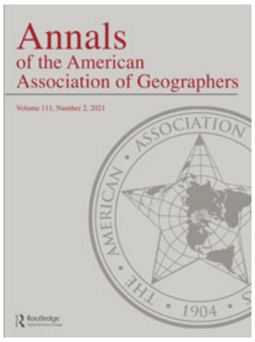

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The Test of Time: Using Historical Methods to Assess Models of Ecological Change on California's Hardwood Rangelands

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Geographers and environmental scientists use conceptual models to understand ecological processes and support management decisions. Most of these models are based on short-term experiments and field observations, which might not account for longer term forces that shape ecosystems over decades to centuries. How can scholars use historical sources and methods to improve conceptual models of ecological change? In this article, we present the results of a study that employed methods from environmental history and historical geography to assess three conceptual models that researchers have used to study ecological changes on California's hardwood rangelands: the succession and climax, state and transition, and cyclical replacement models. The succession and climax model fared poorly at all spatial scales. The historical record contained substantial evidence to support the predictions of the state and transition model at the small spatial scale of the plot or field (0.1–100 ha) and the very large spatial scale of the hardwood rangeland bioregion (4 million ha). The cyclical replacement model performed well at the intermediate scale of the landscape or typical cattle ranch (100–10,000 ha). Historical data and methods hold considerable untapped potential for assessing, building on, and improving conceptual models of ecological change in geography and the environmental sciences. *Key Words: California, historical methods, models, rangelands, scale.*

Rangelands cover between one third and one half of Earth's ice-free land surface, contain rich natural resources, produce essential animal protein, and provide homes for nearly a quarter of the human population (Havstad et al. 2009; Sayre 2017). In the western United States, rangelands comprise more than half the land area—encompassing woodlands, shrublands, grasslands, deserts, and alpine meadows (Havstad et al. 2009)—where they are used for livestock grazing, conservation, recreation, timber production, and watershed protection (Asner et al. 2004).

Over the past century, researchers have used several conceptual models—including the succession and climax, state and transition, and cyclical replacement models—to study and manage diverse rangelands (Derner et al. 2012; Figure 1). Conceptual models are "simplified version[s] of reality" that scientists use to improve their understanding of ecosystems, support management decisions, and predict future changes (Hagget 1965, 19). Yet, despite the growing technical sophistication and quantitative rigor of range science (Briske, Fuhlendorf, and Smeins 2005), scholars continue to debate how valid and applicable these models are under various social and ecological conditions (Knapp and Fernandez-Gimenez 2009; Brenner 2011; Brunson 2012; Sayre et al. 2012). In response, some scholars are now calling for more qualitative, place-based, and historical research to contextualize, build on, and evaluate the validity of key models in rangeland science (Sayre 2004; Sayre et al. 2012; Lave et al. 2014).

This article responds to these calls with an interdisciplinary approach that uses historical methods and evidence to assess conceptual models of ecological change. Our study draws from diverse natural science, social science, and historical scholarship but moves beyond previous works by introducing a new approach for evaluating models using the historical record. Our results show that combining scientific and historical methods in creative new ways can increase our understanding of contemporary geographic patterns, socioecological systems, and environmental change. For this study, we focused on central California's hardwood rangelands, but our approach is applicable to diverse geographic regions and ecological systems.

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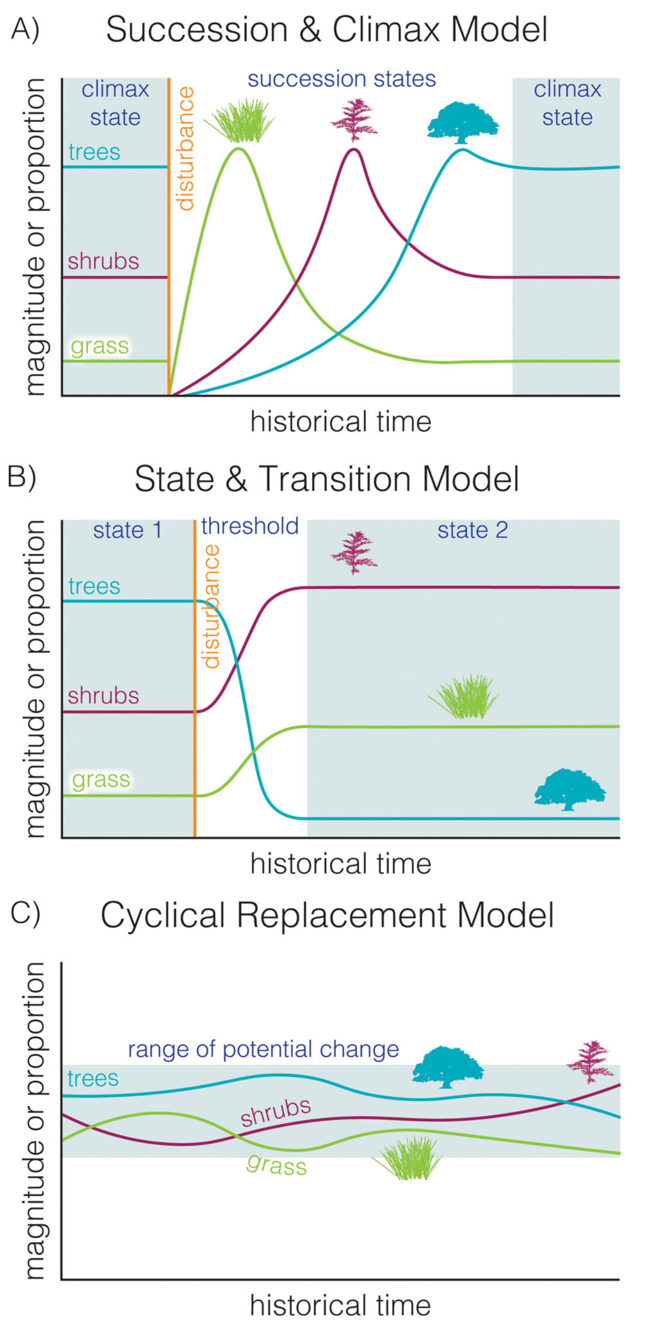


Figure 1. Predictions of conceptual models in range science. (A) After a major disturbance, such as a severe fire, vegetation on a site will recover through a series of stages. In the absence of other intervening factors, vegetation will eventually return to its climax state. (B) Vegetation on a site will remain stable until one or more forces push it over a threshold, leading it to rapidly reorganize into a new durable state. (C) Vegetation at a point on the landscape will change over time due to the interactions among plant species, which might facilitate or inhibit the growth of other species. If these interactions remain consistent, then proportion of a landscape in various vegetation types might also remain consistent.

In this study, we posed three questions: one methodological, one empirical, and one epistemological. (1) Can historical methods provide sufficient evidence to identify patterns of ecological change in California's hardwood rangelands? (2) If so, does the historical record display the kinds of patterns predicted by any of the three scientific models of ecological change mentioned earlier? (3) More broadly, can historical methods be used to assess scientific models of ecological change?

In the pages that follow, we argue that although historical methods cannot replace scientific research, they offer a crucial—and underused—complement that can reveal strengths and weaknesses of ecological models and point to contexts and cases in which certain models might outperform others. Historical methods are especially useful in identifying the spatial scales at which these ecological models are most useful and applicable.

For our study sites, the historical record was uneven and incomplete, but it contained sufficient information to draw key conclusions and complement established and ongoing scientific research. We found that the succession and climax model poorly described vegetation changes on our study sites, at all spatial scales. The state and transition model performed well at the scales of the large (4 million ha) bioregion and small (0.1–100 ha) field. The cyclical replacement model performed well at the intermediate (100–10,000 ha) scale that includes our three study sites, as well as many working ranches in this region. None of these models, however, provides meaningful insights into the sociocultural forces that drive rangeland change, the full diversity of resources and values that rangelands provide, or the interactions among sociocultural and biophysical variables that shape these landscapes.

Background

Over the past century, scientists have developed a series of conceptual models of rangeland ecosystem dynamics. These models seek to explain patterns of change and continuity over time, but investigators usually have based them on short-term experimental or observational research, extrapolating their results to larger areas and longer time periods (e.g., Corbin and D'Antonio 2004). For our study, we selected three models that have shaped how geographers, ecologists, and others understand California's hardwood rangelands.

Succession and Climax

During the first three decades of the twentieth century, Clements developed the notions of succession and climax, resulting in one of ecology's most enduring and controversial conceptual models. According to Clements (1916), a site's physical properties, particularly its climate and soils, produce a cohesive plant community that tends toward equilibrium (Worster 1977). These communities respond to disturbances in predictable ways (B. H. Walker 1993; Briske, Fuhlendorf, and Smeins 2005; Masutti 2006; Sayre 2017). Modest disturbances, such as regular grazing, can arrest succession in a prolonged subclimax, or "seral," state. Following a major disturbance, however, most sites will pass through a series of successional stages, eventually returning to their climax condition (Sayre 2010; Figure 1A).

By the 1920s, state and federal agencies, including the U.S. Forest Service, were using the succession and climax model as a guide for managing rangelands by calculating the number of livestock to permit in an area each year based on the amount of available forage (Sayre 2017). This approach soon encountered problems. Ranchers and range managers noted that grazing could have severe long-term impacts, which were difficult to predict before damage was done (Sampson 1919). The succession and climax model also failed to explain why some western rangelands (Westoby 1979; Westoby, Walker, and Noy-Meir 1989; George, Brown, and Clawson 1992), from Arizona and New Mexico (Glendening and Paulsen 1955; Buffington and Herbel 1965; Bahre and Bradbury 1978; Floyd et al. 2003; Asner et al. 2004; Gibbens et al. 2005; Sayre 2010) to California (Biswell 1956; Heady 1958), seemed to have shifted to new, relatively stable, but often less productive, vegetation types.

State and Transition

In 1989, Westoby, Walker, and Noy-Meir argued that the succession and climax model was insufficient to explain these observed patterns, particularly in very dry climates where "episodic events are important and influences of grazing and intrinsic vegetation change act intermittently" (271). As an alternative, they proposed a state and transition model in which rangelands remain stable for extended periods until natural events or human actions—or some combination of these two—push them over a threshold, triggering rapid, qualitative shifts to durable new states (Westoby, Walker, and Noy-Meir 1989; Laycock 1991; B. H. Walker 1993; Stringham, Krueger, and Shaver 2003; Briske, Fuhlendorf, and Smeins 2005). State transitions often begin with changes in soil properties, producing new biochemical and hydrologic regimes, which lead to changes in the vegetation even as the climate remains stable (Butzer and Helgren 2005). The state and transition model thus predicts that the vegetation in an area will remain relatively stable for long periods, but from time to time these stable states may be punctuated by rapid and dramatic transitions (Figure 1B).

Westoby, Walker, and Noy-Meir (1989) explained that their state and transition model was "necessarily an abstraction" (268). Yet it reflected a broader shift in the environmental sciences toward models featuring nonlinear dynamics, tipping points, and multiple stable states (Lewontin 1969; Holling 1973; May 1977; Wu and Loucks 1995; Beisner, Haydon, and Cuddington 2003). Within a decade, the state and transition model eclipsed the succession and climax model as an organizing framework for range science and management in diverse regions (George, Brown, and Clawson 1992; Behnke, Scoones, and Kerven 1993; Bestelmeyer et al. 2009; Sayre 2017).

Cyclical Replacement

In California, a third, less well-known approach also has proven useful for understanding point-level shifts in vegetation. The cyclical replacement model, proposed by Aubréville (1938), posits that biological interactions among plants facilitate change from one vegetation type to another at a given location (Yeaton 1978). In California's hardwood rangelands, Callaway and Davis (1993) used air photos to determine annual transition rates—the probability that a site would shift, for example, from sage scrub to grassland or oak woodland—among cover types. These point-scale replacements could result in gradual changes in the proportion of cover types over time or they might cancel out, fostering stability at the landscape scale (Figure 1C). Cyclical replacement dynamics might be important in systems that exhibit frequent point-level transitions even as the total proportion of land covered by various vegetation types remains relatively constant.

Study Area

California Hardwood Rangelands

Hardwood rangelands cover around 4 million ha of valley and foothill terrain in California, including grassland, sage scrub, chaparral, savanna, and woodland (Davis 2016). Their Mediterranean climate, typified by warm, dry summers and cool, wet winters, supports nineteen species of native oaks, the dominant trees of these diverse and distinctive landscapes, as well as more than 300 vertebrate animal species and around 90 percent of California's rare and endangered species (Huntsinger and Bartolome 1992; Stromberg, Kephart, and Yadon 2001; Barry, Larson, and George 2006).

California's hardwood rangelands were among the most densely populated regions in the current area of the United States prior to European contact, but we know little about their histories or ecologies before the eighteenth century (Huntsinger and Bartolome 1992; Holstein 2001; Stromberg, Kephart, and Yadon 2001; Heise and Merenlender 2002; Gamble 2005). Most ecologists no longer believe that perennial bunch grasses uniformly dominated this region's grasslands and woodland understories. Yet, botanical and paleoecological studies, using pollen cores and other sources (Dingemans et al. 2014), suggest that hardwood rangelands did experience significant changes in their understory plant communities during the eighteenth and nineteenth centuries, including the widespread establishment of dozens of exotic grass and forb species.

Beginning in 1769, Franciscan friars established a chain of missions in coastal and valley hardwood rangelands from San Diego to Sonoma, triggering dramatic ecological changes, as well as the demographic collapse of indigenous populations. By the early nineteenth century, the missions' free-roaming livestock herds probably numbered at least 400,000 cattle and 300,000 sheep (Cleland 1941; Burcham 1956, 1957, 1961; Larson-Praplan 2014). Between 1834 and 1836, Mexican authorities secularized the missions, granting land to favored patrons. By 1846, California had a population of around 110,000, with at least 500 working ranches (Burcham 1956).

The California Gold Rush and U.S. statehood ushered in another period of change. Between 1850 and 1920, the state's human population grew to more than 3.4 million. Anglo-American settlers dispossessed the hardwood rangelands from their remaining indigenous inhabitants and Hispanic landowners and instituted a more efficient, but also more volatile and ecologically destructive, market-oriented system (Igler 2001).

Beginning in the 1920s, Arthur Sampson led an effort through the University of California's (UC) Cooperative Extension to restore and conserve hardwood rangelands using scientific principles. After World War II, ranchers sought to produce more commodities from their lands to support a booming population. Between 1950 and 1976, California's cattle population grew by 280 percent (Burcham 1981). Seeking to increase stream flow and stimulate forage growth, Cooperative Extension specialists advised ranchers to their clear their lands (Alagona 2008). Ranchers responded by converting around 360,000 ha, one twelfth of the state's hardwood rangelands, from woodland and chaparral to annual grassland pastures (Huntsinger and Standiford 1990).

This phase ended around 1980. Rural areas that had seen little population growth in more than a century began to attract commuters and retirees, leading to increases in property values, taxes, subdivisions, and clashes between longtime residents and newcomers (P. Walker and Fortmann 2003; Wacker and Kelly 2004; Huntsinger et al. 2010). Changes in agricultural economics, including the explosion in demand for wine grapes, led to shifts in land ownership and the conversion of rangelands to crops, spurring additional conflicts (Merenlender 2000). Today, California's hardwood rangelands differ from other Western rangelands, most of which are publicly owned and relatively remote. Around 80 percent of California's hardwood rangelands are privately owned, and many are within a couple hours' drive of major metropolitan areas, leaving them vulnerable to residential development and other land use changes (Alagona 2008; Easterday et al. 2016).

Study Sites

Our three study sites were the Hastings Natural History Reservation in Monterey County, the Hopland Research and Extension Center in Mendocino County, and Sedgwick Reserve in Santa Barbara County. Together, these sites capture the ecological richness and diversity of California's hardwood rangelands and comprise a latitudinal transect representing the northern, central, and southern portions of the state (Table 1, Figure 2).

Table 1. Study sites

	Hastings Natural History Reservation	Hopland Research and Extension Center	Sedgwick Reserve
Date of UC acquisition	1937	1951	1997
Location	Carmel Valley, Monterey County	Russian River Valley, Mendocino County	Santa Ynez Valley, Santa Barbara County
Administered by	UC Berkeley and the UC NRS	UC Davis and the UC Division of Agriculture and Natural Resources	UC Santa Barbara and NRS
Area	960 ha	2,168 ha	2,388 ha
Distance from Pacific Coast	29 km	51 km	24 km
Elevation	467–953 m	152–914 m	289–792 m
Average annual precipitation	53 cm	104 cm	38 cm

Note: UC = University of California; NRS = Natural Reserve System.

These sites also represent a diversity of grazing and use histories, and each was acquired by the UC in a different period. Farming and ranching began at the Hastings Natural History Reservation in the 1860s, but the reserve has prohibited these activities since its establishment in 1937. Founded as a sheep research and extension station in 1951, the Hopland Research and Extension Center hosted ambitious experiments during the 1960s and 1970s designed to increase stream flow, improve forage productivity, and reduce livestock losses to predators. In 1956 and 1965, scientists there converted a 110-ha pair of opposite-facing slopes from blue oak woodlands to grasslands using mechanical treatments (Watershed I), herbicides (Watershed II), fire, and aerial reseeding. Sedgwick Reserve, established in 1997, was part of an 1845 Mexican land grant. Grazing has occurred there sporadically for more than 175 years (Hamilton 1997). Since its establishment as a university reserve, Sedgwick has hosted research on a variety of topics including oak regeneration, burrowing rodents, the effects of livestock on plant communities, and livestock grazing as a management tool.

Methods

We developed a seven-step approach for using historical evidence to assess scientific models of ecological change on California's hardwood rangelands.

(1) We selected study sites based on how well each potential site represented the diversity of California's hardwood rangelands and on our ability to find sufficient sources to study their histories. Preliminary archival surveys and discussions with university staff indicated that our three sites had some of the most robust historical record collections of the UC system's natural reserves and extension centers.

(2) We collected diverse historical data pertaining to our sites. We began our work by focusing on records held at our three sites and affiliated university facilities. To fill in gaps and build confidence in the accuracy of these records, we collected several hundred additional documents and other sources from off-site locations, including archives, databases, libraries, government offices, and personal collections owned by private individuals. Our main categories of sources were *primary texts* including court records, U.S. General Land Office records, accounts by early naturalists and government surveyors, fire records, old maps, county and state stocking records, field station reports, newspapers; *unpublished studies* including data sets in station files and oral history interview transcripts; *published studies* identified using various bibliographies and databases; and *historical images* including snapshots, repeat photography series, and aerial photographs (Figure 3). We also conducted several *interviews*.

(3) After scouring the historical record, we chose seven indicators of change: vegetation, fire, livestock, wild ungulates, carnivores, precipitation, and soil erosion (Table 2). To qualify for inclusion, a potential indicator had to be either ecologically important or socially important, and it had to have sufficient sources to enable us to draw conclusions, either quantitative or qualitative, about patterns of change over time. The potential suite of indicators available based on these criteria was limited by what people in the past thought was important enough to document and preserve, but despite these limitations,

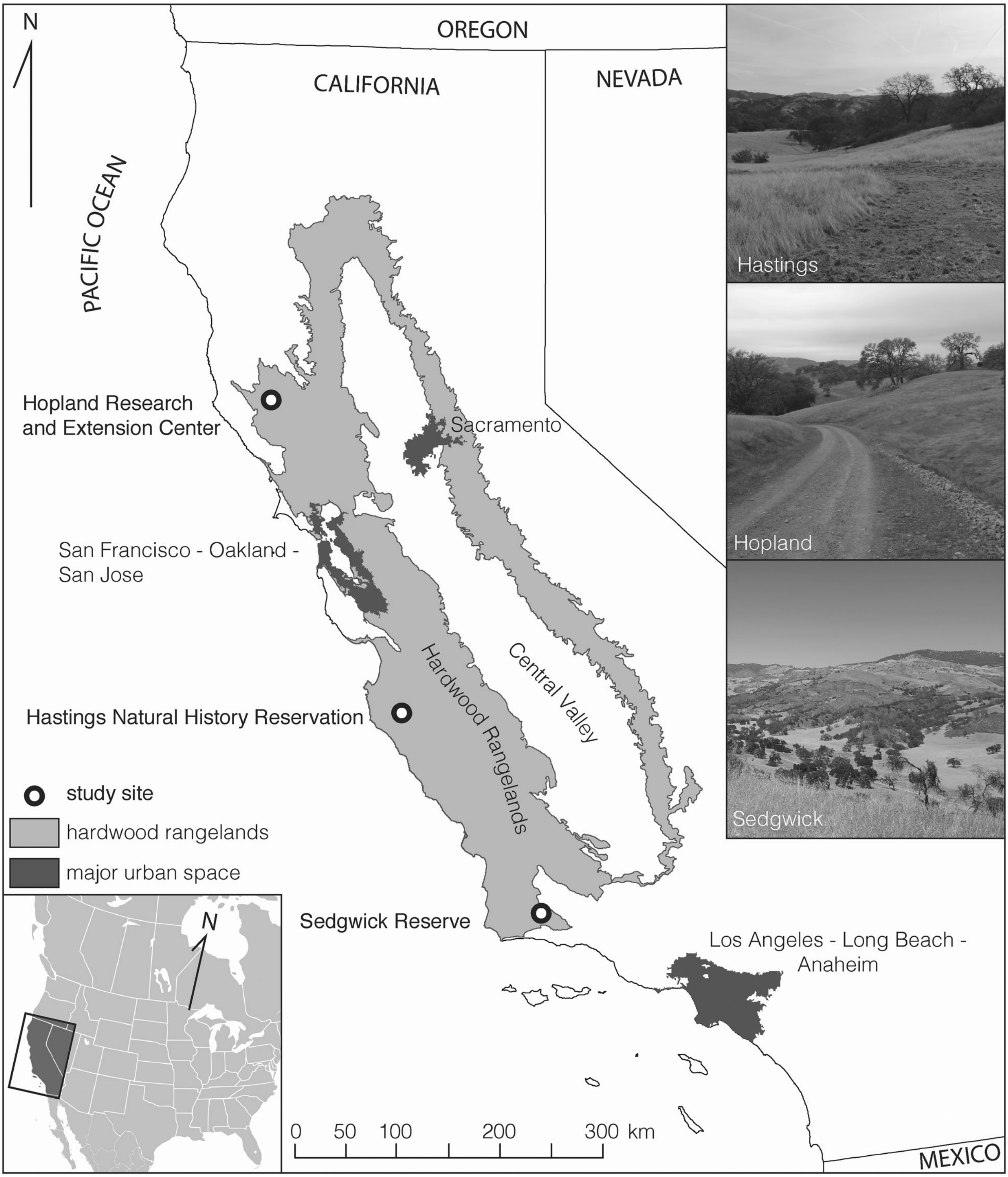
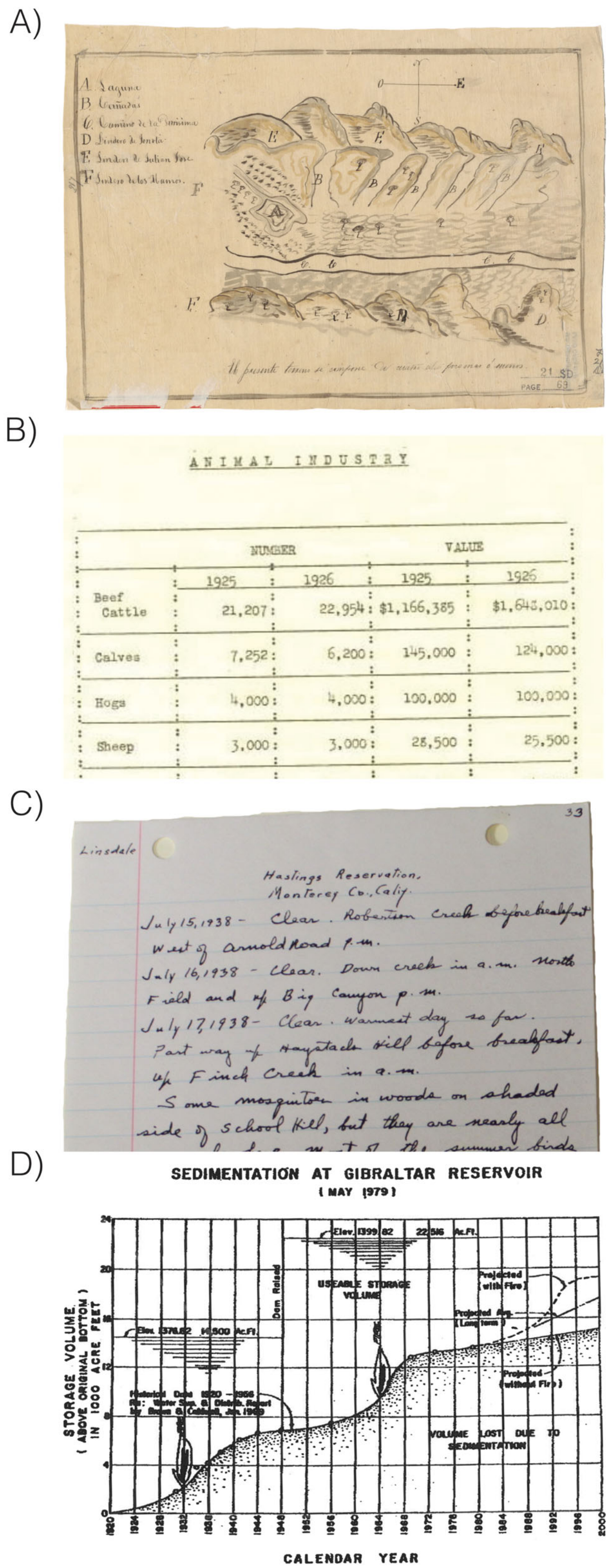


Figure 2. Study sites. Hardwood rangelands extent from Environmental Protection Agency Level III Ecoregion 6. *Source:* https://www.epa.gov/eco-research/ecoregion-download-files-state-region-9#pane-04. Photographs by authors (2016).

our approach provided a more holistic view of rangeland ecological change than most traditional studies focusing on livestock and forage. This approach built on, but went beyond previous indicator-based rangeland research (e.g., Bestelmeyer et al. 2003; Fernandez, Neff, and Reynolds 2008) by integrating multiple historical indicators into a single study and by using these indicators to assess models of change.



ANIMAL INDUSTRY

	NUMBER		VALUE	
	1925	1926	1925	1926
Beef Cattle	21,207	22,954	$1,166,385	$1,643,010
Calves	7,252	6,200	145,000	124,000
Hogs	4,000	4,000	100,000	100,000
Sheep	3,000	3,000	28,500	25,500

Figure 3. Sample sources. (A) Diseño of Rancho La Laguna de San Francisco, including Sedgwick, c. 1845 (Volume 21 SD, Documents Pertaining to the Adjudication of Private Land Claims in California, circa 1852–1892, Bancroft Library); (B) Santa Barbara Agricultural Commissioner crop report, 1926 (with permission, County of Santa Barbara, https://countyofsb.org/uploadedFiles/agcomm/Content/Other/crops/1926.pdf); (C) Jean Linsdale's observational notes on Hastings, 1938 (with permission, Museum of Vertebrate Zoology, UC Berkeley, MV2A.MSS.0118, Box 19, File 21, Hastings Natural History Reservation Collection); (D) Sedimentation at Gibraltar Reservoir linked to area fires, 1979 (with permission, City of Santa Barbara).

(4) We then analyzed the historical record, exploring our sources for insights about changes over time for each indicator. Most of our sources provided only qualitative information, but we were able to quantify vegetation change since the mid-twentieth century. We quantified change by identifying both the earliest and most recent high-quality aerial photographs for each site, recording the vegetation on these photos at 1,000 randomly generated points, and then comparing the results for each time step to identify trends. We also set out to assess the robustness and reliability of our sources by finding areas where they offered corroborating or conflicting accounts for a given indicator on each site. Known as triangulation (Denzin 1978; Philip 1998), this approach enables researchers to identify knowledge gaps, areas of conflict or correspondence among sources, and broad or emergent patterns that might not be apparent from a single source. Triangulating also enabled us to compare, contrast, and integrate sources representing various spatial and temporal scales.

(5) We developed two kinds of representations of change over time: narratives and visualizations. Drawing from the work of Foster et al. (2002), who used historical evidence to study wildlife population trends in New England over four centuries of landscape change, we compiled detailed narrative histories for the seven indicators on each of our three sites. We then visualized these patterns of change by producing graphical timelines capturing key events and trendlines (Figure 4). To do this, we input all of our data for all indicators and sites into a spreadsheet (see http://blogs.ubc.ca/timpaulson/resources/data/). We generated line graphs from quantitative data for most indicators and plotted trends from qualitative data on wild animal populations on an absent–low–high scale, we plotted fires and soil slips as discrete events represented by vertical lines, and we compared our narrative histories and visualizations to better understand the changes represented in each.

Table 2. Sources available for sites and indicators

	Hastings Natural History Reservation							Hopland Research and Extension Center							Sedgwick Reserve						
Source type	Vegetation	Fire	Livestock	Wild ungulates	Carnivores	Precipitation	Erosion	Vegetation	Fire	Livestock	Wild ungulates	Carnivores	Precipitation	Erosion	Vegetation	Fire	Livestock	Wild ungulates	Carnivores	Precipitation	Erosion
Aerial photos	x							x							x						
Bathymetric data/reports							x														x
County livestock inventories			x							x								x			
Expert opinion	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Fire data		x							x							x					
Herbarium records								x													
Historical precipitation modeling						x							x							x	
Maps		x							x						x						
Mexican land grant records			x							x					x		x				
Newspapers																	x				
Off-site archives	x			x				x													
On-site archives	x	x	x					x	x								x				
Oral histories								x		x		x		x			x				
Published research and data	x							x	x	x	x	x		x	x	x					
Site livestock data										x							x				
U.S. General Land Office records	x		x							x											
Weather station data						x							x							x	
Wieslander (Vegetation Type Map) survey	x														x						

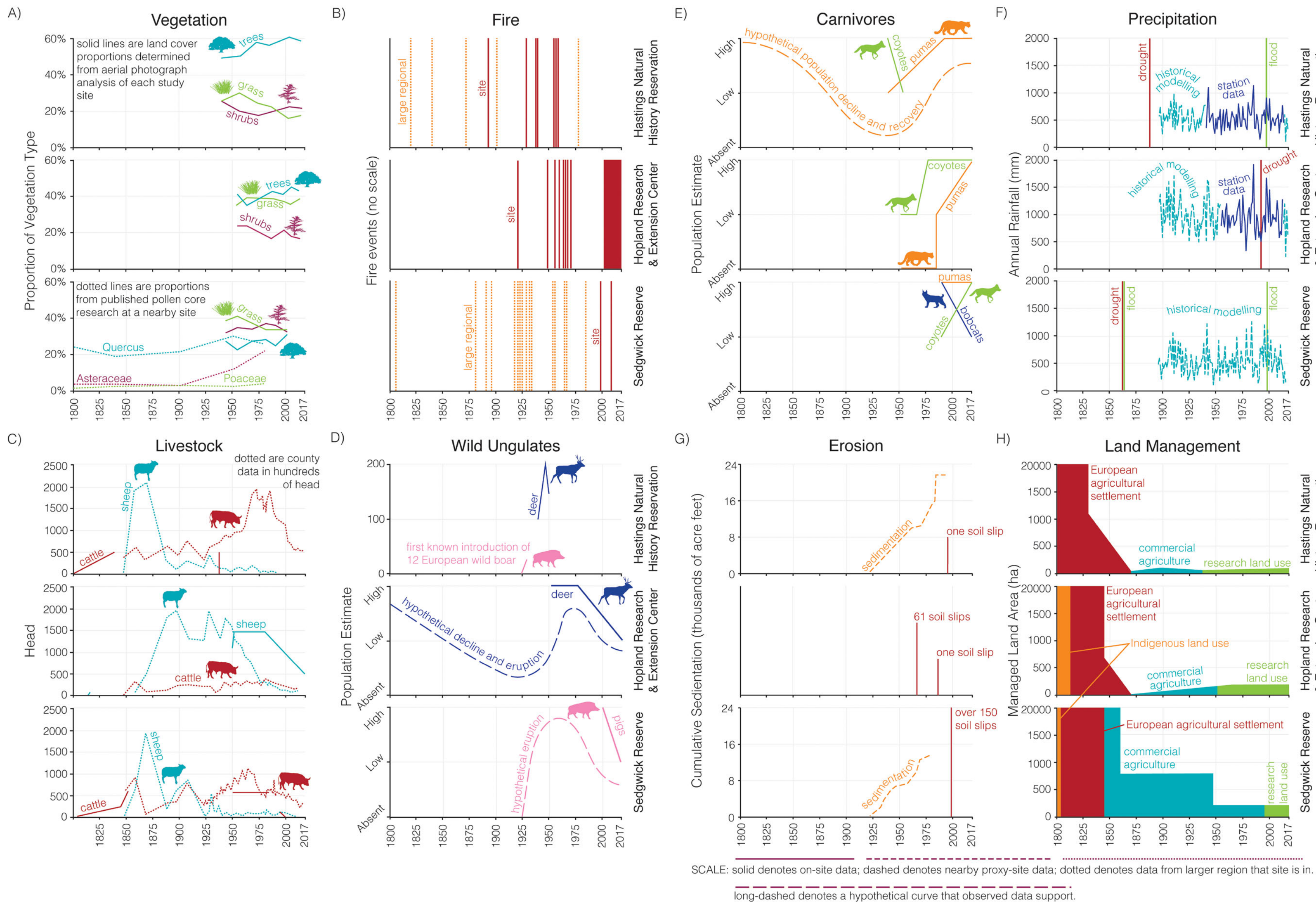


Figure 4. Timeline graphs for sites and indicators. (A–G) All plotted lines correspond to existing historical evidence unless labeled hypothetical. (H) Land management periods and site size are included for reference. Please see supplemental material for source data and references (http://blogs.ubc.ca/timpaulson/resources/data/).

Table 3. Results of aerial photography land cover analysis

	Hastings Natural History Reservation	Hopland Research and Extension Center	Sedgwick Reserve
Air photos available	1939–2014	1954–2014	1943–2014
Change in grass	–0.27	+0.11	–0.14
Change in shrubs	–0.12	–0.27	+0.14
Change in trees	+0.21	+0.04	+0.05

Note: Table shows relative change in cover percentage from earliest to most recent photograph sampled.

(6) After obtaining our initial results, we administered a qualitative survey to a dozen experts familiar with our study sites. We selected the individuals for this process based on previous knowledge of researchers familiar with these sites and on recommendations from field station staff. Our survey asked each expert to describe any known shift in each of our indicators qualitatively or quantitatively and also how the expert knew this. Through this process, we solicited feedback both about historical trends and about additional sources to consult for further information. We incorporated this feedback and these sources into subsequent analyses and drafts.

(7) We concluded by comparing the results of our historical research with qualitative predictions about change over time offered by the three conceptual models described previously. This involved tracing long-term patterns of change, zooming in to identify key moments in the historical record that could reflect the kinds of patterns of change predicted by these three models, and zooming out to consider the social, ecological, and scientific contexts of these formative moments.

Results

In this section, we summarize our findings. We do not, however, cite primary sources, including scientific publications more than thirty years old, in the text or figures due to the voluminous scope of these materials. A full list of our sources can be found in the online supplemental materials at http://blogs.ubc.ca/timpaulson/resources/data/.

Vegetation

In recent decades, conservationists have worried that oak woodlands in California are declining due to land use change, poor recruitment, and other factors. On our sites, however, we found a broad pattern of stability at the landscape scale, with only modest transitions among vegetation cover types, from 1769—when extensive written records for this region first appear—to 2017.

Records from the late eighteenth and early nineteenth centuries were vague and impressionistic, describing general patterns over large areas or offering specific information of dubious accuracy. The first systematic studies—including General Land Office surveys conducted in the 1870s and 1880s, and Wieslander Vegetation Type Maps produced in the 1920s and 1930s—portray landscape mosaics of oak woodland, sage scrub, chaparral, and grassland like those we see today in areas that have not since been developed for agricultural, residential, or commercial uses. Aerial photographs, starting between the 1930s and 1950s, offer some of the best data for these sites (Table 3, Figure 4A). At all three sites, areas intentionally cleared of trees and brush showed little sign of regrowth (Figure 5).

Fire

Despite the well-known importance of fire in these landscapes, on our three sites fires tended to be small, set by people, and quickly extinguished. Archival and published sources for Hopland indicate that small fires were frequent during the first half of the twentieth century, increasing after 1951 under university management. Expert feedback for Hastings indicates that small fires set by trespassers and others have been common, probably increasing in recent decades, whereas expert feedback for Sedgwick pointed to a handful of small fires since 1950, during a broader period of aggressive fire suppression. In July 2018, the massive Mendocino Complex Fire

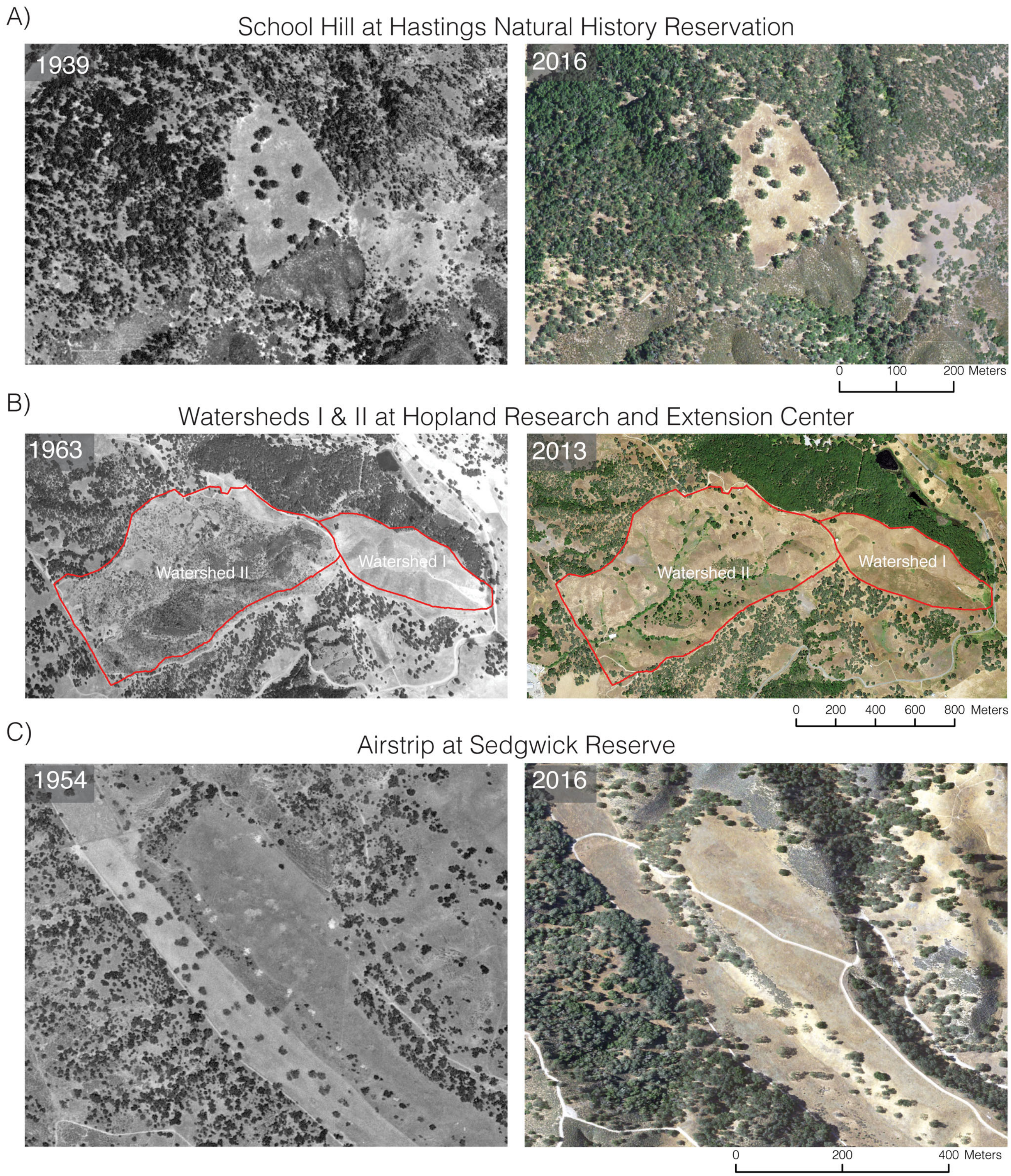


Figure 5. State transitions. Evidence of permanent, qualitative changes on lands deliberately converted from woodland to grassland for experimental or agricultural use.

charred 1,200 ha, or 56 percent, of Hopland. Because this event occurred after we began our research, we did not include it in our analysis. It does, however, demonstrate the importance of spatial scale and rare, contingent events in shaping the landscapes of these ranch-sized parcels.

Livestock

Our research showed that, despite broad generalizations in the literature about grazing on California's hardwood rangelands, our three sites each had idiosyncratic grazing histories. These neither reflected macroeconomic trends nor significantly altered landscape-scale vegetation patterns (Figure 4C). Although site-level data were limited, we were able to compare livestock trends on our sites to trends at the regional scale after 1850, when agricultural census data became available at the county level.

Low-intensity livestock grazing began on all three sites between the 1770s and 1810s. From the 1830s to 1850s, ranchers expanded their operations, establishing herds numbering in the hundreds. Both Hopland and Hastings saw brief livestock booms in the 1860s, followed by a three-decade-long decline. Hastings changed hands in the 1890s, becoming a more modern cattle ranch until 1937, when the university acquired the site and grazing ceased. Hopland grew into a large-scale sheep operation in the 1940s, and university managers maintained a herd of 1,300 to 1,600 breeding ewes into the 1970s, which has since declined to about 500.

The owners of Sedgwick have long touted its history as a cattle ranch. The current university reserve was part of a Mexican land grant beginning in 1845, and cattle have occupied the site almost continually ever since. Yet we found little evidence that Sedgwick has ever hosted a large-scale cattle operation. Only once, in 1908, when the site's owner proposed to move 15,000 head of cattle from Arizona—a transaction we could not verify as actually having occurred—might intensive grazing have taken place on this site. Throughout most of the rest of its history, Sedgwick was not a fully operational working ranch; it served as a hobby farm for its wealthy urban owners who sold modest grazing leases to local cattlemen.

Wild Ungulates

Populations of the two most important wild ungulates on our study sites, mule deer (*Odocoileus hemionus*) and wild boar (*Sus scrofa*), have fluctuated over time in response to public and private management actions, including stocking and hunting.

Mule deer populations in California declined, due to unregulated hunting and other factors, during the nineteenth century, bottoming out at around 200,000 by 1910 (Hunter 1924). State laws and other favorable factors, including some forest management practices, enabled them to recover by the middle of the twentieth century. The state's deer population peaked at more than 2 million by 1960 and then dropped again to around 500,000 by 2016. We do not have site estimates of deer populations for Sedgwick, but observational data and published research from Hastings and Hopland suggest that the sites experienced peak deer populations relatively early (Figure 4D). From 1951 through the 1970s, the number of deer at Hopland fluctuated between 550 and 1,000. Today, it probably contains fewer than 200 mule deer. At Hastings, managers observed a doubling of the deer population within ten years of terminating livestock grazing and hunting in 1937.

Pigs arrived in California by the eighteenth century, but the population appears to have remained modest until the 1920s, when additional introductions of wild boar for sport hunting brought this species to new areas, including Monterey County near Hastings according to archival sources. By the early 1980s, wild pigs lived in thirty-three of California's fifty-eight counties, and biologists estimated a population of around 75,000. Today, California's wild pigs number between 200,000 and 300,000, but expert feedback suggests a recent decline in pig populations on Sedgwick as they boom elsewhere.

Carnivores

Hunting, poisoning, habitat loss, and other forms of persecution—including state and federal control programs—reduced the numbers of many of California's native terrestrial carnivores beginning in the nineteenth century. The California grizzly (*Ursus arctos*), once common on the hardwood rangelands, declined from an estimated population of 10,000 in 1848 to zero by 1925. Wolves also disappeared from California by the 1920s, returning in small numbers only in 2011. We have only a general sense of long-term population trends for California's remaining carnivores and little information about their occurrence at specific sites, but results support the hypothesis that puma (*Puma concolor*) and coyote (*Canis latrans*) populations declined to a low point in the early twentieth century, recovering somewhat beginning in the 1970s (Figure 4E).

From 1907 to 1963, California maintained a puma bounty and control program, which netted a total of 12,461 individuals. In 1990, California voters passed an initiative outlawing the hunting of pumas, except in cases where these animals were deemed a threat to public safety or private property. In 1985, observers documented pumas at Hopland for the first time. In the years since, they have been seen more frequently or photographed on remote, motion-triggered camera traps on all three of our study sites.

The coyote is the best-studied carnivore on California hardwood rangelands. Studies conducted at Hopland suggest that coyotes there can maintain stable population numbers with up to 70 percent annual mortality. When sheep grazing ramped up at Hopland after 1951, the coyote population boomed, despite intensive predator control efforts. After grazing ceased at Hastings in 1937, the coyote population there appears to have declined. These patterns suggest that although ranch-scale management efforts can affect predator populations, changing regional conditions are probably more important in determining the growth rate and carrying capacity of terrestrial carnivores.

Precipitation

Based on nearby weather station data and historical modeling from the PRISM climate group (http://www.prism.oregonstate.edu), there are no clear long-term trends in precipitation for any of our three sites since 1895 (Figure 4F). Our study period falls within a relatively stable dry phase at the millennial scale (Dingemans et al. 2014). Yet variability in annual precipitation, including extreme events, has had major impacts on our three sites. In 1862 and 1863, for example, a severe drought, followed by flooding, killed most of the cattle in the vicinity of Sedgwick. In 1877, a severe drought killed some 400 head of cattle around Hastings. Precipitation patterns associated with major El Niños, in 1995 and 1998, were linked to vegetation changes on Hopland and increased rates of erosion at Sedgwick.

Soil Erosion

Erosion occurred on all three sites and was linked to precipitation, fire, slope, soil, grazing, and farming. At Hopland, floods in 1955 and 1964 appear to have resulted in few, if any, mass movements. In the decade after researchers cleared Watershed II, however, sixty-one small soil slips occurred, followed by a larger slip in 1985. In recent decades, road improvements at Hopland have helped reduce erosion in vulnerable areas.

In the vicinities of Sedgwick and Hastings, bathymetric records from nearby reservoirs show continuous sedimentation throughout the twentieth century, with spikes following large fires. Some gullies at Hastings likely began forming before grazing concluded in 1937. Heavy rains in 1995 triggered the only known mudflow at Hastings on an ungrazed slope. At Sedgwick, record rainfall in 1998 resulted in more than 150 small soil slips, with the greatest impacts on areas of grassland and sage scrub that had histories of grazing (Figure 4G).

Discussion

In this section, we return to the three questions posed at the beginning of this article.

Can Historical Methods Provide Sufficient Evidence to Identify Patterns of Change on California's Hardwood Rangelands?

Our multipronged historical indicators approach enabled us to learn enough about these sites to track broad patterns of change over time. We identified key contexts, driving forces, common trends, and emergent patterns that would have been difficult to discern using shorter term experimental or observational methods. We also found evidence for contingent—unpredictable, one-time—events that shaped our study sites, sometimes in profound ways. Such contingent events are seen as critical in fields such as earth science and evolutionary biology, but they remain difficult to incorporate into conceptual models in ecology (Jackson et al. 2009).

To fully answer the question of whether historical methods can provide sufficient evidence to identify patterns of change, however, we must define the term *sufficient evidence*. The goal of most historical research on the environment is neither to isolate variables and test their effects nor to achieve statistical significance from small, nonreplicable samples of unique past events. Rather, the goal of such work is to identify key contexts, driving forces, proximate causes, broad patterns, complex processes, and dynamic relationships that foster patterns of continuity or change. Investigators do this by collecting and interpreting primary sources and assembling these sources into coherent narratives that highlight important events and explain long-term trajectories. They achieve their goals when their work reveals, enlightens, and generates further questions (Gaddis 2002).

As with all historical research, in our study individual sources rarely painted a complete and accurate picture (Motzkin et al. 1996). We found fairly abundant information about cows, grass, and water on our sites in the later twentieth century but far less about conditions prior to this period or other potentially important ecological factors. Most of our data sets came from one-off snapshots rather than repeat or long-term longitudinal studies. These data sets documented processes at different spatial and temporal scales, making them difficult to integrate. Most information was not recorded with the purpose of contributing to later historical scholarship, which created a mismatch between past aims and present uses (Merenlender et al. 2001). A lack of reliable metadata hampered our ability to evaluate and contextualize the information we found, and our research was laborious and time-consuming. These impediments often have prevented range scientists from employing historical methods, suggesting a need for more collaboration among ecologists, geographers, and historians to better understand complex socioecological systems and change.

Despite these limitations and challenges, the diverse evidence we collected and analyzed proved sufficient to chart key patterns of change over time across a range of indicators. By collecting diverse sources, using mixed methods to analyze them, and employing creative approaches to integrate them, historical research can provide a crucial accompaniment to traditional methods in range science.

Does the Historical Record Display the Kinds of Patterns Predicted by Any of the Three Scientific Models of Ecological Change Mentioned Earlier?

Our research suggests that different models perform better in different contexts, and at different scales. A historical approach can enable us to identify the spatial scales at which various models prove most accurate and useful.

The succession and climax model poorly describes documented changes on our three study sites—at all spatial scales. In lightly disturbed areas, such as those that had experienced relatively cool fires, most trees survived and the grass or chaparral understory quickly regrew. Following more intense disturbances, however, like hotter fires or intentional clearing operations, we found little evidence that affected areas followed a series of successional stages or returned to their predisturbance states.

The succession and climax model remains important in these ecosystems, however, not because of its ecological value but because of its historical influence in shaping how scientists and ranchers studied and managed hardwood rangelands. In 1937, for example, Hastings' founder, Joseph Grinnell, wrote that this site would serve as an example of "'agriculture in reverse'; for the purpose is to observe the sequence of biotic events on an area long grazed and in part cultivated, toward recovery of 'primitive' conditions of flora and fauna." Grinnell thought that the "exact, original balance can of course never now be expected," but he believed, like Clements, that nature would heal itself (Unpublished Hastings historical files, quoted in Alagona 2012: 652). Over the next few decades, annual reports for Hastings seemed to confirm Grinnell's prediction (Alagona 2012). Yet sixty years later, Hastings' longtime director Mark Stromberg and his colleague James Griffin (1996) found that human-induced disturbances had permanently altered the areas in which they had occurred. Today, these areas still show little if any sign of returning to their predisturbance states.

Our evidence suggests that the state and transition model is a useful tool for understanding ecological change on California's hardwood rangelands that best fits either the very large area of the entire hardwood rangeland bioregion (4 million ha), or much smaller areas the size of a typical stand or pasture (0.1–100 ha).

At the bioregional scale, nonnative species came to dominate California's grasslands and woodland understories during the Spanish colonial era and have continued to do so in many areas for more than 200 years (Wester 1981). This transition began early, with the first European contacts, and then continued in the late eighteenth and early nineteenth centuries. We know that these processes transformed California's hardwood rangelands, even if we do not know exactly what came before (Holstein 2001; Bartolome et al. 2014).

This account comes with two qualifications. First, the extent of this transition in understory vegetation varies, with most areas retaining a diverse native flora and some boasting understories still dominated by native species (Corbin and D'Antonio 2004; Seabloom 2007; Mordecai et al. 2015). For areas with large proportions of exotic species, a precise account of their transitions—their timing, duration, extent, and exactly which native species these newcomers replaced—remains a subject of debate (Bartolome et al. 2014). Second, temporal scale also matters in understanding these patterns. Changes that took decades two centuries ago might appear to us, with the limited precision and resolution of our sources, all but instantaneous. Changes that appear to have unfolded gradually might have occurred during brief transitions when socioecological changes and anthropogenic pressures coincided with extreme natural events such as floods, droughts, or fires (Corbin and D'Antonio 2004).

The state and transition model also applies well to more recent shifts on the smaller spatial scale of the woodland stand or pasture (Figure 5). In 1959, for example, scientists at Hopland set out to determine whether they could convert blue oak woodlands to treeless pastures and whether these converted pastures, now known as Watersheds I and II, would produce more forage and water (Alagona 2008). Brooks and Merenlender (2001) found that, after more than four decades, cleared areas showed little evidence of natural reforestation. This was partly due to the severe treatments these areas had undergone. These observations suggest, however, that, even if these sites had some successional tendencies, these were insufficient to overcome such intense disturbances. Our research pointed to similar processes on School Hill at Hastings and the old airstrip at Sedgwick, where oak clearing produced durable new grasslands (Figure 5).

Although the state and transition model describes changes in bioregions and fields, grouping these two scales under the same label runs the risk of conflating different processes. On the bioregional scale, grazing appears to have played a key role by altering soil conditions and facilitating the spread of exotic species. For smaller scale shifts, however, grazing played little if any direct, causal role. The small-scale transitions we identified mostly resulted from intentional human interventions. These activities may have facilitated grazing, and grazing may have helped maintain the altered conditions in these areas, but grazing did not cause these changes. This distinguishes our California hardwood rangelands from other ecosystems described in the literature in which grazing might have played a more direct role, at all spatial scales.

The cyclical replacement model, although less well known than the other two models we assessed, offers a plausible account of how the interactions among plant species shape California's hardwood rangelands at the intermediate spatial scale (100–10,000 ha) of the landscape or ranch. Using aerial photographs and other sources, we found that, beginning in the early to mid-twentieth century, the proportion of land cover in various vegetation types on our three study sites remained relatively stable. Some locations retained their vegetation type for decades, whereas others transitioned from one type to another in a shifting mosaic. These point-level transitions did not lead to qualitative changes in the proportion of vegetation cover types at the landscape scale.

Although the state and transition and cyclical dynamics models both offered important insights, none of the three models we assessed fully explained the ecological histories of our sites, or the complex, contingent, and contextual factors that shaped these histories. These factors include proximate causes of specific, local changes like fires, floods, and droughts, as well as management actions, scientific experiments, and workplace accidents. They also include larger driving forces such as population growth, demographic changes, rising property values, and market demand for rangeland resources.

Our work corroborates the work of social scientists (Huntsinger and Bartolome 1992) who have found that changes in hardwood rangeland ecosystems tend to occur when changes in land ownership and management trigger complex feedbacks. Under consistent ownership and management, hardwood rangeland vegetation may remain stable for extended periods. California's hardwood rangelands are more resistant to change than some other western rangelands due to a number of factors, including their relatively mild climates. Our indicators approach also demonstrated, however, that stability in the vegetation should not be confused with stability in other key aspects of these ecosystems, including biodiversity and charismatic wildlife, which are increasingly important to diverse Californians.

Can Historical Methods Be Used to Assess Scientific Models of Ecological Change?

Until now, environmental historians, historical geographers, and historical ecologists have used science in their work in three ways. They have used scientific methods to better understand past changes. They have borrowed scientific data and conclusions, treating them as secondary sources in their narratives. They have also historicized science, treating it as a primary source to show how its ideas and practices have changed over time. Our study offers a fourth approach: using historical data and methods to assess scientific models of ecological change.

In the philosophy of science, testing a model can mean several things. It can mean finding statistical significance in a data set, "ground-truthing" model results with empirical research, replicating a modeling study to determine whether its results remain consistent, calibrating results among multiple models, or homing in on the best models by eliminating competing ones that render less precise or accurate results. To even qualify for testing, many scholars argue, a model must make falsifiable predictions (Popper 1959).

History cannot "test" scientific models in a formal, mathematical way. History only happens once, and in the absence of replicable trials, it lacks the statistical capacity to disprove scientific hypotheses. Historical evidence and methods can, however, provide key contextual information, as well as valuable tools for assessing the strengths and weaknesses of various models. This approach has the benefits of drawing from multiple sources, revealing patterns of change over long periods of time, placing these changes within their social contexts, and enabling us to track phenomena at several scales of spatial and temporal organization.

The historical indicators approach we used here most resembles ground-truthing in the sense that we searched for empirical evidence that corresponded to or conflicted with predictions from three scientific models. We then used this evidence to draw qualitative conclusions about the performance of these models when projected onto past processes and events. Yet, our approach goes beyond simple ground-truthing. Whereas ground-truthing usually refers to checking model results with field observations, especially to fine-tune models, our approach turns to the historical record to assess the fidelity of models more broadly.

The historical record contains a paradox that every geographer and environmental scientist should understand. On the one hand, it contains a wealth of complex information that could, at some spatial or temporal scale, support the predictions of almost any model. On the other hand, the historical record's complexity makes it impossible for any single model to account for all the patterns of change and continuity the sources reveal. Even the most nuanced scientific models paint relatively simple pictures of ecological change because the purpose of these models is to distill systems to their fundamental parts. Our historical indicators approach uses voluminous historical data and combines ecological with sociocultural approaches to capture a more intricate picture that better reflects the complexity of the historical record.

Conclusions

We draw five conclusions from this study. First, the historical record, with all of its diversity and complexity, contains some evidence, at some scale, for almost any model of change. This does not mean that every model fits every event, process, or context equally well. Different models work better in different cases. Range scientists and managers have too often assumed that models that seemed to work well in one case will do so in another. The historical indicators approach provides a useful method for better assessing the utility of a model in a particular context.

Second, no single model can explain ecological change on California's hardwood rangelands. Trends in the historical record often involve several key processes interacting in complex ways. Even specific, one-time events almost always have multiple causes and consequences, requiring detailed empirical research to understand them. Some key events shaped our sites in profound ways but had no connection to any of the models we examined.

Third, assessing the fit of any scientific model to past events and processes depends on the spatial and temporal scales of analysis (Pickup, Bastin, and Chewings 1998; Carpenter et al. 2001; Valone et al. 2002; Bestelmeyer et al. 2003; Sayre et al. 2012). The state and transition and cyclical replacement models both captured important features of hardwood rangeland dynamics, but they did so at different spatial scales. The temporal scale of our study, from 1769 to 2017, excluded formative events further in the past, as well as key current events, such as the Mendocino Complex Fire of 2018.

Fourth, the three scientific models discussed here all focus on vegetation in the form of land cover, but hardwood rangelands contain diverse values of growing interest to the people who live near them and use them. The traditional focus on vegetation reflects an effort by scientists to understand the basic properties of these systems (Fernandez, Neff, and Reynolds 2008), but it also reflects a history in which rangelands were deemed useful mainly for their capacity to produce forage for livestock (Sayre 2017). Today, Californians increasingly value hardwood rangelands for their watershed, ecological services, open space, recreational, and wildlife habitat values, suggesting a need for new socioecological models.

Fifth, for more than a century, this focus on vegetation encouraged researchers to study rangelands as a single, unified systems. Rangelands were healthy or unhealthy, disturbed or undisturbed, stable or unstable, in one seral state or another. Our historical indicators approach shows that rangeland dynamics are extraordinarily complex, with various indicators trending at different rates and in different directions. The history of hardwood rangeland vegetation tells us little about the histories of other socially or ecologically important components of these landscapes (Bestelmeyer 2006; Gillson and Hoffman 2007; Havstad et al. 2009). Scientists and managers need new ways of talking about rangelands that reflect their historical complexity and contemporary social values, and that integrate ecological with sociocultural research (Sayre 2004; Herrick et al. 2012).

Fifth, despite impressive growth in fields such as paleoecology, historical ecology, and environmental history, historical evidence and methods remain underused resources in the environmental sciences. Nowhere is this more the case than in the discipline of geography, where historical methods, once prominent in the field, have receded in recent decades—and at great cost (Wynn et al. 2014). A fuller understanding of environmental change and human–environment relations will require scholars in geography and related fields in the environmental sciences to reengage with history, historians, and historical methods in creative new ways.

Supplemental Material

The compiled data that support the findings of this study, as well as references for all data sources, are available as a table in figshare and on the Web site of the corresponding author, Tim Paulson, at http://blogs.ubc.ca/timpaulson/resources/data/. The supplemental material can also be accessed on the publisher's wesbite at http://dx.doi.org/10.1080/24694452.2020.1782168. The table presents data in quantitative or qualitative form on seven indicators (vegetation, fire, livestock, wild ungulates, carnivores, precipitation, and erosion) for three sites on California's hardwood rangelands from 1800 to 2017. Land management transition periods and managed property size are also included for reference and comparison. Many of these data are visualized in Figure 4.

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