). Relatively little is known about the characteristics of these landscapes prior to significant Euro-American modification.

Here we present research combining a range of historical data sources, with particular attention to mid-1800s surveys and maps, to reconstruct 150 years of decline in extent and stand density of Valley oak woodlands and savanna in a landscape of central coastal California. We report pre-Euro-American stand density, diameter at breast height (dbh), and distribution. For one large, particularly well-documented woodland stand, we also estimate the oak population size at three points in time (1850s, 1939, and 2005). Results are discussed within the context of land use history. We conclude by considering the implications of the reconstructed pre-Euro-American contact conditions for ongoing conservation and restoration efforts.

Methods

Study area

The study area covers approximately 265 km^2 of the southern Santa Clara Valley in the Central Coast Ranges of California (lat 37° 00´N, long 121° 33´W; Fig. 1). The valley is characterized by a typical Mediterranean climate with cool, wet winters and warm, dry summers, and is protected from strong oceanic influence by the Santa Cruz Mountains. Precipitation ranges between 250-500 mm annually, 90% of which occurs between the months of November and April. We defined the upland boundary of our study area as the contact between Quaternary alluvial deposits of the valley floor and surficial bedrock of surrounding foothills (Knudsen et al. 2000). Spanish/Mexican cattle ranching replaced indigenous management here in the early 1800s. Since 1950, the orchards and other irrigated agriculture that superseded ranching in the twentieth and late nineteenth century have given way to increasing development pressure from the highly urbanized Bay Area. Today, 37% of the southern Santa Clara Valley is in urban or suburban land use, 50% of the area is devoted to irrigated agriculture, and roughly 13% remains in grasslands, riparian forest and scrub, and oak woodland (Jones & Stokes 2006).

Historical ecology strategy

We reconstructed mid-nineteenth century oak distribution and stand density using witness tree records and associated field notes from General Land Office (GLO) surveys. Data used to corroborate these reconstructions and refine the distribution of oak stands included eighteenth century Spanish explorers' journals, nineteenth century traveler accounts, nineteenth century maps, Mexican land grant records, and twentieth century landscape and aerial photography. We used methods of source inter-calibration to bring together this nonstandard dataset composed of information from different eras, social contexts, and authors (Swetnam et al. 1999; Grossinger 2005). Where possible, data were incorporated into a digital spatial database for GIS display and analysis. Aerial photographs from 1939 and 2005 were used to estimate twentieth century Valley oak distribution and population levels.

GLO witness tree records

Initiated by the U.S. Continental Congress's Land Ordinance of 1785, the Public Land Survey field notes of the GLO provide some of the most detailed descriptions of landscape and vegetation prior to the extensive environmental changes following European contact (Buordo 1956). Progressing from Ohio to the West Coast, the GLO survey reached Santa Clara County in 1851. The survey established townships of 36 mi^2 (94 km^2) divided into square mile (2.6 km^2) sections, ideally forming a square grid at a resolution as fine as the quarter-section (0.8 km). However, many areas in California, including the study area, lack a complete network of inner township section lines due to private Mexican land grant holdings (White 1991; Grossinger et al. 2007).

To establish section corners and quarter-section points (mile and one-half mile points), surveyors recorded the species, diameter, azimuth, and distance from the survey points for up to four “bearing” trees, ideally one tree per quadrant (White 1991). In addition, "line" trees encountered along survey lines were recorded with species and diameter. Associated field notes contain qualitative descriptions of the landscape and ecosystems encountered, usually including the over- and understory composition.

We adapted methods developed by the Forest Landscape Ecology Lab at the University of Wisconsin-Madison to store, display, and analyze the GLO data within a GIS environment (Manies 1997; Radeloff et al. 1998; Sickley et al. 2000). One of the primary benefits of the ArcMap (ESRI) form developed by the Wisconsin group is its ability to place survey points efficiently and accurately within a contemporary spatial coordinate system. The resulting database can be easily manipulated for subsequent analyses. Such data have been used most often to reconstruct historical forest structure and composition in the Midwest and Northwest and only rarely in California oak woodland and savanna systems (Radeloff et al. 1999; Collins & Montgomery 2001; Bloom & Bahre 2005; Brown 2005).

Density estimation

Researchers have employed a variety of methods to determine density estimates from GLO bearing tree data (Bouldin 2008). The most commonly used is the point-centered quarter method developed by Cottam and Curtis (1956), who showed empirically that density is equal to the inverse of the square of the mean distance from a point to a tree (Radeloff et al. 1999). However, this formula is problematic with small sample sizes or when applied to populations with large-scale non-randomness (Bouldin 2008). For this reason, we used the more robust Morisita (1957) formula:

$$D = \left(\frac{gk-1}{N}\right)\sum_{i}^{N}\frac{k}{\pi\sum_{j=1}^{k} r_{ij}^{2}}$$

where g is the bearing tree distance rank for the quadrant (g=1), k is the number of quadrants with bearing trees, N is the number of survey points, r is the distance in meters from the survey point to a bearing tree, and i and j are the index numbers for the survey points and quadrant numbers. To calculate density in trees/m^2, all bearing tree distances were converted to meters from the recorded links or chains. This method avoids some of the limitations of the point-centered quarter method by estimating density at single points prior to aggregating across an area. Using this formula requires the assumption that the trees are randomly distributed locally about a single survey point and that the points are well distributed across the areas being aggregated. It also requires at least two bearing trees, which forced us to exclude five survey points out of a total of 43, a tradeoff we were willing to make to reduce estimation bias, especially considering other available corroborating data sources.

Surveyors may have been biased in selecting trees within certain quadrants or angles, species that are long-lived or those with easily marked bark, or individuals that are well-established and healthy (Radeloff et al. 1999; Collins & Montgomery 2001; Kronenfeld & Wang 2007). A variety of species, including sycamores and willows, were recorded, suggesting that surveyors were sensitive to recording closest trees, regardless of species. Unfortunately, we have no way to infer whether surveyors were biased in selecting trees based on their size or health (Bouldin 2008), but they clearly used a wide range of tree sizes.

Mapping and spatial heterogeneity

Our mapping the extent of woodland, savanna, and grassland habitat types was an iterative process that utilized soil maps (USDA 2007), digitally scanned and orthorectified historical air photos, early maps, and GLO data (Grossinger et al. 2008). We defined three cover types based modern vegetation classification methods: grassland (0–10% cover), oak savanna (10–25% cover), and oak woodland (25–60% cover) (Sawyer & Keeler-Wolf 1995; FGDC 1997; Allen-Diaz et al. 1999; Davis et al. 2000).

Using 1:24,000 county soil survey maps, we classified soil polygons as likely or not likely to contain oaks based on the chi-square association between soil type and 1,976 relict canopy-layer (>15 m crown diameter) Valley oaks identified in 1939 aerial photography (Neu et al. 1974). These trees were digitized based upon their distinctive size, shape, and groupings (Brown 2002; Sork et al. 2002; Mahall et al. 2005). This is likely a conservative estimate of the 1939 population, as clumped individuals can be difficult to discriminate due to contiguous canopies (Mahall et al. 2005). We verified that oak losses were relatively evenly distributed across the heavily agricultural valley such that the relict oaks of 1939 could allow for meaningful correlations.

We refined the historical habitat map using other data sources that helped us to distinguish dense woodlands from the surrounding savannas and grasslands. We identified woodland areas from explorer narratives specifying denser areas and early maps depicting densely spaced trees next to open plains or "scattered oaks." We also used the GLO bearing tree dataset and associated notes, including survey corner points with no bearing trees as evidence of grasslands or other habitats characterized by few oaks (Table 1).

We used the historical map to identify spatially contiguous woodland and savanna populations, and estimated average densities for each population using GLO survey records. Although this approach reduced the number of points per population density estimate, it also reduced the risk of combining points from different environments that may have supported systematically different population densities. We focused on two extensive and well sampled populations for a more detailed analysis of tree diameter distribution and basal area in woodland and savanna vegetation types.

To further explore change over the past 150 years, we estimated the number of canopy oaks in the largest woodland stand of the mid-1800s habitat map, the Morgan Hill woodland, as it contained the greatest number of GLO points and was clearly defined and corroborated by a number of independent sources. The number of trees was determined as the product of the mean Valley oak density in a population unit times the area of that unit. We censused canopy oaks in this same area in 1939 and 2005 using aerial photography. Only trees that were also present in 1939 were mapped from the 2005 imagery. Estimates were supported by inspection of surviving trees in the higher quality 2005 NAIP imagery as well as limited ground truthing.

Results

Stand density

Early European travelers to the southern Santa Clara Valley described a complex oak woodland and savanna landscape with tree density varying at both local and landscape scales. In one of the first explorations of the valley in 1772, Crespí recalled that "much of it was well grown with oaks and live oaks" (Crespí & Bolton 1927). Another explorer encountered "magnificent clusters of oaks" that created "one continuous vista of unexampled beauty" (Wise 1850). Geologist William Brewer described a region of oaks near present-day Morgan Hill that was "four or five miles wide covering the middle" and noted his entry into a "belt of scattered oaks" in a region to the southeast (Brewer 1974). In 1774, explorer Palou summed up the density variation across the valley:

> …the plain we were keeping on through was much grown up with white oaks and live oaks, and we came across some patches of thick woods of these same trees (Brown 2005).

Dense oak woodland habitat was frequently identified in surveyor field notes, other written accounts, and cartographic evidence. Common terms such as "grove" and "woodland" distinguished stands with higher tree densities. Other suggestions of higher stand density include descriptions such as "a heavy growth of oak timber" or "densely timbered" (Thompson 1857; Harrison circa 1888). We found that areas described textually as woodlands or groves by explorers and GLO surveyors consistently corresponded with wooded areas as shown by dense tree symbols on maps. This suggests that these patterns were apparent to multiple, independent observers.

The GLO bearing tree dataset supports these observations with more quantitative as well as spatially descriptive information. Most points are spaced approximately every half-mile along the township and range lines, which intersect every six miles (9.66 km), although additional points from meander lines and land grant surveys cover other parts of the study area (Fig. 2). The study area contains a total of 168 witness trees, of which 86% are oaks and 71% are “white” oaks (presumed Valley oaks given the strong association of Blue oaks (*Q. douglasii*) with foothills rather than valley floors in this region). Of that total, 101 Valley oaks are bearing trees with recorded distances to survey points and 123 Valley oaks are reported with diameters. In addition to the dominant Valley oaks, other arborescent oaks within the valley potentially included Coast live oak (*Q. agrifolia*), Black oak (*Q. kelloggii*), and Blue oak. This is supported by the GLO bearing tree dataset, where secondary species included over 5% black oak and 3% live oak, as well as 10% riparian species (including willow, sycamore, and alder).

Tree densities calculated for selected populations showed significant within-population variation as well as variation across populations and habitat types. Within five identified woodland populations, estimates of mid-nineteenth century Valley oak stand densities range from 2.2 to 48.9 trees/ha. The largest and most well-defined stand, the Morgan Hill woodland, averaged 29.8 trees/ha. Average nearest neighbor distance for the five woodland populations was 18.1 ± 3.8 m SE, with a range of 1.0 m to 58.5 m. For the four savanna populations, densities ranged from 1.8 to 3.7 trees/ha. The savanna region with the most survey points, the Boundary savanna, averaged 3.7 trees/ha. Within the savanna populations, nearest neighbor distances averaged 34.2 ± 4.3 m SE, with a range of 5.0 m to 77.4 m (Table 2, Fig. 2).

Valley oak dbh in the GLO tree diameter dataset averaged 56.0 ± 2.7 cm SE , with the greatest number of trees within the 40 to 50 cm size class. The Morgan Hill woodland dbh average was 49.1 ± 3.0 cm SE, with proportionately fewer large and small trees, whereas Boundary savanna oaks were much larger (76.6 ± 6.5 cm SE) with a bimodal distribution (Fig. 3). From the density and dbh data, we calculated a basal area of 7.5 m^2/ha for the Morgan Hill woodland compared to 1.7 m^2/ha for the Boundary savanna (Table 3).

Spatial distribution of oaks

Oak woodland dominated the northern section of the study area while more southerly sections, outside wet meadows, were largely covered by less dense oak savanna or grassland. Within the savanna systems, however, areas of dense groves or woodland appear at locally favorable sites. The variation in relative density across the valley shown by the GLO dataset is supported our additional data sources.

Remnant oaks in 1939 were positively associated with several loamy soil types and gravelly loams (Brown 2005; Grossinger et al. 2008) and negatively associated with clays and some silty, sandy, and clay loams (Table 4). The well drained loams and gravelly loams are largely associated with the valley's alluvial fans.

Other evidence also associates high oak density with alluvial fan deposits. An 1840s-era diseño of the northern study area depicts a large oak woodland, or "roblar," in the shape of a fan on the eastern side of the valley, in the approximate location of the Morgan Hill woodland (Fig. 4). This area corresponds with Coyote Creek's broad fan, composed of gravelly soils (USDA 2007; Sowers et al. 2009). The Morgan Hill woodland was also distinguished in early accounts, which referred to the area as "Dunne Woods" and noted that:

> ...on the eastern side of the valley, is a large area of virgin soil, beautiful level valley land, covered with wide-reaching oaks, ably fine vine land (Harrison circa 1888).

In addition, a landscape photograph of the Dunne Woods circa 1900 suggests relatively high Valley oak densities (Fig. 5).

The shift indicated by GLO density data from high oak density in the north to an overall less dense region to the south is also corroborated by other sources. In addition to the GLO data (survey points with no bearing trees and the field notes of "open plains"), several narrative sources discuss the lack of trees in the southern, central valley region. In 1861, William Brewer described this pattern:

> First a ride of eighteen miles across the dead-level plain, tedious and monotonous… but at last a belt of scattered oaks is entered. Then we strike up a canyon, on the Pacheco Pass… (Brewer 1974)

Similarly, Broek (1932) described the southern region as a "treeless plain," affirming a stark lack of trees in contrast to other parts of the valley.

Oak population change over time

By extrapolating oak density estimates from GLO bearing trees across soil units, we estimate about 74,000 ± 26,000 mature oak trees existed within the 2,140 ha Morgan Hill woodland stand prior to significant Euro-American modification. This compares to only 313 probable Valley oaks identified in the 1939 aerial photography, and 112 Valley oaks persisting in 2005 (Fig. 6). This represents a 99% loss between the mid-1800s and 1939, and an additional 50% loss between 1939 and 2005. Within the 265 km^2 study area, the overall mapped pre-Euro-American extent of oak woodland (33 km^2) and oak savanna (57 km^2) was 90 km^2, or 34% of the landscape. By comparison, recent mapping shows 1.64 km^2 of "mixed oak woodland and forest" and "Valley oak woodland" in a 212 km^2 sub-area, less than 0.8% of the area (Jones & Stokes 2006). Most of the oak loss since the mid-1800s can be attributed to land conversion for cropland and urban development as opposed to lack of tree recruitment in remnant stands. This is evident in the extensive coverage of agricultural development within the valley floor by the time of the 1939 aerial photography and expansion of urban development since then (Fig. 7a & 7b).

Discussion

Documenting long-term change in Mediterranean oak woodlands and savannas

Archival aerial photography has been used in Mediterranean Europe and California to quantify twentieth century land use change and oak population dynamics in oak woodlands and savannas (Brown & Davis 1991; Sork et al. 2002; Carmel & Flather 2004; Plieninger 2006). To obtain longer records of oak dynamics, researchers have relied on dendroecological techniques (e.g., (Harvey 1989; Rozas 2005), pollen records (Mensing 1998), chronosequence analysis (Plieninger et al. 2003) or early historical records of the kind used in this study (Bloom & Bahre 2005; Brown 2005). The long history of relatively intense oak woodland exploitation and management in Europe makes it difficult to directly relate our findings to structurally similar Mediterranean oak ecosystems (Huntsinger & Bartolome 1992; Plieninger et al. 2003), However, the few long-term studies that have been undertaken suggest that these systems have all undergone extensive modification and systematic changes in tree size distribution and density well before the advent of remote sensing or modern forest inventories. As a result, historical reconstructions fill an important information gap, despite the effort required and the unavoidable uncertainties inherent in resulting ecological reconstructions.

Land use regimes and Valley oak loss in the Santa Clara Valley

The GLO surveys occurred at the cusp of rapid settlement and cultivation of the Santa Clara Valley, a time when oak tree density and distribution were probably not significantly changed from pre-Euro-American conditions. GLO surveyors noted only occasional cultivated fields, although cattle ranching was well established. While some trees were undoubtedly removed near settlements or used for firewood and occasionally for fence posts, the predominant land uses into the late 1860s were livestock grazing and the production of hay and grain, which did not directly conflict with the presence of oaks. To the contrary, cattle ranchers considered oaks a benefit to rangeland, since they provided shade for stock (Jepson 1910; Bartlett 1928). Thus, while oak recruitment may have been affected by this time, it is unlikely that canopy oak distribution and density had been appreciably altered.

The effect of indigenous land and fire management on oak woodlands is not well documented. In the Coast Ranges indigenous populations may have averaged relatively high densities of 1-3 persons/km^2 (Keeley 2002; Allen-Diaz et al. 2007). While they did not engage in intensive agriculture, native peoples routinely burned coastal and foothill landscapes, a practice that would have promoted grasslands over shrublands (Keeley 2005) but may have had only small effects on oak establishment and early growth (Tyler et al. 2006). Given the longevity and the fire-tolerance of mature Valley oaks, it is reasonable to assume that woodlands and savannas described in the earliest maps and accounts were well established before the contact period.

Intensive grazing almost immediately followed Euro-American contact and would have likely overshadowed any effects of reduced fire frequency on oak demography. Indeed, some researchers have suggested that, while the structure and composition of the landscape encountered by Spanish explorers was likely modified by indigenous land management, subsequent Euro-American land use practices may have replaced and then exacerbated effects of the indigenous fire regime (Keeley 2002).

In the last decades of the nineteenth century, Valley oaks were cleared to establish fruit and nut orchards that replaced grain fields and pastureland (Shortridge 1986). By the beginning of the twentieth century, only scattered trees remained along orchard margins or as remnant stands within homesteads or small pastures. These agricultural lands occupied most of the valley. By the 1930s, orchards covered about 65% of cropland and "nearly three-quarters" of the irrigable land (Blackie and Wood 1939).

Urban and suburban expansion following World War II has further impacted oaks, although at a slower rate. The lack of oak recruitment is now apparent as older trees die and fewer young trees take their place. The 99% loss documented for the Morgan Hill woodland is comparable to the estimated 95% loss of pre-Euro-American riparian Valley oak forest and woodland habitat due to agricultural land conversion in the San Joaquin Valley (Kelly et al. 2005) and follows the general but poorly quantified pattern of Valley oak loss throughout much of its range in California (Jepson 1910; Allen-Diaz et al. 2007).

Changes in Valley oak stand structures

The historical evidence synthesized in this study suggests that Valley oak woodlands were far more extensive and densely stocked than twentieth century air photos would suggest. Our reconstruction of oak density based on the GLO dataset is reinforced by the consistent relationship between these reconstructed densities, surveyor notes, and independent maps. The reconstructed basal areas (7.5 m^2/ha) are not, however, outside the range reported in other studies of oak woodlands in other parts of California. Allen-Diaz et al. (2007) report that basal areas in pure Valley oak woodland reach 17 m^2/ha. In the Santa Lucia Mountains of California, Griffin (1976) documented Valley oak basal areas as high as 61.3 m^2/ha and speculated that this was approaching an upper limit for the species. In comparison to the woodland densities of 29.8 Valley oaks/ha we found, Sork et al. (2002) reported an average 1944 density of 1.48 Valley oaks/ha within Sedgwick Reserve in Santa Ynez, California. Also on Sedgwick Reserve, a 2005 report found overall 1943 oak densities of 13.5 trees/ha and as high as 29.2 trees/ha based on 20 oak woodland stands identified in 1943 aerial photography (Mahall et al. 2005). In another study, Keeler-Wolf (1989) reported a wide range in Valley oak stand structure along alluvial terraces in Monterey County, California: 13 trees/ha with a basal area of 13 m^2/ha in "open savanna" to 200 trees/ha with a basal area of 32 m^2/ha in younger forest stands.

Our spatially explicit reconstruction shows that Valley oak stand structure varied considerably across the Santa Clara Valley. The association of the historical vegetation pattern with modern soil maps and landscape features such as alluvial fans allows for interpretation of physical controls on oak distribution and abundance. The oft-revered vision of large grand oaks dotting the valley floor is only part of the story: some regions of the valley supported a different stand structure of smaller, more densely packed oaks, while others were absent of oaks. For some areas in today's valleys, the large oaks left may have once been surrounded by many smaller oaks. Because the valleys were settled so early, perceptions of historical valley floor landscapes are subject to a shifting baseline and likely reflect these impacts more than for foothill and other more recently affected areas of California's oak woodlands.

Opportunities for restoration

Once one of California's distinctive habitats, Valley oak woodlands and savannas are now greatly reduced in extent and increasingly isolated. While there is limited potential for large-scale restoration of complete valley-floor ecosystems, extant fragments do remain throughout much of California. A historical landscape perspective demonstrates the magnitude of loss, which is particularly valuable in fragmented ecosystems where landscape level characteristics are often obscured. Within rural landscapes with diminished oak densities, historical data offer information about the density, dbh distributions, spatial characteristics, and soils associations needed for designing restoration plans. While this analysis focused on the dominant tree species, ecosystem restoration efforts would also benefit from incorporating density and distribution characteristics of secondary species such as the live and black oaks reported in the GLO dataset and recent research into the herbaceous, understory component (Hamilton 1997; Minnich 2008).

In addition to rural applications, the urban, suburban, and agricultural environments that have supplanted many Valley oak lands should not be overlooked for the restoration of certain ecological functions. The information presented here could be used to re-introduce the spatial patterns and range of historical oak densities of 2 to 30 trees/ha as well as set minimum densities or age structure targets. Such efforts would not preclude urban landscape features, including a mix of urban forest species. Scattered oaks could theoretically be interspersed with denser woodlands in locally favorable areas, including parks or areas of open land (Fig. 8). They could be effective median and even street trees in some contexts, which has been recognized by some urban planners. Through well-designed urban forestry and planting programs coordinated across municipalities, it is possible that density and distribution patterns similar to the native oak woodlands and savannas could be strategically re-introduced within California valley floors. Similar approaches to historical analysis and ecological restoration may be effective other regions that underwent early land use change.

Oaks re-introduced in an urban setting could increase genetic connectivity among relict populations, improve habitat quality and connectivity for a number of oak-associated wildlife species, particularly birds (Manning et al. 2006), and provide shade, nutrient and water retention and other ecosystem services associated with urban street trees (Grossinger et al. 2007). Such benefits could support local populations' resiliency to climate change and the trees could even be considered for carbon storage credits. Although simply increasing oak density would not restore all oak woodland and savanna functions, bringing back historical densities into the contemporary setting could reestablish valuable components of a functioning ecosystem for a much larger area, including many formerly oak dominated valleys in central and southern California.

Implications for Practice

- For the Mediterranean climate systems with a long history of change, reconstructing the historical landscape can provide baseline information needed to guide and assess restoration efforts.
- Valley oaks occurred in a wide range of densities and spatial patterns; these can guide landscape level restoration strategies.
- Despite intensive development, rural, agricultural, and urban landscapes still provide opportunities to reintroduce Valley oaks at historical densities, establishing important ecosystem functions.

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Table 1. Complementary attributes of different, independent data sources.

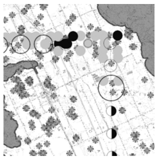
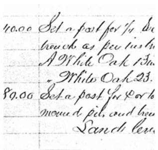
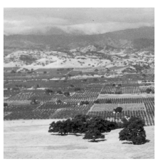
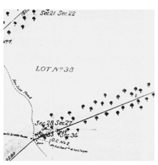
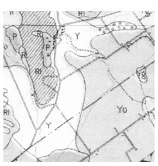
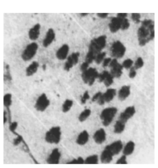
Example	*Data Sources*	*Use of data*	*Era*	*Spatial Coverage*	*Spatial accuracy*
	GLO bearing tree data	Point density estimates, refine habitat boundaries	1850s-1870s	Distributed point data	High
	GLO field notes	Corroborate relative density, refine habitat boundaries	1850s-1870s	Point data distributed across study area	High
	Narrative accounts	Corroborate relative density and location	1770s	Limited areas	Usually general
	Landscape photography	Corroborate relative density	1880s	Limited areas	Depends on source
	Maps	Refine boundaries of woodland and savanna extent	1830s	Individual maps cover many parts of study area	Depends on source
	Soil surveys	Establish correlation with soil type and tree presence	1900s	Continuous for study area	High
	Aerial photography	Estimate oak population, establish correlation with soil type and tree presence	1930s	Continuous for study area	High

Table 2. Estimated Valley oak density based on General Land Office survey bearing tree data showing the estimated density for grouped populations.

Valley oak stands	*No. of survey points*	*No. of trees*	*Density (trees/ha)*	*Standard error*
Morgan Hill woodland	12	29	34.58	12.31
Morgan Hill woodland (E)	2	7	48.87	17.50
Gilroy woodland (N)	2	5	2.15	0.21
Gilroy woodland	2	5	8.95	3.32
Gilroy woodland (E)	2	7	15.20	10.52
Boundary savanna	10	22	3.00	1.59
Central savanna	2	4	3.46	2.55
Pacheco savanna	2	4	2.29	1.75
Gilroy savanna	4	9	1.80	0.42

Table 3. Estimated basal area (m^2/ha) for selected representative woodland and savanna populations.

Valley oak stands	*No. of survey points*	*No. of trees*	*Mean tree basal area (m2)*	*Basal area (m2/ha)*
Morgan Hill woodland	22	41	0.22	7.49
Boundary savanna	18	33	0.57	1.70

Table 4. Selected soil type associations with Valley oaks digitized from the 1939 aerial photography. Expected oaks represent the expected frequency of trees if the total of all observed oaks were distributed proportionately by the area of each soil type within the study area. The significance level alpha of 0.1 (the 90% confidence interval) is used to indicate whether oaks are positively or negatively associated with particular soil types.

Name	*Area (ha)*	*Percent of total area*	*Observed oaks*	*Expected oaks*	*Percent of total oaks*	*Oaks/ha*	*Signif. α = 0.10*
Arbuckle gravelly loam, 0 to 2 percent slopes	1515	7.0%	153	99	10.8%	0.10	+
Pleasanton gravelly loam, 0 to 2 percent slopes	665	3.1%	129	44	9.1%	0.19	+
Pleasanton gravelly loam, 2 to 9 percent slopes	505	2.3%	157	33	11.0%	0.31	+
Pleasanton loam, 0 to 2 percent slopes	1707	7.9%	166	112	11.7%	0.10	+
San Ysidro loam, 0 to 2 percent slopes	1228	5.7%	126	80	8.9%	0.10	+
Campbell silty clay loam	536	2.5%	11	35	0.8%	0.02	-
Campbell silty clay, muck substratum	951	4.4%	29	62	2.0%	0.03	-
Clear lake clay	425	2.0%	6	28	0.4%	0.01	-
Clear lake clay, drained	591	2.7%	15	39	1.1%	0.03	-
Clear lake clay, saline	598	2.8%	3	39	0.2%	0.01	-
Cropley clay, 0 to 2 percent slopes	715	3.3%	21	47	1.5%	0.03	-
Pacheco clay loam	651	3.0%	20	43	1.4%	0.03	-
Pacheco fine sandy loam	794	3.7%	27	52	1.9%	0.03	-
Willows clay	2379	11.0%	9	156	0.6%	0.00	-
Willows soils, eroded	387	1.8%	0	25	0.0%	0.00	-
Zamora clay loam, 0 to 2 percent slopes	846	3.9%	16	55	1.1%	0.02	-

Figure 1. Study area location to south of San Francisco Bay, in the southern Santa Clara Valley.

Figure 2. Map of reconstructed historical vegetation patterns, with several component data sources. Circled areas used for representative woodland and savanna populations. Map includes data compiled from mid-nineteenth century General Land Office surveys (tree species and minimum distance to nearest tree) and probable valley oaks mapped from 1939 aerial photography.

Figure 3. Distribution of Valley oak diameter breast height (dbh) data for all Valley oaks within the study area and for selected representative woodland and savanna populations.

Figure 4. Early diseño of the Ojo de Agua de la Coche Land Grant depicts a fan-shaped oak woodland area on the eastern side of the valley, just south of where Coyote Creek bends northward. The later confirmation map also depicts widespread trees within the valley. Surveyors and explorers passing through the area also remark on the denser nature of the oaks (U.S. District court, Northern District [184-?], courtesy of The Bancroft Library, UC Berkeley).

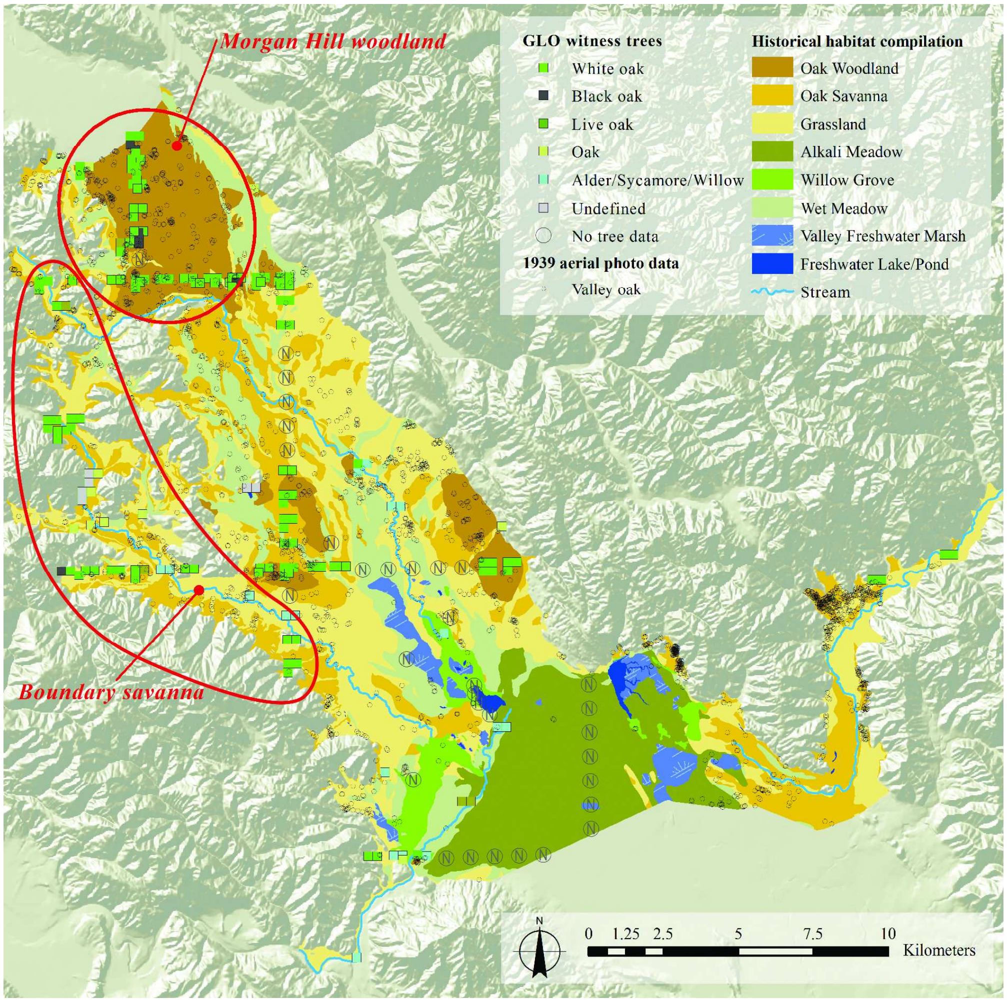
Figure 5. A circa 1900 view of the Valley oak woodlands that dominated south Santa Clara Valley near Morgan Hill. The "Dunne Woods" were converted to agriculture later than most areas within the valley, allowing this photograph to capture a remnant of the historical woodland (courtesy of the Morgan Hill Historical Society).

Figure 6. Decline in Valley oaks in the Morgan Hill woodland population over time based on estimates reflecting the early settlement period, the period after agricultural intensification, and contemporary estimates. Error bar for 1860 estimate represents $\pm$ 1 standard error.

Figure 7. (a) In this 1935 photograph, orchards cover most of the formerly wooded Morgan Hill area. Remnant isolated trees are mostly associated with farm homesteads. In the far right background, groups of oaks can be seen in remnant pasturelands. (Unknown 1935, courtesy of the Santa Clara Valley Water District). (b) Contemporary landscape photograph from 2008 showing the same general area now largely urbanized.

Figure 8. Conceptual model of past and potential future landscape trajectory. (a) Circa 1860: Valley oaks occur in varying densities. Visitors identify dense groves, areas of “scattered” trees, and open “glades.” Dirt roads go around trees and, for the most part, so do ranching and early agricultural activities. (b) Pre-World War II: Most of the valley floor has been cleared for orchards, but a few trees remain in pasturelands, along roadsides, and as a shade trees in towns and on farms. (c) 2008: Despite some preservation of existing trees, oak decline continues. Residential and commercial development expands into former orchards. (d) Future restoration model: Similar densities and patterns to historical conditions could be achieved through strategic planting and stewardship along roads, in parks and yards, and other spaces.

Figure 1. Study area location to south of San Francisco Bay, in the southern Santa Clara Valley.
76x88mm (600 x 600 DPI)



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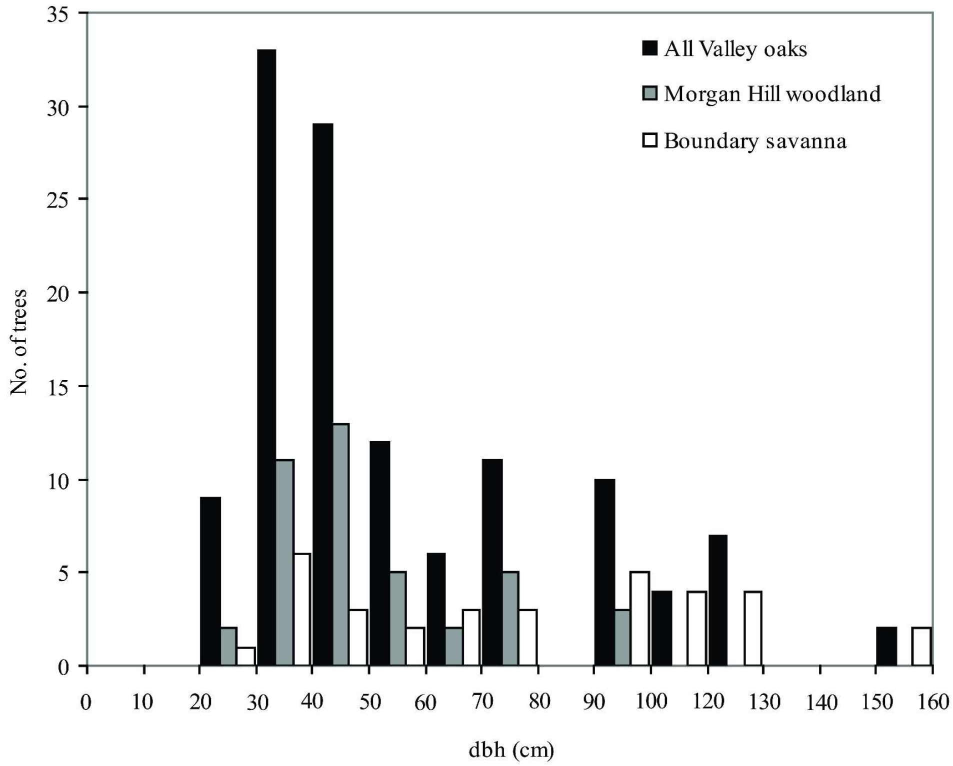
160x159mm (600 x 600 DPI)



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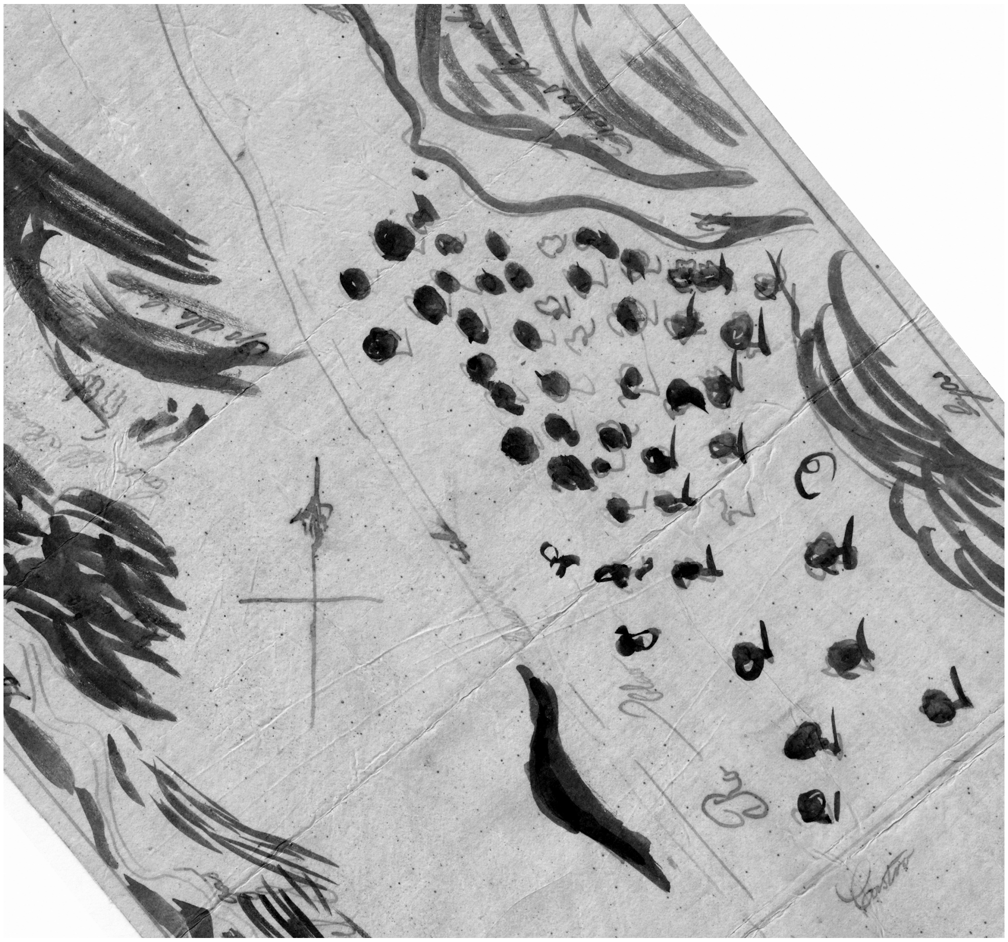

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196x183mm (300 x 300 DPI)

Figure 5. A circa 1900 view of the Valley oak woodlands that dominated south Santa Clara Valley near Morgan Hill. The "Dunne Woods" were converted to agriculture later than most areas within the valley, allowing this photograph to capture a remnant of the historical woodland (courtesy of the Morgan Hill Historical Society).
199x131mm (300 x 300 DPI)

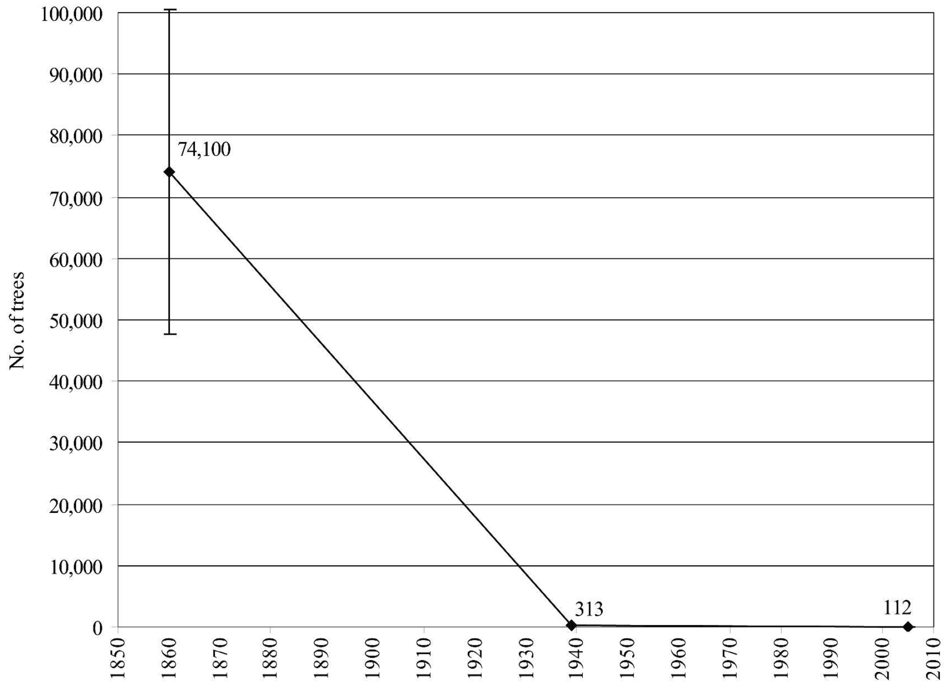
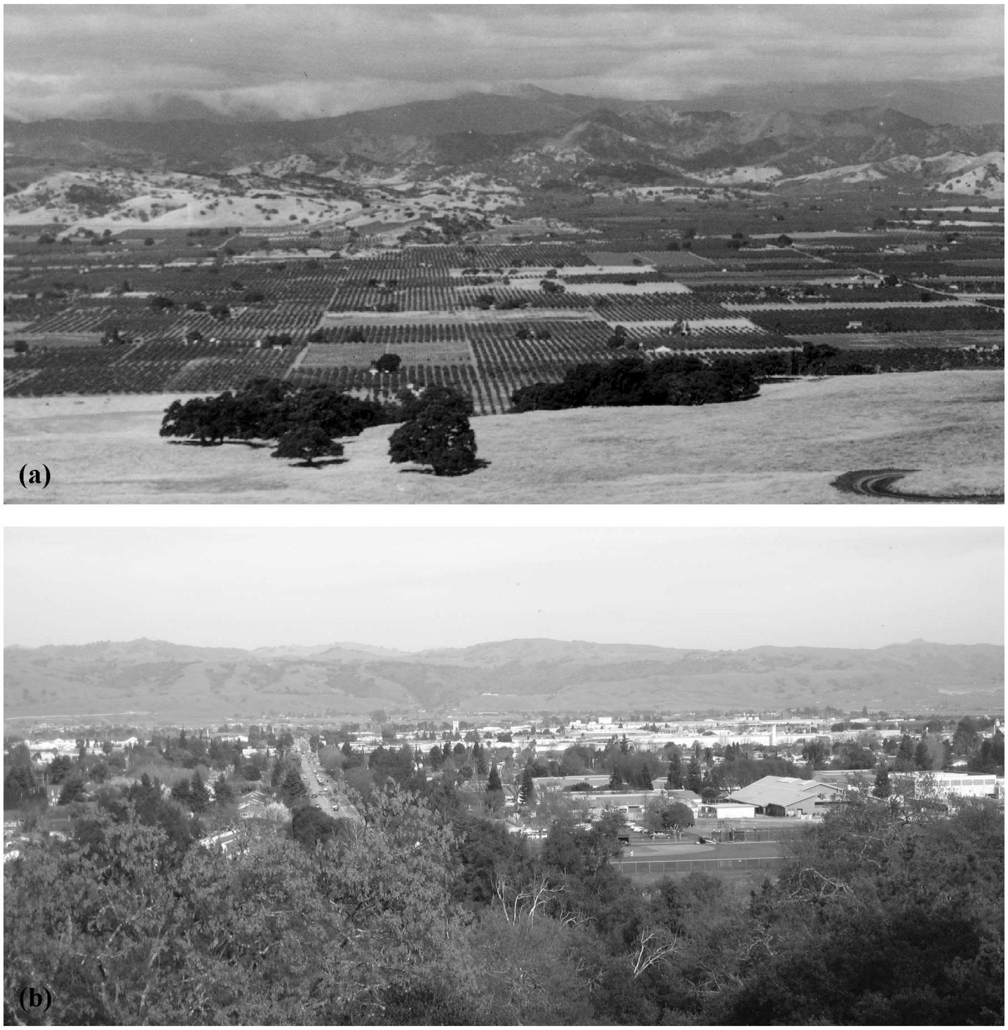


Figure 6. Decline in Valley oaks in the Morgan Hill woodland population over time based on estimates reflecting the early settlement period, the period after agricultural intensification, and contemporary estimates. Error bar for 1860 estimate represents ± 1 standard error.
152x113mm (600 x 600 DPI)



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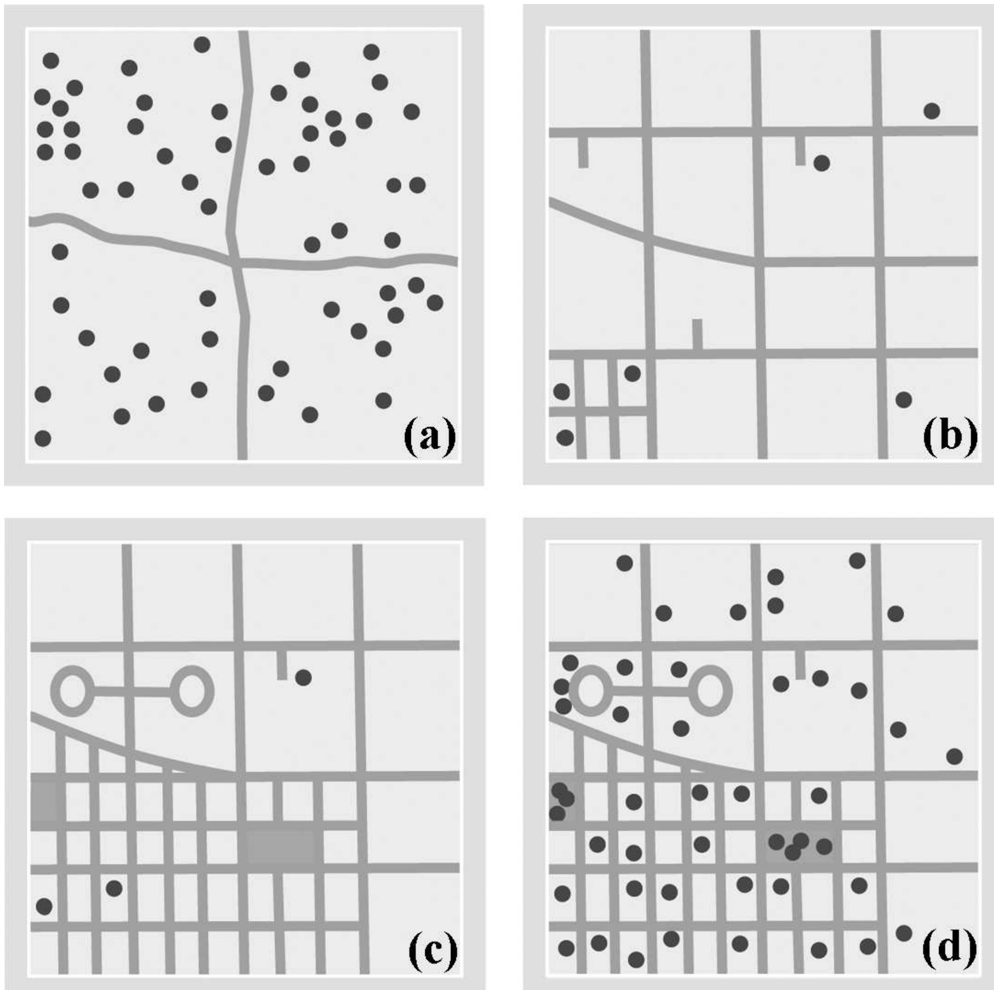
152x155mm (300 x 300 DPI)



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92x91mm (300 x 300 DPI)