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RESEARCH ARTICLE

Historical landscape ecology of an urbanized California valley: wetlands and woodlands in the Santa Clara Valley

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Abstract Historical records provide information to land managers and landscape ecologists attempting to understand current trajectories in altered landscapes. In this study, we synthesized a heterogeneous array of historical sources to reconstruct historical land cover in California's Santa Clara Valley (a.k.a. "Silicon Valley"). To increase and assess accuracy, we used the triangulation of overlapping, independent data sources and the application of certainty level standards. The region has been subject to extensive urbanization, so we also evaluated the applicability of historical landscape reconstructions to the altered landscape. We found evidence for five major land cover types prior to significant Euro–American modification. Valley freshwater marsh, wet meadow, alkali meadow, willow grove, and valley oak savanna have all experienced extreme decline (85–100%) since Euro–American settlement. However, comparison of historical land cover patterns to contemporary land use suggested several new strategies for environmental recovery, despite the limitations of surrounding urbanization. We also observed a temporal shift in riparian habitat along the mainstem of Coyote Creek, from a relatively open mixture of riparian scrub, sycamore woodland, and unvegetated gravel bars to dense riparian forest, likely resulting from stream flow regulation. By identifying former land cover patterns we provide a basis for evaluating local landscape change and setting restoration targets, including the identification of residual features and under-recognized land cover types. These findings suggest that reliable historical landscape reconstructions can be developed in the absence of standardized historical data sources and can be of value even in highly modified regions.

Keywords Landscape history · Urban ecology · Landscape heterogeneity · *Platanus racemosa* · *Populus fremontii* · *Quercus lobata*

Introduction

Historical landscape reconstruction can be a valuable tool for regional habitat conservation and restoration (NRC 1992; Swetnam et al. 1999; Steiner 2000). Understanding conditions before extensive modern disturbance helps scientists and managers set restoration references and targets, develop landscape-level conservation strategies, and evaluate the success of these endeavors (White and Walker 1997; Goals Project 1999; SER 2004). By creating longer-term data sets that describe a given system, historical

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landscape reconstructions can help explain contemporary landscape patterns, which are often shaped by prior human impacts that have been forgotten or overlooked (Foster and Motzkin 1998; MacDougall et al. 2004; Pearce and Grossinger 2004).

As ecologists learn more about California history, the importance of local ecological history has grown. Successional models lacking accurate understanding of earlier conditions and the history of human impact have at times led environmental policy astray. For example, decades of restoration efforts have aimed to "reestablish" *Nassella*-dominated bunchgrass prairies in the Central Valley of California based upon broad assumptions by Clements (1920) that were grounded in scant historical data. Research using more historical information has shown that the "bunchgrass paradigm" was largely false (Anderson 1997; Hamilton 1997; Holstein 2001) and that California's rangelands were historically more diverse (with varying dominance by rhizomatous grasses and other range types). Similarly, fire suppression policies in the western US based on climax state successional models have led to dangerous accumulation of fuels and increases in catastrophic wildfire because of overlooking historical, more open conditions and the effects of indigenous land use, especially burning (Stephens and Ruth 2005; Stephenson 1999; Keeley 2005). In these and other cases, scientists and managers would have benefited from a more detailed and accurate "picture of the past"—but this information is generally not available.

Once a historical perspective is sought, the problem becomes a methodological one. What data are available to generate a historical understanding of local and regional ecological patterns? And how can conclusions drawn from nonstandard, qualitative historical data be documented with sufficient rigor and transparency? In this study, we answer these questions by assembling an unusually diverse range of historical documents to reconstruct the historical extent of wetlands and woodlands along Coyote Creek, on the east side of Santa Clara Valley, California (known internationally as "Silicon Valley"). Using concepts of triangulation (Denzin 1978; Roe 1998), we assign certainty levels and historical references to assertions made about historical land cover types, embedding the documentary basis of landscape reconstruction within a Geographical Information System (GIS). By producing a synthetic map of an urbanized area prior to extensive landscape modification, we develop a historical landscape perspective to inform the conservation of the local natural and cultural heritage.

Approaches to historical reconstruction

Regional reconstructions of historical landscapes have been conducted for a variety of landscapes, including forest ecosystems (e.g., White and Mladenoff 1994), shorelines and estuaries (e.g., Goals Project 1999; Van Dyke and Wasson 2005), and river valleys (e.g., Andersen et al. 1996; Collins et al. 2003; Oetter et al. 2004). Most reconstructions have been based primarily on consistently available and relatively standardized historical source materials. In the US, the Public Land Survey (PLS) of the US General Land Office (GLO) is widely used as a primary source for the study of forest landscapes (e.g., Delcourt and Delcourt 1996; Manies and Mladenoff 2000; Bolliger et al. 2004; Andersen and Baker 2006), while the Topographic sheets ("*t*-sheets") of the US Coast (and Geodetic) Survey underlie historical mapping of coastal wetlands and estuaries (e.g., Dedrick 1985; Kearney et al. 1988; Goals Project 1999; Borde et al. 2003; Van Dyke and Wasson 2005). Similarly, 17th- and 18th-century cadastral maps have been used to reconstruct land cover transitions in northern Europe and Scandinavia (Cousins 2001). These efforts can refer to a substantial literature on the use and interpretation of these sources (e.g., Shalowitz 1962; Crowell et al. 1991; Schulte and Mladenoff 2001; Mladenoff et al. 2002; Whitney and Decant 2005).

For the reconstruction of historical vegetation cover of coastal valleys in central and southern California, however, there is no primary, well-validated historical source material. While US Coast Survey maps provide detailed information about the intertidal margins of these valleys, they rarely extend inland past the region of tidal influence (Grossinger and Askevold 2005). PLS records are also less applicable for reasons specific to the history of California. From the Russian River (~120 km N. of San Francisco) south to the Mexican border, the Spanish–Mexican colonial history resulted in a unique legacy of land distribution, precluding standard PLS datasets and altering the nature of land divisions, property boundaries, and early survey records (Robinson 1979). This study thus tested whether an unusually broad historical data search could overcome the absence of any single reliable data source for the study area.

We also expected that different types of historical documents might provide useful information for different land cover types. Recognizing the challenges of assessing the accuracy of historical mapping (Harley 1989), we used multiple document types to enable triangulation, or cross-referencing, of independent data sources to improve assessment of accuracy. Triangulation, the concept of examining phenomena from diverse vantage points, can be a way to establish the reliability of qualitative interpretations by using multiple data sources and approaches (Campbell and Fiske 1959; Roe 1998).

Coastal valleys such as the Santa Clara Valley are more intensively developed than many areas previously subject to historical land cover reconstructions. As a result of extensive urbanization and relatively recent residency (most families have come to the area in the past 30 years), there may be less understanding of the native habitats that characterized the area in recent historical times. Nevertheless, there is strong interest in environmental restoration among the local citizenry and natural resource agencies.

Local ecological questions

As a result of this new interest, a number of large-scale restoration and conservation planning efforts are currently underway in the Coyote Creek watershed, including the South Bay Salt Pond Restoration Project, the Santa Clara Valley Water District's (SCVWD) Natural Flood Protection Program, the Fisheries and Aquatic Habitat Collaborative Effort, and the Santa Clara Valley Habitat Conservation Plan/Natural Community Conservation Plan (HCP/NCCP). Although there have been a number of qualitative explorations of local historical conditions (e.g., Clarke 1952; Mayfield 1978; Goals Project 1999; Brown 2005), these have been limited in geographic scope or land cover types, and have not directly addressed the emerging management questions (e.g., Cloak and Buchan 2001). As a result, questions remain about the historical landscape ecology. Three ecosystem types are of particular interest: freshwater marsh, riparian communities, and valley oak savanna.

Perennial, non-tidal valley floor freshwater marsh provides habitat for several protected native species, including the California red-legged frog (*Rana aurora draytonii*), Western pond turtle (*Actinemys marmorata pallida*), and tri-colored blackbird (*Agelaius tricolor*). Consequently, freshwater marsh is a target of current conservation and restoration plans for the Santa Clara Valley (Jones and Stokes 2006; SCVWD 2006 a, b). However, no information currently exists about the historical distribution of freshwater marshes in the valley. We expected historical sites to be limited, given the semi-arid climate, but historical records might indicate sites with suitable topographic, edaphic, and/or groundwater conditions for present-day restoration.

Riparian plant communities are considered to have high value for native wildlife species (NRC 2002; RHJV 2004) and are of particular conservation interest in the Santa Clara Valley (SCVWMI 2003; Jones and Stokes 2006). Presently, most of Coyote Creek's mainstem is densely forested and assumed to be a remnant of historical conditions (SCVWMI 2003). However, in the more rural part of the valley, the creek's riparian cover is sparse. One reach has been identified as being representative of sycamore alluvial woodland, a relatively rare land cover type (Keeler-Wolf et al. 1996). We endeavored to determine the extent to which current riparian forest conditions are representative of historic conditions.

Valley oak (*Quercus lobata*) is recognized as one of California's most threatened oaks, largely because of its association with fertile valleys subject to agricultural and urban/suburban development. Interest in restoring native trees in the state's developed coastal valleys as part of urban forestry programs is growing among city agencies and other local organizations (e.g., Green 2006). In Santa Clara Valley, there remain questions about the extent of former savanna and whether the trees formed open savannas (<30% cover; Allen-Diaz et al. 1999) or more dense woodland/forest (Schick 1994; Friedly 2000). We developed evidence to document the historical extent and landscape pattern of valley oaks in the study area.

Since historical vegetation cover types can be forgotten over time in heavily modified systems (Grossinger 2005), we created a complete land cover map for the area, including other less-"high profile" land cover types. These data would also provide landscape context for the restoration of target habitats.

Study area

Coyote Creek originates in California's Central Coast Range and enters the Santa Clara Valley near the city of Morgan Hill. The creek follows a northwesterly route across the east side of the valley before meeting the southern end of San Francisco Bay (Fig. 1). The Coyote Creek watershed is the largest in the Santa Clara Basin, covering about 90,000 ha. The landscape reconstruction focused on the valley floor portion of the watershed, comprising 23,000 ha and currently inhabited by about 505,000 people (US Census 2000).

The region is characterized by a mild Mediterranean type, semi-arid climate. It receives 250–500 mm annual precipitation, of which 90% occurs during November through April (McKee et al. 2003). The valley is a very gently sloped alluvial plain of Late Quaternary origin. Rapid suburban expansion began following World War II, but intensive ranching and agriculture started over a century earlier. The area was colonized beginning in the 1770s, with the local Mission Santa Clara (de Asis) established in 1777. Major dams constructed in 1936 (Coyote Dam) and 1950 (Anderson Dam) currently regulate over 75% of watershed discharge.

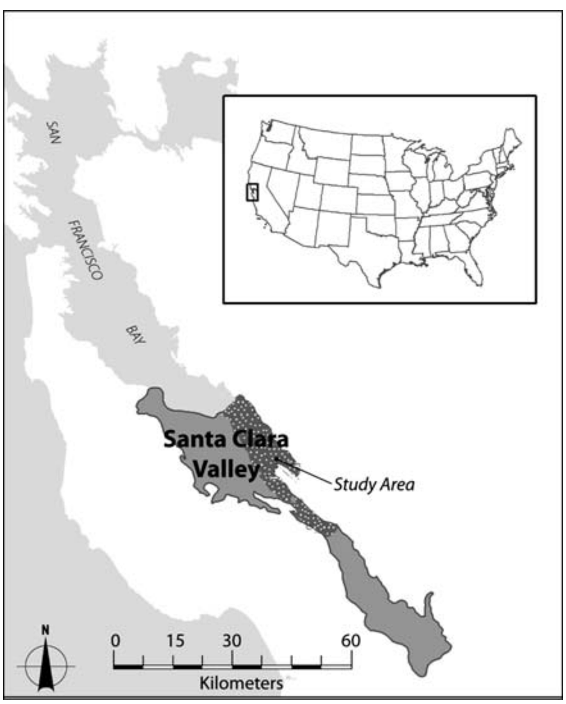

Fig. 1 Study area location on the east side of Santa Clara Valley, at the southern end of the San Francisco Bay area

Today, most of the area can be considered urbanized. The study area supports an average of about 2,200 people per square kilometer (US Census Bureau minimum population density for "urbanized" areas is core areas with 386 people per square kilometer and surrounding areas with overall density of at least 193 per km^2 (US Census Bureau 2000).). Recent land cover mapping by Jones and Stokes (2006) and ABAG (2000), classifies 80% ($\sim$186 km^2) of the study area as urban, residential, or infrastructure, and approximately 14% as agricultural/rural. The agricultural/rural areas of the valley floor persist almost exclusively in Coyote Valley, at the southern end of the study area.

Methods

Data collection

We assembled a diverse range of historical records spanning more than a century (Fig. 2) and compiled these data into a map of landscape patterns prior to significant Euro–American impact. Several thousand historical records at over two dozen archival institutions were examined. These included major regional archives such as The Bancroft Library (TBL) at the University of California, Berkeley (UCB) and the Bureau of Land Management (BLM; Sacramento, CA) as well as local organizations such as the Dr. Martin Luther King Jr. Public Library (San José), History San José, SCVWD, and the Santa Clara County Surveyor's Office (SCCSO). Materials and their archival provenance included Spanish explorers' accounts (late 1700s, e.g., Palou 1774 in Bolton et al. 1930; from local libraries), Mexican land grant maps and court testimony (1840s–1870s; from TBL), PLS records (1850s–1860s; from BLM), early city and county maps (1850s–1910s, e.g., White 1850; Herrmann 1874; from SCCSO, SCVWD, and local libraries), early American journals and histories (1840s–1900s, e.g., Foote 1888; Manly 1894; from local libraries, historical societies, and used bookstores), 19th-century paintings and drawings (1860s–1890s, e.g., Gray and Gifford 1869; from local libraries and the Library of Congress), US Geological Survey maps (1890s–1910s; from SCVWD), US

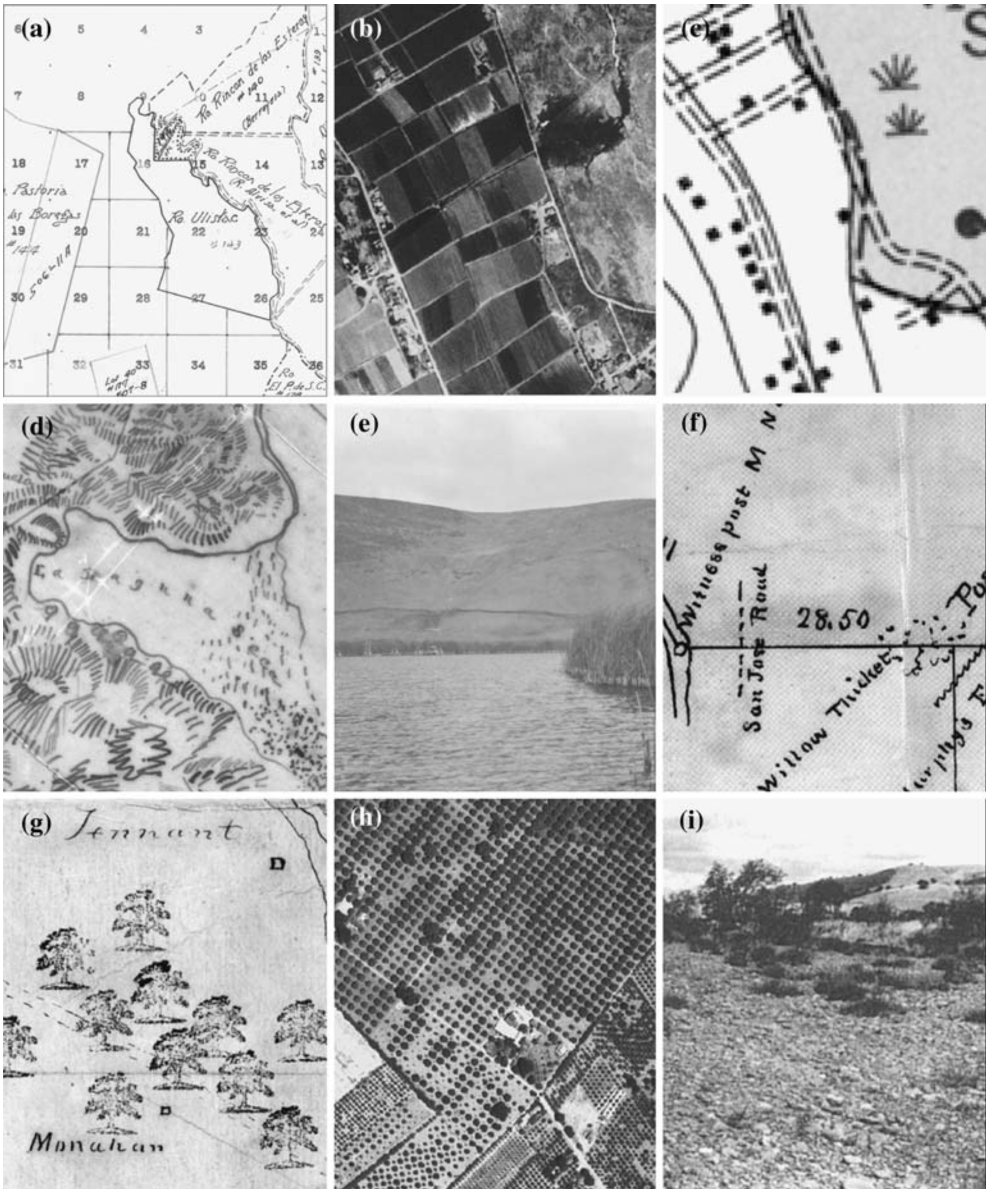

Fig. 2 Some examples of historical records. (**a**) PLS index card showing the combination of standard sectional and irregular land grant boundaries. (**b**) Aerial photography (USDA 1939) shows a distinct boundary between high quality arable land and poorly drained alkali meadow (upper right). The dark irregular feature at upper right is suggestive of a freshwater marsh. (**c**) The marsh and the land use boundary visible in the aerial photograph are corroborated by a later soil survey (Gardner et al. 1958). (**d**) A Mexican *diseño* shows the Laguna Seca wetland complex (Lyman 1847). (**e**) A landscape photograph produced during the reclamation of Laguna Seca (SCVWD Vault 1916). (**f**) Willow groves are described as "Willow Thicket" in a PLS map Thompson 1857a). (**g**) A grove of valley oaks is indicated in a Mexican land grant confirmation survey (Healy 1859). (**h**) Valley oaks are visible as scattered large trees within an orchard (USDA 1939). (**i**) Unvegetated gravel surfaces and riparian scrub in a photograph of the Coyote Creek channel bed (Pickwell and Smith 1938). A, courtesy of BLM; D, F, and G courtesy of The Bancroft Library, UCB; E, courtesy of the SCVWD; I, courtesy of the Cooper Ornithological Society

Coast (and Geodetic) Survey maps (1850s–1890s; from NOAA), landscape paintings and photography (1860s–1910s, e.g., SCVWD Vault 1916; Shortridge 1986; from local libraries and historical societies), aerial photography (1939–1940s; from SCVWD, UC Santa Cruz, UCB, and USGS Western Region

Library), soil surveys (1900s–1940s; from Natural Resources Conservation Service and used bookstores), and ecological research/collections (1890s–1950s, e.g., Smith 1905; Pickwell and Smith 1938; from scientific journals and the California Natural Diversity Database). We found that critical evidence did come from a wide range of material types, including written and graphic materials, Spanish and English-language documents, professional and non-professional surveys, and materials from throughout the historical era.

Our earliest records were generated prior to California's statehood, including the journals of early explorers and, in particular, Mexican land grants. Prior to American ownership, most of central and southern California's coastal valleys were distributed to Mexican citizens, in irregular units that followed physiographic features such as hills, stream courses, and other natural landmarks, rather than a rectangular grid (Allen 1932; Clay 1999; Hornbeck 1979; Fig. 2, panel a). Prospective grantees were required to submit maps called *diseños* ("sketches") of their desired grant lands to the Mexican government (Fig. 2, panel d). They present descriptive information about land cover since, in the absence of abstract boundaries, natural landscape features were used to distinguish properties (Bowman 1943; Brewster 2006). Later, professional surveys (often by the PLS) ratified these boundaries, producing well-controlled maps of confirmed land-grant boundaries (Bowman 1943), largely during the 1850s and 1860s (Fig. 2, panels f and g).

Land cover classes

We found evidence for five land cover types of special interest: valley freshwater marsh, wet meadow, alkali meadow, willow grove, and valley oak savanna. Valley freshwater marsh refers to palustrine, emergent freshwater wetlands (Cowardin 1979) typically dominated by bulrushes (*Schoenoplectus* spp.) Wet meadows are temporarily or seasonally flooded grasslands characterized by poorly drained, clay-rich soils. Alkali meadows, or alkaline grasslands, are also characterized by clay-rich soils but have a high residual salt content and a distinctive, salt tolerant plant community, including some species characteristic of vernal pools or swales (Baye et al. 1999; Holstein 1999). We also documented willow groves (forested wetlands dominated by *Salix lasiolepis*; Cooper 1926), and valley oak savanna (grassland dominated by valley oaks with other subdominant tree species; Brown 2005). We described sycamore alluvial woodland (Keeler-Wolf et al. 1996) and riparian scrub along the Coyote Creek mainstem, but did not find sufficient detail to distinguish these types from each other; they were mapped as a single riparian unit.

Interpretation of historical documents

Accurate interpretation of documents produced during different eras within differing social contexts can be challenging (Harley 1989; Grossinger and Askevold 2005). To address these concerns we carried out background research into the techniques and reliability of the available historical records. Since the number of local professional surveyors during the 19th century was relatively small, we were able to determine the more and less reliable individuals from local histories (e.g., Arbuckle 1986) and our own assessment of multiple documents by the same surveyor. Askevold (2005) provided assessment of the techniques and origins of a number of the relevant record types for the area. Additionally, we intercalibrated independently-produced documents to assess accuracy (see Fig. 2, panels b/c and d/e). This approach, which requires document redundancy, provides the only independent verification of the accuracy of original documents and of our interpretation of them, given the unavoidable absence of replicate samples and predetermined methods (Grossinger 2005; Grossinger and Askevold 2005).

We examined historical data for evidence of conditions prior to significant Euro–American modification. Despite decadal-scale variability, climatic characteristics during the period from which historical data were obtained (1770s–1940s) were relatively stable (Dettinger et al. 1998). Land use was much more variable during this time, so we focused on discerning natural from anthropogenic features. We developed a detailed understanding of the temporal trends in land use history (Fig. 3) and were careful to map only features that were clearly not the result of recent land use. For example, while we use early aerial photography (USDA 1939) to identify probable valley oak trees, we mapped only very large trees (≥ 15 m canopy diameter) likely of

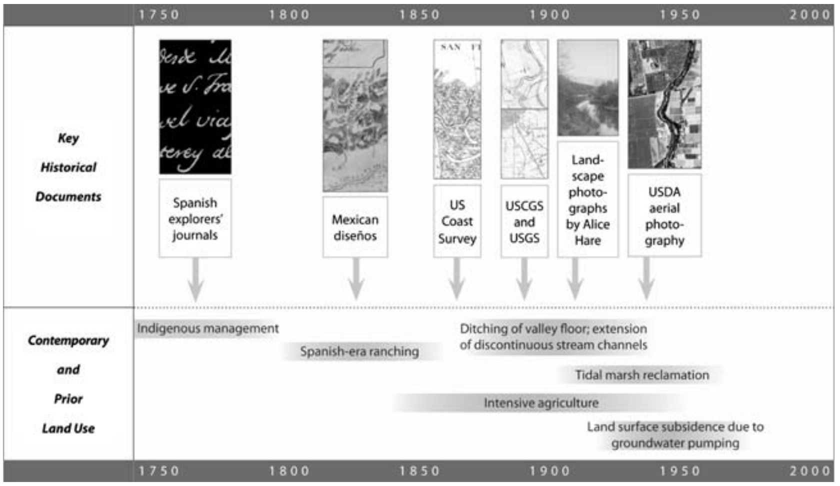

Fig. 3 Timing of selected important historical document types in relation to local land use history. While some documents follow substantial landscape modifications, they can be used in concert with earlier materials to interpret prior conditions

pre-Euro–American vintage (based on preliminary age/size relationships developed for valley oak trees in Napa Valley (134 km to the north; Ruygt, Rae, and Grossinger, unpublished data)). We attempted to document features using multiple sources across the focal time period to assure persistence and accurate interpretation. Often features whose general presence was indicated by Spanish/Mexican era sources could be confirmed and mapped in greater detail based upon later American sources despite surrounding land use changes.

GIS development

Accurate historical maps with pertinent land cover information were georeferenced to contemporary orthorectified aerial imagery (AirPhoto USA, LLC 2002) using ArcGIS 9.0 (ESRI). We also developed a continuous historical aerial photomosaic for the study area based upon the earliest available imagery (75 images, ca. 1939) using the Leica Photogrammetry Suite module of ERDAS Imagine 8.7. The photomosaic was particularly useful for identifying residual valley oak savanna and wetlands within the pre-urban, agricultural setting. We also compiled less precise spatial (including narrative) information on a USGS quadrangle base map, which was scanned and georeferenced for use in constructing the GIS.

We synthesized selected historical data into a GIS to create a picture of historical land cover. To record the variations in source data and confidence level associated with different features, we developed a set of attributes to record both historical sources and estimated certainty levels. The application of attributes on a feature-by-feature basis allows users to assess the accuracy of different map elements and identify the original sources, serving as a catalogue of information sources (Grossinger 2005).

Certainty levels were assigned based upon qualitative or quantitative assessment. Our confidence in a feature's interpretation was assigned on a relative scale based on the number and quality of sources, and our experience with the particular interpretation (Table 1). The accuracy of the area of a mapped feature was assessed as follows. Using the available historical data, and ancillary data such as topography and adjacent features, we mapped the most well supported spatial extent for the feature. We then estimated how much larger and smaller the feature could be drawn while fitting all constraints, and assigned the corresponding classification. Similarly, for certainty of location we estimated the range of possible geolocations based on all available evidence, located the feature in the center of this range, and measured the estimated possible error. The standards for size and location classes were initially developed based on previous mapping experience, then refined during the course of the mapping effort to accommodate the actual range of local evidence.

Assessment of triangulation and uncertainty

To quantify the triangulation of data sources in the historical land cover mapping, we calculated the average number of independent historical records (see Table 2, Note 1) supporting each mapped feature

Table 1 Certainty level standards

Certainty level	Interpretation	Size	Location
High/ "definite"	Feature definitely present before Euro–American modification	Mapped feature expected to be 90–110% of actual feature size	Expected maximum horizontal displacement less than 50 meters
Medium/ "probable"	Feature probably present before Euro–American modification	Mapped feature expected to be 50–200% of actual feature size	Expected maximum horizontal displacement less than 150 meters
Low/ "possible"	Feature possibly present before Euro–American modification	Mapped feature expected to be 25–400% of actual feature size	Expected maximum horizontal displacement less than 500 meters

of a given land cover type. To provide an indication of the uncertainty associated with mapping each land cover type, we summarized the extent of mapped area classified as high, medium, or low certainty.

Past and present spatial extent

We used the GIS to calculate the total area of each land cover type. Only features classified as definite (high) or probable (medium) for their interpretation were included. To assess the uncertainty of area measurements, we also we calculated total areas based on the recorded certainty levels for size. Using the numerical standards for size certainty (Table 1), we created "worst-case" minimum and maximum values for each feature (e.g., all high features could be 10% smaller or 10% larger). To determine the possible range for each land cover type, we totaled all of the minimum area values and all of the maximum area values.

To compare historical and modern spatial extent, we used recent land cover mapping by Jones and Stokes (2006). This data set covered 87% of the study area, so our comparison was limited to the area in common. Corresponding classes were selected based on narrative descriptions of the modern land cover classes (Jones and Stokes 2006). We also compared the historical land cover patterns to existing land use to determine potential restoration opportunities, and conducted limited field surveys to identify the residual or remnant features at these sites.

Results

Assessment of triangulation and uncertainty

Individual features mapped through the historical reconstruction were documented on average by 2.8 independent sources (Table 2). Overall, most features (78%) were recorded by two or more independent historical records. The level of triangulation varied by land cover type. Four of the five focal land cover types (valley freshwater marsh, wet meadow, willow

Table 2 Historical source triangulation and uncertainty by land cover type

Land cover type	*n*	Average number of sources[a]	% with multiple sources[b]	Area by certainty level (%)[c]		
				High	Medium	Low
Valley freshwater marsh	10	2.8	80	81	16	3
Wet meadow	14	2.2	71	100	0	0
Alkali meadow	13	2.2	54	100	<1	0
Willow grove	17	3.9	88	2	97	<1
Valley oak savanna	17	2.6	88	61	17	21
Total	71	2.8	78	75	13	12

[a] Average number of independent historical sources per feature polygon

[b] Percentage of land cover class features (polygons) with multiple sources

[c] Percentage of land cover class area assigned high, medium, or low certainty of size

grove, and valley oak savanna) demonstrated triangulation by multiple sources more than 70% of the time; only 54% of the alkali meadows exhibited multiple source documentation. Most of the mapped area (75%) met the high standard for size certainty. However, the spread between high, medium, and low certainty varied dramatically by land cover type, reflecting the different arrays of source materials and interpretive approaches supporting each type. The certainty level was also independent of the measures of triangulation (average number of sources, % with multiple sources). For example, high values for "% with multiple sources" did not directly translate to high mapping confidence, suggesting that source quality is more important than source quantity and cannot be inferred directly from the number of sources.

Valley freshwater marsh

We documented 10 valley freshwater marshes that could be confidently described (high or medium interpretation certainty) as preceding Euro–American influence. Based on the historical and ancillary (e.g., topographic) evidence for spatial extent, these marshes had a total area of 330 ha, or 3% of the mapped area (Table 3; Fig. 4). Nearly all of the valley freshwater marsh area was classified as high or medium certainty, producing minimum and maximum estimates of 270 ha and 438 ha, respectively.

Because of their limited distribution and relevance to human land use, locations of perennial wetland tended to be well recorded by historical documents, with 80% documented by multiple sources (Table 2). The area of valley freshwater marsh has declined by 88% in the portion of the study area with comparable mapping. Using the minimum and maximum estimates, the decline has been 85–91% (Table 4).

Wet meadow

Seasonally-flooded wet meadows covered an estimated 2,400 ha prior to Euro–American modification (22% of the study area). While this land cover type had a lower extent of triangulation (2.2 sources per feature, 71% with multiple sources) than most other types, we rated all wet meadows as having high size certainty level. This reflected the high reliability of mapping of poorly drained basin soils by soil surveys (Gardner 1958; Lindsey 1974) and corroboration with visible differences in soil texture, moisture, and/or land use in early aerial photography (USDA 1939; Fig. 2, panels b and c). The boundary between sloped alluvial fan deposits and basin soils was readily discernible to soil surveyors in the field (Reed 2005).

The location of probable valley oak trees collected independently from early aerial photography also provided indirect confirmation of the accuracy of the wet meadow and alkali meadow reconstructions, since the trees would not be expected to persist in poorly drained clay soils. Of 1,098 large trees identified from aerial imagery only 15% were located within wet/alkali meadow areas, and more than half the coincident trees were located close to the edges of the meadows (<150 m). Wet meadow decline is on the order of 98% (Table 4).

Alkali meadow

Seasonally flooded alkali meadows were also a significant land cover component, comprising an estimated 1,637 ha, or 15% of the mapped area. Like wet meadows, alkali meadows relied more heavily on a single source of relatively recent origin (USDA soil surveys specifying alkali effects) but were corroborated in many places by independent and earlier information. These included Mexican land case

Table 3 Land cover in eastern Santa Clara Valley prior to substantial Euro-American modification

Land cover type	% Area	Mapped area (ha)	Minimum estimate (ha)	Maximum estimate (ha)
Valley freshwater marsh	3	330	270	438
Wet meadow	22	2,401	2,161	2,641
Alkali meadow	15	1,637	1,472	1,804
Willow grove	2	165	84	327
Valley oak savanna	58	6,158	4,261	11,552

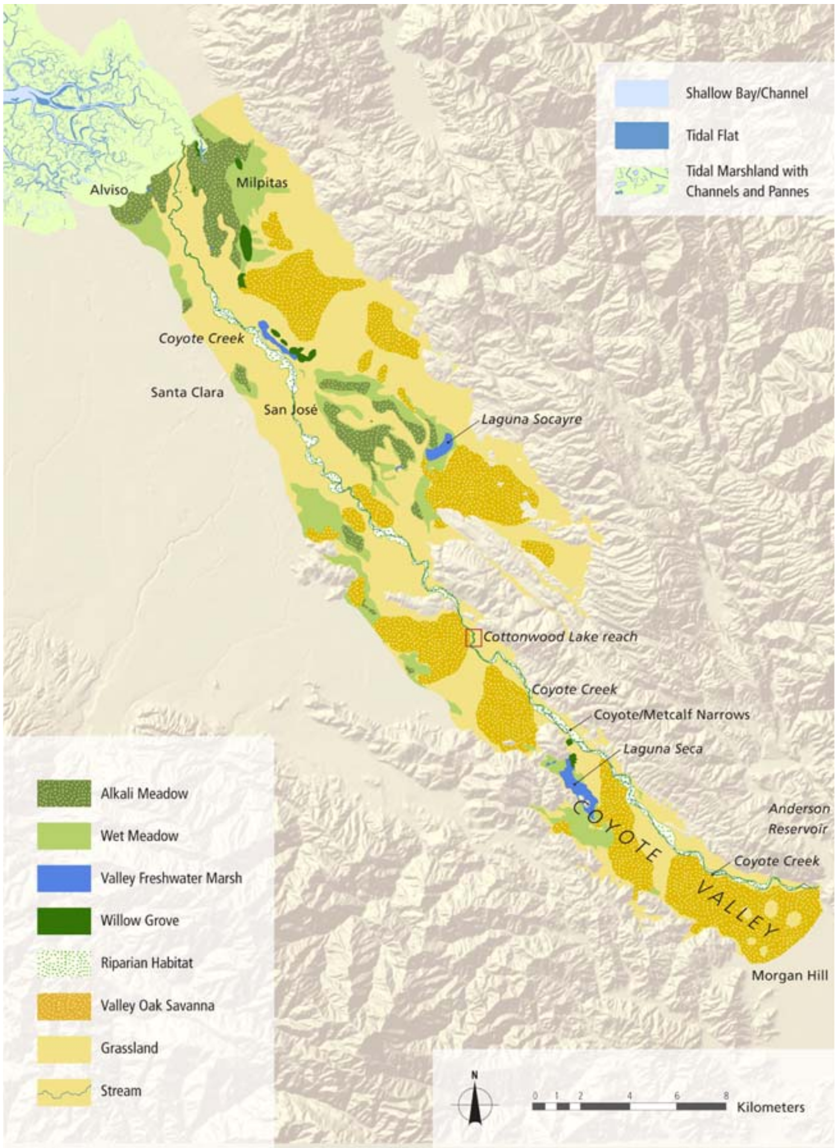

Fig. 4 Reconstructed land cover map of the valley floor along Coyote Creek prior to significant Euro–American modification. For context, several land cover types additional to those discussed here are shown (intertidal features, grassland, and stream courses) from related studies (SFEI 2005; Grossinger et al. 2006). The box shows the location of Fig. 5

Table 4 Land cover change in eastern Santa Clara Valley

Land cover type	Pre-Euro–American modification			2006		
	Total (ha)	Minimum estimate (ha)	Maximum estimate (ha)	Total (ha)	% Decline	Potential range (%)
Valley freshwater marsh	328	268	436	40	87.8	85.0–90.8
Wet meadow	1,884	1,696	2,072	31	98.4	98.2–98.5
Alkali meadow	913	819	1,006	[0]	[100]	–
Willow grove	92	45	196	[0]	[100]	–
Valley oak savanna	6,099	4,207	11,486	11	99.8	99.7–99.9

Analysis covers only the area in common between this study and Jones and Stokes (2006), excluding 13% of our study area. The range estimate uses the minimum and maximum area estimates, which are based on the certainty level assignments for each feature (see Table 2). Bracketed values indicate land cover types not mapped because of low present-day representation testimony (e.g., Pico 1860, who describes "*salitroso* or alkali lands" in the 1840s), PLS notes (e.g., soil "strongly tinctured with alkali"; Day 1854), and botanical records (e.g., alkali milk-vetch (*Astragulas tener* var. *tener*); Smith 1905). This land cover type has experienced a complete or near complete decline and is not represented by contemporary land cover mapping.

Willow grove

Forested wetland areas dominated by willows represented a relatively small percentage of land cover prior to Euro–American modification (2%, or 165 ha), yet were noteworthy landmarks widely used to demarcate property boundaries. As a result, this cover type was extensively documented by mid-19th-century Mexican and American maps, resulting in a high average number of sources (3.9). However, because willow groves were highly amenable to farming and rapidly removed, the historical reconstruction relies more heavily on imprecise Mexican-era maps, resulting in substantial uncertainty in the size (but not the presence) of these features. While willows are common along local creeks today (Jones and Stokes 2006), stand-alone groves not associated with channel banks (referred to as *sausals* in Spanish documents) are not represented in contemporary land cover mapping.

Valley oak savanna

Although substantial uncertainty is associated with the historical reconstruction of valley oak savanna, it was clearly a major land cover type, with an estimated total area of 6,158 ha. Most of these features (88%) were documented by multiple sources, but the delineation of boundaries was not precise, as indicated by 21% of the mapped area receiving low size certainty. Despite a wide potential error in aerial estimates (4,261 ha–11,552 ha), even the minimum estimate for valley oak savanna area far exceeded each of the other four land cover types.

Portions of the oak savanna were documented by identification of 1,098 large valley oak trees from aerial photography, based upon their distinctive size, shape, and groupings (Brown 2002; Sork et al. 2002) and calibration with visual surveys of existing trees, as well as land grant and GLO maps. The relatively open, savanna character of the oak lands was well-documented by some of the earliest descriptions of the area, which refer to the valley as "studded" (Mission records ca. 1782 in LoCoco n.d. [1777–1842]) with oaks in a "park" setting with trees and low understory vegetation (Vancouver 1984). These accounts were corroborated by landscape photographs, lithographs, and the repeated use of the term "scattered" by GLO surveyors to describe valley oak distribution (Healy 1857; Thompson 1857b; Brown 2005).

Comparable land cover mapping indicates that the extent of valley oak savanna has declined by 99.8%. Even given the wide range in potential historical land cover estimates, the decline remains extreme: 99.7–99.8%.

Riparian habitat

Historical data indicated several types of riparian cover along Coyote Creek, but were not sufficiently detailed to delineate these classes individually. However, sufficient information was available to detect a substantial temporal shift in land cover along much of the creek, from relatively open sycamore alluvial woodland, riparian scrub, and unvegetated gravel bars to more dense and homogenous riparian forest.

Evidence for pre-modification riparian conditions included frequent large, unvegetated gravel bars shown by local maps (Herrmann 1874, 1905), gravel bars and riparian scrub visible in early aerial photography (USDA 1939), and a detailed description of the riparian scrub community of the creek's "gravel beds" prior to dam construction (Pickwell and Smith 1938). The presence of sycamore alluvial woodland was indicated by mid- and late-19th-century GLO and county survey notes (e.g., Howe 1851; Day 1854; Wallace 1858) and written accounts identifying sycamores as the dominant riparian tree along most of Coyote Creek (e.g., Healy 1857, Taylor ca. 1850 in Carroll 1903). These data are corroborated by the earliest aerial imagery (USDA 1939), which shows an open savanna/woodland riparian structure with broad, gravel-dominated floodplains, characteristic of sycamore alluvial woodland. Field identification of residual, present-day trees confirmed the species identification.

Presently, dense forest dominated by cottonwood (*Populus fremontii*) is the most prevalent riparian habitat downstream of Anderson Reservoir (Cloak

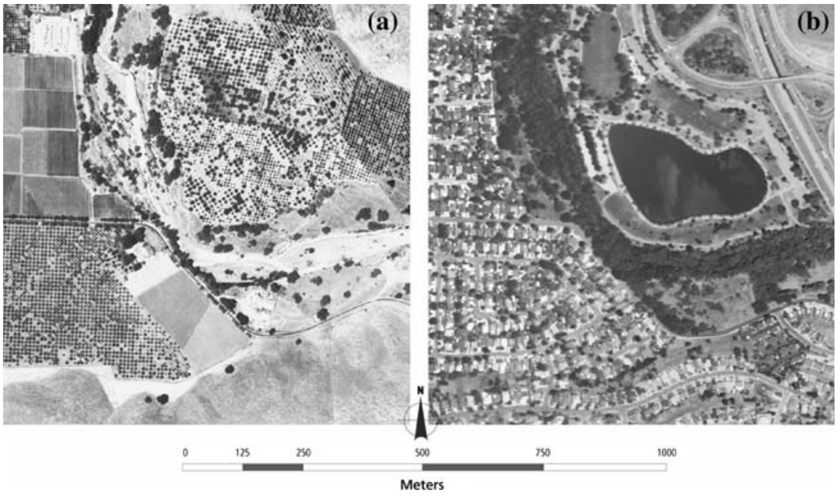

Fig. 5 Coyote Creek at the present-day location of Cottonwood Lake in 1939 (**a**) and 2005 (**b**), showing changes in channel and riparian characteristics. Despite suburban expansion into the formerly agricultural area, the channel has not been channelized or filled. Yet the active channel area has narrowed and riparian trees have colonized much of the formerly sparsely vegetated, braided channel

and Buchan 2001), reflecting a dramatic change from earlier historical conditions (Fig. 5). Of Coyote Creek's 43 km valley floor length, we estimate that this type of habitat conversion has affected at least 25 km.

Discussion

As an epicenter of modern industrial and technological growth, Silicon Valley presents obvious limitations to the conservation of native land cover. However, despite 80% urbanization, the lands along Coyote Creek exhibit substantial opportunities for the restoration of former landscape elements. We argue that historical landscape reconstruction should play a role in identifying sites and strategies which, because of the extensive landscape modification, are not readily obvious.

Former conditions and landscape change

Prior to Euro–American modification, the eastern Santa Clara Valley supported a heterogeneous native land cover. Mosaics of valley oaks and grassland occupied the more well-drained alluvial fans and natural stream levees of Coyote Creek (Cooper 1926; Brown 2005). These areas became the most productive agricultural lands (primarily fruit orchards) and experienced rapid urban expansion in the second half of the 20th century. Lower lying basin areas with clay soils were characterized by wetland habitats, including seasonally wet meadows, alkali meadows, willow groves, and freshwater marshes. Poor drainage characteristics hindered the expansion of agriculture and slowed urbanization of these historically less-valuable areas (Broek 1932).

Loss of native land cover has been extreme, with the five major land cover types each experiencing a decrease of more than 85%. Some land cover types that have not been directly removed by development have nevertheless experienced substantial change, such as the open riparian habitat along Coyote Creek that has converted to dense forest.

The present riparian habitat has typically been considered to be an intact remnant of historic vintage (Cloak and Buchan 2001; SCVWMI 2003), but has largely formed since 1940. This habitat conversion is probably due to changes in stream hydrology, including flood control and summer water release for groundwater recharge associated with the installation of Coyote Dam in 1936 and Anderson Reservoir in 1950, which have dramatically decreased peak winter flows and increased dry season flows (McKee et al. 2003). While this type of vegetation shift on regulated (e.g., Ligon et al. 1995) or urbanized (White and Greer 2006) rivers in the western United States is not uncommon, the local effects are significant. For example, lesser nighthawk (*Chordeiles acutipennis*) commonly nested in the unvegetated gravelly channel beds in the 1930s (Pickwell and Smith 1938) but is no longer a breeding resident, likely due to the change in riparian character and loss of gravel bars resulting from water management (Fig. 5).

In the southern portion of the study area, stream reaches have exhibited much less riparian cover conversion, probably because summer discharges for groundwater recharge have been routed around this reach. Because of the reduced riparian cover relative to downstream reaches, this reach had been considered degraded and increased tree cover recommended (Buchan and Randall 2003). Understanding the landscape history explains this anomalous present-day habitat as remnant of historical alluvial woodland habitat rather than fragmented forest resulting from land use impacts.

Restoration and conservation implications

The historical landscape reconstruction shows that the study area, a relatively flat alluvial valley, nevertheless supported a complex pattern of land cover types with very different ecological characteristics. These patterns, which are related to persistent characteristics such as soils and topography, suggest that restoration efforts for particular land cover types may be more successful in some places than others, which could affect the prioritization of sites for conservation. For example, the distribution of valley freshwater marsh was highly limited in this semi-arid region, with only 10 marshes identified. The restricted distribution suggests that sites with topographic and hydrological characteristics conducive to sustainable wetland restoration are naturally rare and should be strongly considered for conservation and restoration where they are available. Freshwater marshes should also be considered as part of larger wetland mosaics including willow groves, wet meadows, and alkali meadows.

Overlaying historical distribution with contemporary land use revealed a number of specific sites with conservation potential. While most former seasonal and perennial freshwater wetland areas were, as would be expected, heavily developed, we identified one area with significant potential for restoring a mosaic of wetland habitats, and several others with some potential. Laguna Seca (Fig. 2, panels d and e), which was drained for agricultural purposes in 1916, remains in agricultural use, retains some surface water in the summer, and has limited development potential because of periodic flooding. Its position in a topographic low point, with adjacent uplands partially protected by public ownership/easement, represents a rare, previously unrecognized opportunity for restoring a naturally-functioning valley floor wetland mosaic in the region.

Residual alkali meadow characteristics, such as saltgrass and seasonal ponds, were found within county parkland and could be enhanced. A number of large public facilities containing undeveloped lands are presently found in the areas of historical seasonal or perennial wetland, including golf courses, parks, airports, and a wastewater treatment plant with substantial buffer lands. With previously depleted groundwater levels having substantially returned as a result of groundwater recharge (SCVWD 2005), these areas may have some wetland restoration potential, although there are additional factors to be considered (e.g., specific site conditions, mosquito control, invasive species, etc.). The largest area of former valley oak savanna not yet intensively urbanized was found in Coyote Valley, an area currently being considered for development. The significant decline and limited overall area for potential restoration suggest this area has significant conservation value for valley oak savanna.

Comparison of historical and modern landscape patterns also suggests different environmental rehabilitation strategies for different land cover types. Whereas restoration of valley freshwater marsh would most likely focus on the few sites of relatively large historical wetland complex, the widespread distribution and “scattered” spacing of valley oak trees (and the persistence of some historic trees) suggest that groves could successfully be reintroduced more widely within the urban framework. While we did not determine stand density in this study, Sork et al. (2002) found a density of 1.19 trees/ha in intact valley oak savanna in Santa Barbara County, California. Given the current density of planted, mostly ornamental trees and the fact that valley oaks are listed as a suitable urban tree in a number of California cities, such a density could be achieved strategically in places, especially marginal to riparian corridors or open space at the valley edges. Where the restoration of the full oak–grassland association is not feasible, this strategy would prevent the disappearance of valley oaks from the local landscape and support other native species, especially oak-associated birds (Rottenborn 1997).

One of the by-products of extreme landscape modification is often an inaccurate perception of earlier landscapes as, over time, characteristics are forgotten or overlooked (Grossinger 2005). Along Coyote Creek, we found that land cover types such as sycamore alluvial woodlands, alkali meadows, and willow groves were significant parts of the pre-Euro–American landscape but have not been generally considered by those charged with the management of native habitats. Yet some of these land cover types have residual components and may have significant restoration potential, despite little present-day recognition.

Identifying these overlooked land cover types through historical research can expand the restoration palette available to present-day environmental managers. Some of these cover types may represent practical long term management options. For example, sycamore alluvial woodland tends to be associated with seasonally-dry stream channels, and may be a more sustainable local target, given the likelihood of extended droughts and water shortages in the future, than the more popular restoration image of dense riparian forest supported by perennial flow. These intermittent reaches may also support native fisheries and avifauna which may not warrant legal protection, but are nonetheless an important component of a functional ecological system (Pickwell and Smith 1938; Leidy 2007). Similarly, we identified areas of former alkali meadow, now urban parkland, that still show the effects of salt-impregnated soils in the form of saltgrass, seasonal pans, and limited success with planted recreational lawns. These problematic sites for managers might lend themselves to alkali meadow restoration.

The restoration and conservation of native habitats in highly populated, intensively managed landscapes such as the San Francisco Bay area inevitably involves many competing demands for the same areas. Yet the Bay Area continues to support a wide range of threatened or endangered species, ranking as a global hotspot of species rarity (one of only six in the US; California Department of Fish and Game and Stermer 2003). The use of historical records is important because urban, suburban, and agricultural development can obscure persisting landscape patterns and processes, preventing environmental managers and the public from making best use of available conservation and restoration opportunities (Collins et al. 2003).

Methodological implications

We suggest that historical landscape reconstruction for much of California's coastal valley landscape requires a different approach than other areas around the world because of its Spanish colonial history. However, extensive historical data are nonetheless available through the acquisition of a wide array of materials from a number of different institutions. Using this heterogeneous range of largely locally-derived data raises challenges, since little previous research is available to validate the use of these data sources. We found that methodological approaches such as triangulation, recording of sources by feature, and the application of certainty attributes can address some of these challenges by adding transparency, reproducibility, and clarification of uncertainty to the historical reconstruction.

The use of certainty standards offers a way to track the cumulative potential error of the mapping endeavor and, by providing a potential error range specific to each cover type, guidance for the appropriate use of historical land cover results. The uncertainty estimates indicate substantial potential error in some of the total areas, but these ranges had relatively little effect on the assessment of decline (Table 4). Landscape change has been so extreme that uncertainty in historical condition is relatively small in comparison.

Documents originating from different eras—with different methods, scale, and purpose—enhanced the interpretation of individual features and the accuracy of mapping. The use of overlapping sources of varying origin may have some benefits over the reliance on a more consistently available, primary historical source material by providing numerous checks against document bias (Harley 1990). Recording the sources of data supporting each mapped feature as GIS attributes facilitated the documentation of a complex process of data synthesis and will allow individual interpretations to be reviewed and revisited. Resulting measures of triangulation, such as the average number of sources and the percentage of features with multiple sources, provided an illustration of the extent of triangulation but were not related to mapping accuracy, as can be seen in Table 2. This indication that source quality cannot be determined directly from the quantity of independent sources suggests that a separate system of assessing and reporting mapping accuracy, such as certainty levels, is necessary to address concerns about mapping confidence.

Future research

Regional scale assessment of historical and contemporary land cover constitutes a first step in identifying potential conservation opportunities and strategies within highly modified landscapes. The next step involves site-specific investigation of whether the conceptual approaches suggested by the regional landscape assessment are possible, given local environmental factors (e.g., groundwater level, the extent of surface soil modification, effects of impervious surfaces, proximity to native/invasive species).

An additional area of study that could further explain historical land cover patterns and expand the palette of restoration alternatives is an examination of pre-colonial, indigenous management regimes (Striplen and DeWeerdt 2002; Striplen 2005). Historical accounts often note the landscape-scale modifications engaged in by the local Tribes (in this case, various Bands of the Costanoan/Ohlone linguistic group). For example, Spanish explorers commonly describe vast areas of "burnt over" ground (Mayfield 1978; Crespi and Brown 2001; Stewart et al. 2002), various types of foods, and utilitarian devices, all largely derived from locally-managed plant material (Blackburn and Anderson 1993). Further investigation into the precise methods, spatial and temporal extent, and ecological role of these precolonial landscape modifications could be instrumental in understanding the relationships between human-modified resources and historical land cover distribution.

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