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Past Forward: Using History to Inform Multi-Benefit Ecosystem Management in Human-Dominated Landscapes

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Past Forward: Using History to Inform Multi-Benefit Ecosystem Management in Human-Dominated Landscapes

By

Erin Emily Beller

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Abstract

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Human-dominated ecosystems are increasingly recognized as a crucial component of biodiversity conservation and ecosystem management, with the potential to support biodiversity, deliver ecosystem services, connect people with nature, and contribute to regional connectivity and management goals. However, understanding what ecosystem conservation, restoration, and management goals and targets are appropriate in such landscapes remains a challenge. We often have an extremely limited understanding of the character and consequences of ecosystem change in human-dominated landscapes as a result of the rapid and extensive transformations of the past centuries, a blind spot that can hamper our ability to manage these landscapes in a way that is place-based, pragmatic, and grounded in local landscape potential.

This dissertation aims to advance the practice of ecosystem management in human-dominated landscapes by exploring how historical ecology, which provides a long-term historical perspective on system patterns, dynamics, and trajectories, can inform a variety of management goals in human-dominated landscapes. I explore three dimensions of the applicability of a historical perspective to multi-benefit landscape management: ecosystem conservation and restoration, managing for ecosystem services such as carbon storage, and managing for ecological resilience.

In Chapter 2, I present the first quantitative and systematic review of the global historical ecology literature across ecosystems and identify the specific recommendations for ecosystem management that have emerged from the global body of historical ecology research over the past two decades. I found clear patterns in the types of recommendations generated by the historical ecology literature, including an emphasis on the role of both habitat remnants and human-dominated landscapes in management, the role of people in landscape stewardship, and the value of a landscape-scale perspective. About one-quarter of studies contained at least one surprising recommendation that revised or challenged status quo management for the study system or site in question, affirming the ability of historical ecology to provide new insights that can adjust how we manage species and ecosystems. I found that fewer than 12% of papers contained recommendations that explicitly addressed ongoing or projected climate change, suggesting

opportunities to integrate findings from historical ecology with other perspectives to create forward-looking management strategies.

In Chapter 3, I use historical datasets to reconstruct landscape-scale changes in an ecosystem service, carbon storage, in Santa Clara Valley over the past ca. 200 years from pre-settlement conditions through urban development. This is the first such examination of temporal changes in carbon storage in an urban area extending before 1900. I found that total tree carbon storage in the study area was ~784,000 to 2.2 million Mg ca. 1800, compared to ~895,000 Mg C today, suggestive of considerable losses of up to 60% of former carbon storage. My results suggest that in Mediterranean-climate ecosystems with heterogeneous tree cover, gains in aboveground carbon storage in formerly treeless areas can be offset by losses in high-biomass former woodland areas, challenging the hypothesis that aboveground carbon storage is likely to increase with urbanization in arid and semiarid environments due to irrigation and tree planting.

Finally, in Chapter 4 I explore the role of history in informing resilience-based ecosystem management in highly modified landscapes. I synthesize and simplify the published literature on mechanisms of ecological resilience into seven dimensions of landscape-scale ecological resilience, along with a set of key considerations for evaluating the current state of a landscape and identifying potential management strategies that could contribute to resilience. I then demonstrate application of the approach through case studies in the agricultural Sacramento-San Joaquin Delta and urban Santa Clara Valley, each of which drew on detailed regional-scale assessments of ecological history and change as a first step to analyze landscape context. This work advances the practice of resilience-based management by providing a structured approach and shared vocabulary for identifying potential opportunities and actions likely to increase landscape resilience in highly modified systems, and ultimately better equip landscapes to sustain biodiversity and function into the future. Taken as a whole, this research underscores the continued value of history as a cornerstone of multi-benefit ecosystem management, even in human-dominated landscapes and in the context of transformations in land use and climate.

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Acknowledgements

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Chapter 1: Introduction

1. Ecosystem management in a changing world

In September 1859, poet and travel writer Bayard Taylor journeyed by carriage through what is now the heart of Silicon Valley. “How shall I describe a landscape so unlike anything else in the world, with a beauty so new and dazzling, that all ordinary comparisons are worthless?” he wrote, describing “groups of giant sycamores, their trunks gleaming like silver through masses of glossy foliage”, “park-like groves of oaks”, and “redwoods rising like towers” (Taylor 1862).

Hyperbole aside, in just a few short centuries Silicon Valley has experienced a dramatic loss of this natural heritage through agricultural transformation and development. Such transformations are emblematic of landscapes worldwide: over 50% of the planet’s ice-free land area has been transformed into human-modified and human-dominated landscapes such as urban areas, agriculture, and rangelands since 1700 (Ellis et al. 2010). Such changes in land use have had often-dramatic consequences for ecosystem health, function, and resilience, and they continue to be the single biggest threat to biodiversity and ecosystem services worldwide (Sanderson et al. 2002, Foley et al. 2005, Barral et al. 2015). For example, land-use changes due to agricultural transformation and urbanization have caused extensive changes from the local to the global scale, including habitat loss, modification, and fragmentation (Cadenasso et al. 2007, Groffman et al., 2014); loss and homogenization of biological diversity (Aronson et al., 2014, LaSorte et al. 2014); and altered nutrient and water cycling (Grimm et al. 2008, Pataki et al., 2011).

Despite these changes, highly transformed ecosystems such as agricultural and working landscapes and urban landscapes—referred to here as “human-dominated landscapes”—are increasingly recognized as a crucial component of biodiversity conservation and ecosystem management. Such landscapes have the potential to support biodiversity, including rare and endemic species (Kuhn et al. 2004, Scherr and McNeely 2008, Halada et al. 2011, Ives et al. 2016, Mendenhall et al. 2016); deliver ecosystem services and connect people with nature (Dearborn and Kark 2010, Power 2010); and contribute to regional connectivity and management goals (Bierwagen 2007, Kueffer and Kaiser-Bunbury 2014, Hobbs et al. 2014). Calls to include such landscapes in landscape-scale conservation planning are changing the scope and scale of conservation efforts.

However, understanding what ecosystem conservation, restoration, and management goals and targets are appropriate in such landscapes remains a challenge. We often have an extremely limited understanding of the character and consequences of ecosystem change in human-dominated landscapes during the rapid and extensive transformations of the past centuries. Data gaps include how ecosystem structure, function, extent, and dynamics have changed over time; the drivers of these changes; and their consequences for biodiversity, ecosystem health, ecosystem services, and resilience. These gaps can hamper our ability to manage these landscapes in a way that is place-based, pragmatic, and grounded in local landscape potential (Higgs et al. 2014).

This dissertation aims to advance the practice of ecosystem management in human-dominated landscapes by exploring how a long-term historical perspective on system trajectories can inform management of these landscapes. History has a long legacy of providing insights that guide—and often fundamentally alter—ecosystem conservation, restoration, and management goals and strategies, predominantly through the field of historical ecology (described in more detail below). However, I propose that application of historical analyses to management of human-dominated landscapes has suffered from two key limitations. First, historical ecology research is primarily based on case studies of specific places; as a result, insights from historical ecology remain highly local and are rarely synthesized. This stands in contrast to other fields such as climate change adaptation, where synthesis and meta-analysis across studies have yielded key insights into priority ecosystem management goals and strategies (e.g., Heller and Zavaleta 2009, Stein et al. 2013). Second, while history is commonly used to understand the implications of long-term ecosystem and landscape change on biodiversity and ecosystem function, it has only infrequently been used to understand the consequences of change on other landscape management priorities such as ecosystem service provision and ecological resilience, particularly in human-dominated landscapes.

Specific objectives of this dissertation are to address these limitations through (1) synthesis of the historical ecology literature to scale beyond the case study and assess patterns in management recommendations emerging from research across the globe, and (2) demonstration of the utility of historical research in understanding the consequences of landscape change on ecosystem service provision and ecological resilience. In particular, I explore three dimensions of the applicability of a historical perspective to multi-benefit landscape management:

- How can a long-term historical perspective inform **ecosystem conservation and restoration** in transformed landscapes?
- What insights can historical data provide about the impacts of land transformation on **ecosystem services**?
- How can history inform managing for **ecological resilience**?

I address these three questions through a combination of geographic scales and approaches, in particular meta-analysis and conceptual framework development at the global level (spanning multiple locations and ecosystem types) and geospatial analysis and case studies at the local level, with a focus on the urban landscape of Santa Clara Valley. The temporal scope of this research is similarly broad, with historical sources extending back several centuries to the 1700s and 1800s.

In the remainder of this introductory chapter, I review the context for this dissertation, including background on the field of historical ecology and the application of a long-term perspective to ecosystem management. Finally, I provide an overview of the objectives and findings of each of the following chapters.

2. Linking history and ecology

The study of ecological patterns, processes, and change over historical time periods is a field known as historical ecology (Beller et al. 2017). Historical ecology examines dynamics and trajectories in species, communities, ecosystems, and landscapes over long time scales; it often, though not necessarily, includes an additional focus on human-environment interactions and the causes and consequences of changes caused by human actions in the recent past (Crumley 2003; Rhemtulla and Mladenoff 2007). The field includes both researchers who wish to document ecological patterns and dynamics in the recent past using historical methods, as well as those interested in *historicizing* ecology—that is, understanding the relationships between nature and human culture over time. (Note that here I distinguish between historical ecology, which is traditionally concerned with ecological dynamics over decadal or century time scales, and paleoecology, which extends to prehistoric and evolutionary timescales; see Dietl and Flessa 2011, Dietl et al. 2015).

While the term "historical ecology" emerged only in the mid-20th century, the field is part of a long tradition of investigation into the relationships between humans and environmental change over long time scales that reaches back to forest history, historical geography, paleoecology, and landscape and environmental history (Szabó 2015). Historical ecology continues to be highly interdisciplinary, drawing on perspectives, tools, and techniques from fields such as ecology, history, anthropology, archeology, and geography (Armstrong et al. 2017). The field has grown rapidly over the past two decades, spurred by the adoption of geographic information systems, widespread digitization of historical documents and maps, and increased concern about the state of future landscapes.

Historical ecology inherently operates at long temporal scales, and frequently also considers large spatial scales. As a result, it draws on a broad range of qualitative and quantitative sources that vary in temporal and spatial coverage, require creative and thoughtful methods to synthesize and interpret, and are often integrated in ways that cross traditional disciplinary boundaries. Data include traditional archival sources such as written documents, maps, oral histories, land surveys, landscape views and photography, along with biological and physical data such as sediment and pollen records, tree rings, species lists, and habitat relationships (Swetnam et al. 1999; Egan and Howell 2001, Vellend et al. 2013). Studies cast a broad net of topics of interest, from traditional ecological questions such as documenting population abundance and community composition, habitat distribution, and ecological processes and functions, to geographic questions such as changes in geophysical patterns and processes (e.g., groundwater dynamics, stream morphology) and socioecological questions such as understanding traditional landscape management and setting goals and objectives for ecological restoration.

3. The shifting role of history in landscape management

While relying on data from the past, historical ecology is an inherently future-oriented discipline. Adopting a long-term historical perspective frequently invites a similarly long-term perspective into the future, and many historical ecologists are concerned with the application of findings to the conservation, restoration, and management of ecosystems (Swetnam et al. 1999). By extending beyond the scale of human memory or observation, historical ecology has been demonstrated to provide new insights that can challenge conventional scientific wisdom and adjust how we manage species and ecosystems (McClenachan et al. 2015, Barak et al. 2015).

Historical ecology has had perhaps a particular affinity with the field of restoration ecology, where the idea of looking to history to understand reference conditions, baselines, and appropriate future targets is central to the field (Balaguer et al. 2014, McDonald et al. 2016).

Recognized issues are associated with the uncritical use of baselines, particularly given environmental variability and extensive legacies of human stewardship of ecosystems (Jackson and Hobbs 2009, Alagona et al. 2012). When treated with care, however, the use of long-term datasets to identify baselines prior to significant modification can be of immense value in setting management targets that more fully reflect change over time, for example in species abundance and ecosystem characteristics. As an example, historical data in marine ecosystem management can increase estimates of former population size and subsequent decline, and influence recovery targets (McClenachan et al. 2012). In river restoration, historical analysis of streams in the mid-Atlantic United States indicated that their characteristic meandering morphology was a result of sedimentation from 17^{th}-19^{th} century milldams, prompting re-evaluation of reference conditions guiding a multi-billion dollar stream restoration industry (Walter and Merritts 2008).

The role of history in ecosystem management has continued to evolve in recent years, particularly with the increasing recognition of the local- to global-scale impacts of climate change, land-use change, invasive species, and other anthropogenic stressors. The concepts of "hybrid" and "novel" ecosystems—that is, ecosystems that diverge from historical conditions as a result of these stressors—have become increasingly widespread, prompting questions about the value of a long-term perspective under such changing conditions (Hobbs et al. 2013, Hobbs et al. 2014, Higgs 2016). This has prompted a shift in applied historical ecology, wherein history is increasingly seen as an inspiration and guide rather than a prescriptive template (Suding et al. 2015). In this context, the use of history to determine target reference conditions is complemented by the use of history to develop a nuanced understanding of cultural legacies and sense of place in addition to ecosystem processes, dynamics, and response to variability and change (Higgs et al. 2014) – across a range of landscapes, from the historical and hybrid to the novel. In addition, as the concept of ecosystem services as a tool to inform ecosystem management has gained traction (Daily et al. 2009), an emerging interest has developed in the use of historical datasets to reconstruct ecosystem service dynamics and trajectories over time (Bürgi et al. 2015, Tomscha et al. 2016).

4. Dissertation overview

The following chapters examine the role of history in informing three interrelated dimensions of landscape management in highly modified ecosystems: ecosystem restoration and conservation (Chapter 2), ecosystem services (Chapter 3), and ecological resilience (Chapter 4). My research is situated at the global scale, through syntheses of the historical ecology and ecological resilience literature, as well as at the local scale, through case studies in carbon storage provision and ecological resilience in Santa Clara Valley (also known as Silicon Valley), California. Santa Clara Valley provides an outstanding case study to explore this topic. Since the rapid transformations over the past ca. 250 years in Santa Clara Valley are broadly representative of overall global trends in land use trajectories from natural ecosystems and indigenous management to intensive agriculture and urban development (Foley et al. 2005), I expect this research to provide insights that are broadly applicable to other regions. In addition, this study takes advantage of the rich array of detailed environmental history and historical ecological data and mapping already produced for Silicon Valley (e.g., Cooper 1926, Broek et al. 1932, Friedly 2000, Brown 2005, Grossinger et al. 2007, Beller et al. 2010).

In Chapter 2, I focus on the role of a historical perspective in informing ecosystem conservation and restoration strategies and activities. I present the first quantitative and systematic review of the global historical ecology literature across ecosystems, and identify the specific recommendations for ecosystem management that have emerged from the global body of historical ecology research over the past two decades. I found clear patterns in the types of recommendations generated by the historical ecology literature, including an emphasis on the role of both habitat remnants and human-dominated landscapes in management, the role of people in landscape stewardship, and the value of a landscape-scale perspective. About one-quarter of studies contained at least one recommendation that revised or challenged status quo management for the study system or site in question, affirming the ability of historical ecology to provide new insights that can adjust how we manage species and ecosystems (cf. Walter and Merritts 2008, McClenachan et al. 2012). I also found substantial overlap between recommendations from historical ecology—a field adopting a long-term, historical perspective—and those generated from the future-oriented field of climate change adaptation, though there are also points of divergence. My results suggest that insights generated from a long-term perspective are an essential component of developing future-oriented approaches to ecosystem management.

Chapter 3 uses historical datasets to reconstruct landscape-scale changes in an ecosystem service, carbon storage, in Santa Clara Valley over the past ca. 200 years—the first such examination of temporal changes in carbon storage in urban areas extending before 1900. I quantify and map historical carbon storage in trees across Santa Clara Valley ca. 1800, then calculate change in carbon storage from pre-settlement conditions, when the region was characterized by oak savanna and woodland habitat, to the current urban landscape to investigate how the amount and spatial distribution of carbon stored on the landscape has changed over time. I found that total tree carbon storage in the study area was ~784,000 to 2.2 million Mg ca. 1800, compared to ~895,000 Mg C today, suggestive of considerable losses of up to 60% of former carbon storage. My results suggest that in Mediterranean-climate ecosystems with heterogeneous tree cover, gains in aboveground carbon storage in formerly treeless areas can be offset by losses in high-biomass former woodland areas, challenging the preconception that aboveground carbon storage is likely to increase with urbanization in arid and semiarid environments due to irrigation and tree planting. My results also demonstrate the feasibility and utility of using pre-1900s historical sources to reconstruct historical trajectories in ecosystem services such as carbon storage over century time scales.

In Chapter 4, I turn to the concept of ecological resilience to explore the role of history in informing resilience-based ecosystem management in highly modified systems and across whole landscapes. I synthesize and simplify the published literature on mechanisms of ecological resilience into seven dimensions of landscape-scale ecological resilience, along with a set of key considerations for evaluating the current state of a landscape and identifying potential management strategies that could contribute to resilience. I then demonstrate application of the approach through case studies in the agricultural Sacramento-San Joaquin Delta and urban Santa Clara Valley, each of which drew on detailed regional-scale assessments of ecological history and change as a first step to analyze landscape context. This work advances the practice of resilience-based management by providing a structured approach and shared vocabulary for identifying potential opportunities and actions likely to increase landscape resilience in highly modified systems, and ultimately better equip landscapes to sustain biodiversity and function into the future.

Finally, in Chapter 5 I conclude with a summary of key findings of my dissertation, along with reflections on directions for future research on the role of history in managing highly modified landscapes. Taken as a whole, this research underscores the continued value of history in informing multi-benefit landscape management. It highlights concrete recommendations and novel approaches for incorporating lessons from history into a variety of landscape management endeavors, from ecosystem restoration to managing for ecosystem services and resilience. My aim is for this dissertation to provide inspiration and guidance for anchoring future-oriented approaches to landscape management in the temporal context unique to each place, even in the context of ongoing and future environmental change. Ultimately, I hope this research helps catalyze integrative approaches that are dynamic, creative, and novel yet rooted in place and past.

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Chapter 2: A Synthesis of Recommendations from Historical Ecology for Ecosystem Management and Restoration

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Abstract
In the context of accelerating environmental change, there is an urgent need to identify ecosystem conservation, restoration, and management strategies likely to support biodiverse and adaptive ecosystems into the future. The field of historical ecology has generated a substantial body of recommendations for ecosystem management, yet these insights have never been synthesized. We reviewed >200 historical ecology studies and analyzed recommendations for ecosystem management emerging from the field. The majority of studies (~90%) derived from North American and Europe, with forests being the focus of nearly half (48%) of all papers. Papers emphasized the need to protect and restore both habitat remnants and modified ecosystems in management, the value of ecosystems as cultural landscapes, and the importance of adopting a landscape-scale perspective for ecosystem management. Nearly one-quarter contained a recommendation that challenged status quo management, underscoring the value of a historical perspective in setting management goals, strategies, and targets. Fewer than 12% of papers contained recommendations that explicitly addressed ongoing or projected climate change, suggesting opportunities to integrate findings from historical ecology with other perspectives to create forward-looking management strategies that are rooted in place and past.

Keywords: historical ecology; ecological restoration; ecosystem management; landscape history; climate change adaptation

1. Introduction

Climate change, land-use change, and other stressors are rapidly transforming ecosystems and landscapes across the globe, necessitating strategies for managing natural systems that foster biodiversity, provide key ecosystem functions and services, and are resilient to environmental change (Foley et al. 2005, Ellis et al. 2013, Grimm et al. 2013, Pecl et al. 2017). Equipping ecosystems to adapt to modern stressors requires consideration of future trajectories that account for variability and change in species, communities, and ecosystems over time (Hansen et al. 2010, Higgs et al. 2014). In this context, there is increasing recognition of the value of considering longer time horizons into the past in order to understand ecosystem conditions, dynamism, and response to environmental change over the time scales necessary for effective management (McClenachan et al. 2012, Gillson and Marchant 2014, Barak et al. 2016).

Historical ecology—that is, the reconstruction of past ecological patterns and dynamics (Rhemtulla and Mladenoff 2007, Beller et al. 2017)—can provide key information relevant to ecosystem conservation, restoration, and management (hereafter referred to as "ecosystem management"). Historical ecology research has long been used to establish baseline conditions and set restoration targets (Alagona et al. 2012) and to characterize ecosystem degradation (Swetnam et al. 1999). In addition, historical studies can serve as a "natural experiment" to study ecosystem response and resilience to past disturbances and climatic changes (Vellend et al. 2013, Nogués-Bravo et al. 2018), elucidate the natural range of variability of an ecosystem (Keane 2009, Safford et al. 2012), identify persistent and novel sites or features in the contemporary landscape (Copes-Gerbitz et al. 2017), and provide information on lost or forgotten species or ecosystems that might serve as inspiration for current and future management, either in the same place or a location with an analog future climate (Grossinger et al. 2007). In many cases, surprising results and management recommendations emerging from historical ecology analyses have altered management priorities and strategies (McClenachan et al. 2015).

While historical ecology has clear application to ecosystem management, examination of these recommendations has remained at the case study level, and a systematic analysis of management recommendations coming from historical ecology literature is still lacking. This restricts our ability to analyze patterns across taxa, places, and systems and may also limit the accessibility of these recommendations for managers who might wish to take advantage of them. Therefore, we conducted a systematic review of published historical ecology studies from both terrestrial and aquatic habitats across the globe over the past 23 years to determine the types of ecosystem management recommendations emerging from the historical ecology literature and the degree to which these recommendations challenge the status quo. Our focus is the historical ecology literature (typically studies that reconstruct ecosystem dynamics at decadal or century timescales using primarily archival sources) rather than paleoecological studies (primarily studies that use fossils, pollen, sediment cores, and other records to reconstruct prehistoric ecosystem dynamics at geologic timescales; Dietl and Flessa 2011, Barak et al. 2016). Though the two approaches are complementary and insights from a wide range of past time periods can yield important insights for management, paleoecology has received relatively more attention in the conservation literature (see for example Willis et al. 2010, Rick and Lockwood 2013, Seddon et al. 2014, Barnosky et al. 2017). Characterizing ecological change over decades to centuries during the historical period is an important but often overlooked dimension of understanding current conditions and prioritizing management strategies (Dearing et al. 2015).

We address four primary questions: (1) What temporal and spatial scales, geographic and land-use contexts, ecosystem attributes, and types of sources characterize the management-oriented historical ecology literature? The few existing surveys of the historical ecology literature largely focus on broad overviews of the field (e.g., Szabó 2015, Beller et al. 2017) or provide qualitative overviews of methods and techniques (e.g., Vellend et al. 2013); there is currently a dearth of understanding of where and how historical ecology studies have been conducted that would yield insights into patterns, strengths, and gaps in the field. (2) What recommendations for ecosystem management have emerged from the global body of historical ecology research? While such syntheses of management recommendations have been influential across other spheres of applied conservation (e.g., climate change adaptation, Heller and Zavaleta 2009), there has been no systematic analysis of the recommendations generated by historical ecology studies, restricting our ability to analyze patterns across taxa, places, and systems. (3) To what extent do recommendations from historical ecological studies challenge status quo ecosystem management recommendations or practices in the study system? While individual case studies have been shown to often fundamentally alter management priorities and strategies (cf. McClenachan et al. 2015), the prevalence of surprising recommendations is unknown. (4) How do recommendations from historical ecology—a field adopting a long-term, past-oriented perspective—compare to recommendations generated from climate change adaptation research, where a long-term, future-oriented perspective is assumed? We focus on climate change given its importance as a global change driver, and the importance in both historical ecology and climate change adaptation of thinking across broad time scales. Our aim with these four questions is to facilitate the integration of insights from historical ecology into the larger conversation surrounding ongoing and future ecosystem management.

2. Methods

2.1. Literature review and selection

In November 2017, we searched the Web of Science database for peer-reviewed journal articles that used archival sources (i.e., sources found in a museum, archive, or other repository; Pearce-Moses 2005) to reconstruct historical ecological conditions and make recommendations for ecosystem restoration, conservation, and management. We developed a search term with four sets of linked criteria: (1) topical (i.e., paper addresses ecological history and/or change), (2) time period (i.e., paper addresses the historical period rather than prehistoric or geological timescales), (3) methodological (i.e., paper uses archival sources), and (4) application (i.e., paper mentions application to ecosystem management). Strings of search terms for each category were linked with the “AND” operator to identify candidate papers of interest (see Appendix A for full search terms). We did not include white papers, technical reports, or book chapters.

To be included, papers had to present empirical data and include at least one recommendation for ecosystem restoration, conservation, or management. In addition, papers must have used at least one type of archival source material (e.g., maps, textual data, aerial imagery, landscape photography, museum specimens; figure 1) dating from before 1940 to characterize historical ecological conditions or change (i.e., not other abiotic characteristics such as water quality, geomorphic change, or carbon). The year 1940 was chosen as a cutoff in order to focus on studies characterizing ecosystem dynamics before the major changes that followed World War II in many regions.

Figure 1. Examples of archival sources used by historical ecology studies. Common sources include maps (a, b); lithographs, drawings, and paintings (c), textual documents such as newspaper articles, diaries, field notebooks, and travelogues (d); resource surveys such as fisheries logbooks, land surveys, and timber surveys (e); and museum specimen collections (f). *(Courtesy of (a) The Bancroft Library, UC Berkeley; (b) U.S. Geological Survey; (c) Claremont Colleges Digital Library; (d) The Jepson Herbarium, UC Berkeley; (e)Yale Peabody Museum, and (f) the University of Iowa.)*

Following the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Moher et al. 2009), we reviewed the titles of the records yielded by this search (n=2,449) to remove duplicates and exclude papers that did not meet the inclusion criteria (n=1,357). We then reviewed the abstracts and full text of the remaining candidate papers (n=1,092) to assess them for eligibility. Of these, 217 papers from 1994-2017 met the criteria for inclusion and were coded for use in this synthesis.

2.2. Paper coding and data analysis

To extract information from eligible papers, we created a database adapted from a similar effort that analyzed biodiversity conservation recommendations in the face of climate change (Heller and Zavaleta 2009). We coded each study's contextual information, including geographic and temporal context (geographic location, land-use context, spatial scale, and time span covered by the study) and ecological focus (focal taxa, ecosystem types, and ecological questions addressed). We also coded methodological information, including the types of historical archival sources and ancillary, non-archival sources (e.g., satellite imagery, contemporary field data, archaeological reports, modeling/simulation) used by each study. We coded eight types of historical archival sources (see table 1): maps, textual documents, resource surveys, field surveys, aerial photographs, landscape photographs, museum and specimen collections, and oral histories.

To analyze ecosystem management recommendations, we transcribed each recommendation as written by the study authors, then assigned them to recommendation categories. Management recommendation categories were modified from previous efforts (Heller and Zavaleta 2009, McLaughlin et al. *in prep*), with additional categories specific to historical ecology added as needed during the coding process. There were 78 possible categories (see table 3); each paper could be coded into a maximum of four. For example, a recommendation to "create more open canopy and understory conditions…[via] prescribed fire, canopy gap creation, and understory thinning" (Fahey and Lorimer 2014) was coded as both "Use prescribed fire" and "Decrease forest density." Recommendations were only coded if they included a specific activity or action that could be taken by an ecosystem manager (e.g., "monitor", "thin forest", "increase connectivity") or a general principle that could inform management actions (e.g., "restore within historical range of variability" or "manage at a landscape scale"). Recommendations for further research were not coded, nor were generic recommendations stating the value of history (e.g., "consider historical baselines"). Recommendations were tabulated across papers, then ranked by frequency to identify the most common recommendations across the global historical ecology literature. Finally, we aggregated these management recommendation types into 12 broader categories: for example, recommendations to focus efforts on a diversity of species, ecosystems, and genes/phenotypes were aggregated into an overall category of "protect/restore biodiversity." We used these 12 categories to identify key themes emerging across papers.

In addition, we coded whether a paper included recommendations that substantially revised or challenged the management status quo for the site or ecosystem in question, as reported by the authors. We also captured whether each paper mentioned ongoing or projected future climatic change, and whether the paper contained recommendations that addressed the potential effects of climate change. All data were analyzed in RStudio v.1.1.456.

3. Results and Discussion

3.1. Characterizing the management-oriented historical ecology literature

In total, we recorded 649 management recommendations from 217 peer-reviewed papers (see Appendix B for full list of coded papers). Study area size was generally large: over three-quarters of papers that specified a spatial scale covered over 100 km^2; median spatial scale covered by paper study areas was 1046 km^2 (IQR 5423 km^2) (figure 2). Study time span was similarly long: nearly three-quarters of papers that specified a time span covered over 100 years; median time span covered by studies was 144 years (IQR 105 years) (figure 3). Study focus spanned ecological scales, from population- and species-level to ecosystem- and landscape-level studies (figure 4d). Ecosystem extent and loss/gain in land cover types, community composition and diversity, and population or species-level abundance or other characteristics (e.g., genotypic/phenotypic diversity or biomass) were each covered by over one-third of studies (42%, 37%, and 34% respectively).

Studies drew on a wide variety of archival source types, with historical maps, textual data, and resource surveys each used by over one-third of articles (table 1). Over three-quarters of studies drew on only one or two source types of the eight categories coded. In addition to historical archival sources, studies drew on ancillary source material to reconstruct prehistoric or contemporary conditions, including field surveys and observations conducted as part of the study (32%), field surveys and observations conducted prior to the study (31%), and satellite imagery (24%).

The majority of historical ecology literature emerged from a few regions and ecosystems. Nearly 90% of studies were from the United States and Europe; only 6% focused on Africa, Asia, or Central/South America (table 2). Terrestrial ecosystems and taxa were most represented, with forests in particular studied by nearly half (48%) of papers (figures 4a and b). Of papers that specified a contemporary land-use context, approximately two-thirds included a landscape characterized by human uses (e.g., urban area, cropland, or forestry), while only one-third of studies included a protected area (figure 4c).

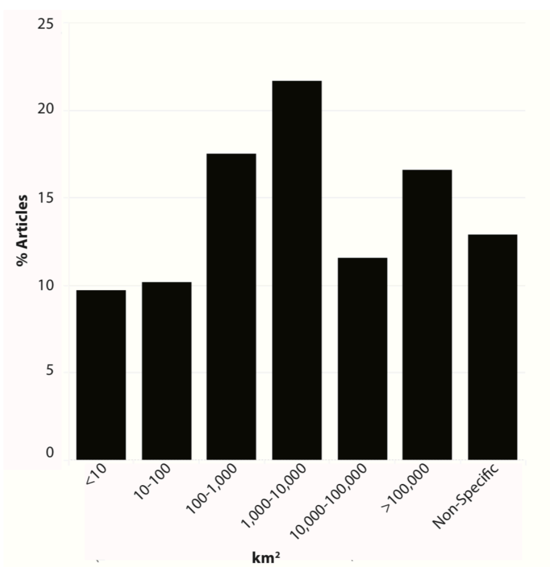

Figure 2. Spatial scale of historical ecology papers coded.

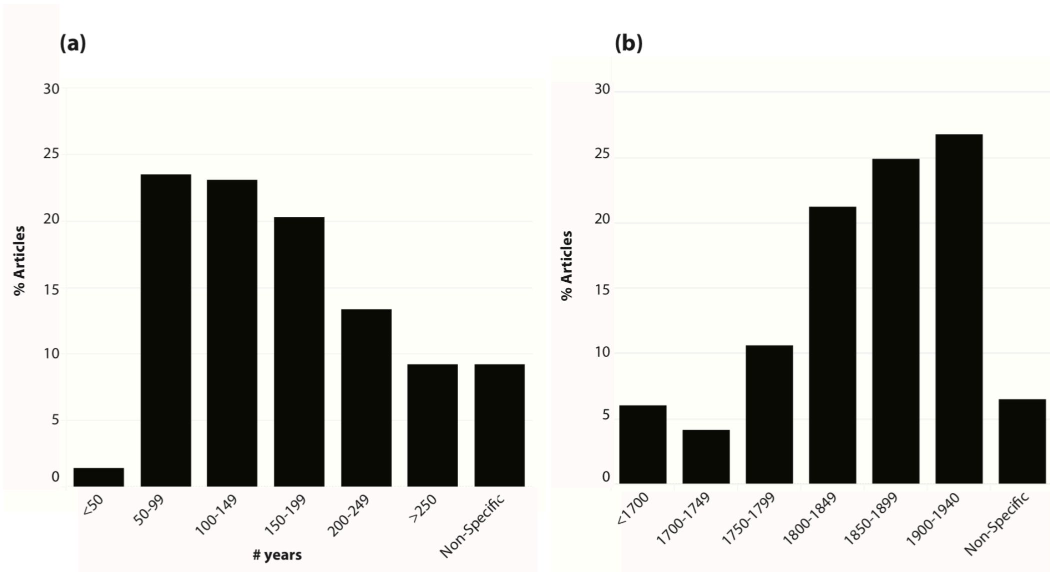

Figure 3. Time span of historical ecology studies coded (a) and study start dates (b).

Table 1. Archival sources used by historical ecology studies.

Source	% of articles
Maps	38
Textual documents *(e.g., newspaper articles, diaries, logbooks)*	37
Land, property, and resource surveys *(e.g., timber surveys, fisheries surveys, land surveys)*	34
Aerial photographs	22
Ecological and scientific field surveys	20
Museum and specimen collections	12
Landscape photographs	8
Oral histories, interviews, and Traditional Ecological Knowledge	7

Table 2. Geographic setting of historical ecology studies. Each paper was coded with up to two study regions (total is therefore greater than the number of studies).

Study Region	**# articles**
Africa	6
Asia	6
Central/South America	7
Europe	
Eastern	*17*
Northern	*18*
Southern	*15*
Western and British Isles	*35*
General	*3*
North America	
Canada	*17*
Mexico	*3*
Caribbean	*4*
U.S. - Mid-Atlantic	*1*
U.S. - Midwest	*17*
U.S. - Mountain West	*4*
U.S. - Northeast	*12*
U.S. - Pacific West	*29*
U.S. - Southeast	*7*
U.S. - Southwest	*10*
General	*2*
Other	
Arctic	*1*
Australia	*7*
New Zealand	*3*
South Pacific Islands	*1*
Multiple (synthesis paper)	*4*

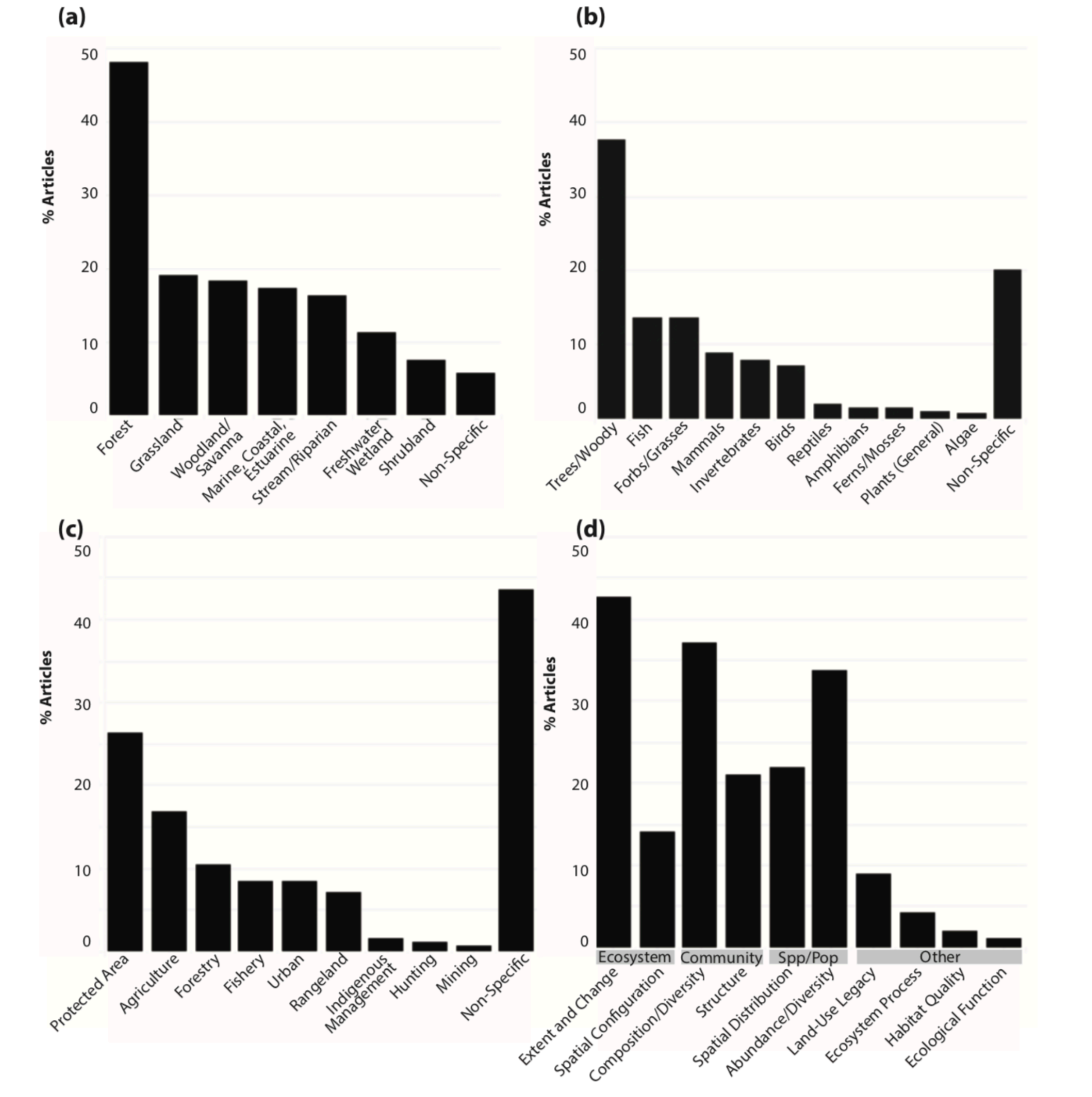

Figure 4. The ecosystem type (a), taxa (b), land use context (c), and ecological study focus (d) of historical ecology papers coded.

3.2. Management recommendation emerging from the global body of historical ecology

The conservation and restoration of former and/or native species, communities, and ecosystems was by far the most prevalent recommendation, found in 38% of all papers (table 3, figure 5). Other common recommendation categories included active management practices (e.g., prescribed fire and grazing management; 27% of papers), increasing connectivity (18% of papers), and protecting/restoring habitat remnants and areas of persistence (18% of articles). Here we highlight three key themes that emerged across studies: (1) the importance of both preserving habitat remnants and embracing the ecological values of human modified ecosystems, (2) the role of people in shaping and stewarding ecosystems, and (3) the value of managing across scales.

Table 3. List of recommendations for ecosystem management, synthesized from peer-reviewed historical ecology articles and ranked by frequency. All categories recommended by >5% of papers are listed here.

Rank	Recommendation	# articles	References (*see Appendix B)*
1	Protect/restore former and/or native species, communities, and ecosystems	60	2, 3, 11, 17, 27, 33, 34, 35, 37, 38, 39, 41, 48, 50, 51, 52, 54, 61, 68, 70, 71, 72, 76, 80, 82, 88, 95, 101, 106, 109, 114, 130, 132, 133, 138, 142, 143, 144, 146, 147, 150, 152, 153, 161, 167, 169, 178, 181, 185, 188, 189, 192, 196, 198, 200, 201, 214, 215, 216, 217
2	Increase connectivity	28	2, 6, 13, 16, 38, 43, 46, 47, 55, 67, 68, 86, 87, 104, 109, 114, 115, 128, 129, 130, 144, 152, 169, 171, 186, 207, 211, 214
3	Silviculture: decrease forest density or don't thicken (e.g., through removal of trees, snags, stumps; thinning, cutting, firewood collection, weeding)	26	7, 21, 23, 32, 50, 51, 71, 75, 80, 95, 108, 112, 113, 117, 118, 119, 130, 135, 137, 148, 149, 152, 179, 183, 193, 194
4	Address direct anthropogenic stressors to ecosystems (e.g., fishing, trawling, dredging, pollution, nutrient loading)	22	1, 5, 14, 64, 72, 78, 79, 96, 106, 121, 125, 131, 132, 133, 134, 139, 146, 150, 157, 160, 164, 196

5	Protect/restore biological structure (age, size, spatial patterns)	21	7, 8, 16, 23, 85, 95, 96, 114, 117, 118, 130, 135, 161, 163, 183, 184, 193, 194, 205, 207, 211
6	Maintain/restore grazing	20	6, 22, 27, 32, 45, 51, 60, 62, 81, 87, 89, 92, 104, 108, 109, 148, 149, 167, 182, 206
7	Employ prescribed fire	19	7, 21, 26, 44, 62, 71, 80, 89, 96, 112, 113, 117, 118, 137, 148, 152, 161, 194, 195
7	Adopt regional perspective, manage at a landscape scale, manage across scales or jurisdictions	19	1, 6, 22, 37, 67, 78, 83, 102, 104, 116, 132, 138, 143, 147, 156, 165, 183, 187, 201
7	Protect/restore biological heterogeneity and complexity	19	8, 23, 31, 70, 81, 83, 93, 94, 96, 104, 117, 135, 137, 152, 162, 173, 180, 183, 205
8	Protect/restore species diversity	18	8, 46, 47, 61, 69, 87, 89, 92, 119, 131, 146, 149, 154, 158, 170, 171, 173, 202
9	Reintroduce species (within range)	17	15, 23, 37, 49, 50, 51, 73, 74, 104, 106, 111, 154, 161, 173, 174, 196, 200
9	Create/enhance protected areas	17	2, 9, 11, 13, 18, 28, 32, 61, 64, 67, 68, 72, 102, 106, 131, 132, 209
9	Practice monitoring (e.g., of key species or populations, of efficacy of restoration efforts)	17	10, 11, 36, 55, 65, 70, 77, 79, 84, 137, 148, 160, 168, 189, 190, 208, 213
9	Protect/restore habitat remnants and fragments	17	6, 28, 59, 73, 75, 88, 91, 109, 121, 128, 140, 157, 168, 171, 177, 195, 212
10	Protect/restore environmental setting, abiotic conditions and processes	15	13, 27, 29, 30, 55, 72, 87, 164, 166, 176, 180, 188, 189, 207, 214
11	Protect/restore uncommon, endangered, rare, or underrepresented species, communities, and ecosystems	14	7, 13, 50, 56, 59, 69, 75, 91, 97, 123, 124, 127, 192, 195

12	Manage at a site scale, consider different approaches for different areas based on land-use history or environmental context	13	12, 13, 20, 59, 81, 88, 91, 108, 130, 142, 178, 180, 187
13	Protect/restore diversity of habitat or ecosystem types	12	2, 22, 59, 90, 91, 95, 148, 155, 166, 171, 187, 192
13	Protect/restore around areas of persistence (e.g., around habitat remnants, in areas of persistence of geophysical conditions)	12	6, 13, 68, 76, 80, 92, 100, 101, 119, 159, 192, 216
14	Protect/restore ecosystem function or process	11	21, 28, 60, 66, 81, 84, 89, 84, 104, 147, 148
14	Protect/restore matrix habitats + human-dominated landscapes – agriculture	11	45, 47, 53, 82, 90, 114, 145, 158, 166, 168, 178
14	Protect/restore old, large trees	11	8, 94, 104, 110, 135, 170, 172, 183, 191, 211, 212
14	Protect/restore novel/no-analog species, communities, and ecosystems	11	19, 22, 43, 81, 84, 99, 106, 124, 128, 130, 195
14	Recognize human-environment interactions, cultural nature of landscapes, influence of land-use history on ecology	11	4, 20, 21, 43, 62, 92, 104, 112, 141, 149, 209

Figure 5. Top ten recommendations for ecosystem management generated by the historical ecology literature, aggregated by overall category (e.g., genetic/phenotypic diversity, species diversity, and ecosystem diversity are lumped into "biodiversity"). Examples provided in the right column of this figure are the more granular recommendations as coded and listed in table 3.

3.2.1 Preserving habitat remnants and embracing modified ecosystems

Studies that used historical data to identify habitat remnants and make recommendations to protect existing remnants and prioritize conservation around them were prevalent. Habitat remnants were seen as having high conservation value given their rarity, biodiversity, ability to act as plant source populations for disturbed areas or newly restored habitat, and role in facilitating wildlife movement across the landscape. In native prairies in Oregon, for example, Duren et al. (2012) found vegetation conversion over the past ca. 150 years to be concentrated in valleys, and recommended that conservation of these low-lying remnant native prairie vegetation be a high priority. In woodland and forest ecosystems, individual old and/or large trees were frequently identified and recommended for increased conservation priority given their rarity in many contemporary landscapes, the difficulty of replacement, and their potential to support biodiversity (e.g., Jönsson et al. 2009, Meador et al. 2010, Plienenger 2012, Lydersen et al. 2013).

Prioritizing restoration and conservation actions in areas around existing remnants was also frequently recommended. In Germany, for example, Wulf et al. (2017) identified areas where deciduous forest had been preserved over 230 years despite overall trends in conversion to coniferous forest, and recommended integration of these "near-natural" stands into restoration projects to facilitate plant colonization into newly restored areas. Remnants were also used to identify sites where habitat persistence over long time scales was indicative of resilience to disturbance or opportunities to take advantage of persistent abiotic conditions or processes. For example, Beller et al. (2016) demonstrated that historical heterogeneity in riparian habitats along a river in southern California, U.S., was driven by persistent geophysical controls on groundwater and surface flow, and used remnant habitats to identify promising areas for riparian restoration where supported by abiotic conditions.

While recommendations to preserve and restore around habitat remnants were prevalent, other recommendations embraced human modifications of the landscape by highlighting the importance of actions in highly modified landscapes and identifying new ecological values of such landscapes. In the city of San Jose, U.S., for example, Whipple et al. (2011) estimated near-complete declines in native oak populations and recommended using historical landscape patterns to re-introduce oaks in an urban context. In an agricultural setting, Grixti et al. (2009) quantified decreases in bumblebees in Illinois, U.S., coincident with 20th century agricultural intensification and recommended wildlife-friendly agricultural practices such as interspersed habitat patches and hedgerows to counteract this decline. Blixt et al. (2015) found that clear-cuts in Sweden on former grasslands supported butterfly species, suggesting the importance of conserving these highly modified habitats as part of the overall landscape mosaic. A study on the spread of the invasive shrub *Lantana camara* across Australia, India, and South Africa (Bhagwat et al. 2012) found that extensive measures to control and eradicate the species over the past 200 years have been largely unsuccessful, and suggested acceptance of the novel ecosystems created by the invasion rather than attempting eradication. Other examples include the use of mining spoil heaps as restoration sites in the Czech Republic (Hendrychova and Kabrna 2016) and the creation of artificial wetlands in Israel to complement protection and restoration of remnant habitats and offset the loss of historical wetlands (Levin et al. 2009). Studies also suggested the conservation and restoration of "intermediate" habitats where they support biodiversity, such as semi-natural grasslands grazed by livestock in Sweden that support grassland plant species (Gustavsson et al. 2007) and second-growth forests in California that protect old-growth forest stands from edge effects (Fritschle 2012).

3.2.2. Recognize ecosystems as cultural landscapes

While a historical perspective is sometimes characterized as a focus on "pristine" or "wild" conditions, historical ecologists have long recognized the legacies of human modification and stewardship of ecosystems and landscapes (Berkes 2004, Jackson and Hobbs 2009). The historical role of humans in shaping landscapes was reflected in management recommendations: in aggregate, management via traditional interventions such as mowing, grazing, fire, and pruning was the second most highly ranked recommendation category, endorsed by 27% of studies. Often, the recommended approaches preserved or mimicked traditional or past landscape stewardship practices, acknowledging the influence of previous land use management regimes on current ecosystem characteristics. For example, Jurskis (2011) demonstrated the lack of fallen timber historically in Australian grassy woodlands due to Aboriginal fire management, and recommended the reintroduction of practices such as broadcast burning and firewood collection to restore habitat heterogeneity and rare species. Recommendations are not restricted to traditional indigenous practices: in the sand-plain woodlands of Massachusetts, U.S., for example, Eberhardt et al. (2003) demonstrated the role of past agriculture in creating heathland and grassland communities and suggested mimicking agricultural practices to restore these habitat types. Recommendations also identified the importance of conserving cultural landscapes. For example, McCune et al. (2013) showed that indigenous management maintained Garry oak ecosystems in British Columbia, Canada, and recommended prioritizing such these landscapes for conservation. Additional recommendations included incorporation of Traditional Ecological Knowledge or other sources of local environmental knowledge into ecosystem management activities (e.g., MacDougall et al. 2004, Kurashima et al. 2017).

3.2.3. Consider landscape context and site-scale differences

The value of a landscape-scale perspective is emphasized by the historical ecology literature, where long temporal scales of investigation are often accompanied by large spatial scales. Studies emphasized the value of a large-scale perspective to enable cross-sector coordination and collaboration across stakeholders and jurisdictions; characterize abiotic gradients, processes, and heterogeneity; and identify and prioritize opportunities to improve connectivity, biodiversity, and other factors across the landscape. The importance of considering landscape context is similarly increasingly recognized in the broader ecosystem management literature (cf. Menz et al. 2013, Hobbs et al. 2017).

For example, in Iowa, U.S., Gallant et al. (2011) used 19th century federal land surveys coupled with modern inventories of wetlands and hydric soils to show dramatic wetland losses across the state, and recommended adoption of landscape-scale perspective on ecosystem change to capture the full range of historical wetland extent and diversity, understand the dramatic transformations of the past centuries, and identify locations most likely to support wetland complexes in the future. The integration of terrestrial and aquatic ecosystem management was also recommended by a number of studies. In the Columbia River Basin in the U.S. Pacific Northwest, for example, Hessburg et al. (2000) characterized changes in forest vulnerability to disturbances such as wildfire and insects; they stressed the influence of upland disturbances on aquatic ecosystem health and recommended the joint consideration of restoration strategies for aquatic and forest habitats. In the marine realm, the synthesis of multiple drivers of oyster decline over more than a century in Scotland led Thurstan et al. (2013) to recommend integrated management of terrestrial and marine impacts on nearshore ecosystems.

The large spatial scales adopted by many studies also generated insights into between-site differences often obscured in site-scale studies. As a consequence, many studies stressed the importance of using different management approaches for areas with divergent land-use histories or abiotic conditions, even if they appear superficially similar, and cautioned against generic "one size fits all" approaches (e.g., Bieling et al. 2013, Fuller et al. 2017). For example, in a study of land-cover change on the French coast, Godet and Thomas (2013) distinguished three types of grasslands in the contemporary landscape based on land-use history and recommended different management pathways for each type. In a desert landscape in New Mexico, Browning et al. (2012) found that soil water holding capacity controlled shrub response to disturbance, and recommended prioritizing grassland restoration on sites with higher near-surface water holding capacity rather than sites with coarse-textured soils in order to maximize their resilience to drought.

3.3. Challenges to status quo management practices

Historical ecology has been recognized for its ability to provide new insights that can adjust how we manage species and ecosystems (e.g., Walter and Merritts 2008, McClenachan et al. 2012. McClenachan et al. 2015). Our study affirms this: nearly one-quarter (23%) of studies contained at least one recommendation that authors explicitly stated revised or challenged status quo management activities. The prevalence of such recommendations emphasizes the value of a historical perspective in shifting our understanding of desirable management goals, strategies, and targets. It also underscores that even "conventional" past-oriented recommendations—for example, to restore former ecosystem conditions—may run counter to current management practices by providing a revised understanding of former conditions.

Studies employed a historical perspective to identify previously unrecognized species, ecosystems, or sites for management. For example, in northern California Grossinger et al. (2007) found evidence of sycamore-alluvial woodland riparian habitats on stream reaches now dominated by dense cottonwood forests, and recommended restoration of these habitats given their rarity and tolerance to drought. Plumeridge and Roberts (2017) reconstructed large declines in fish communities off the coast of England and emphasized the importance of considering rare or extirpated fish as conservation targets that have long been ignored given their lack of economic importance. In southern California, Stein et al. (2010) demonstrated a nearly 90% loss of wetlands since the 19^{th} century and noted that the formerly most widespread wetland types were the most impacted by development yet were rarely included in restoration planning efforts, despite opportunities for recovery where supported by persistent groundwater conditions. In some cases, findings were used to identify new locations for conservation. For example, Feretti et al.'s (2015) reconstruction of sawfish biogeography and extinction in the Mediterranean Sea over ~400 years broadened the species' historical range and suggested previously unidentified sites for sawfish reintroductions.

Studies also questioned or revised existing assumptions about management targets for the species and ecosystem type, population abundance, and community structure appropriate for a given location. For example, Bukowski and Baker (2013) cautioned against current proposals to remove trees encroaching into sagebrush across a four-state region in the western United States, noting that trees naturally occurred in sagebrush habitats and that their removal would not be ecological restoration. In California's Sierra Nevada mountains, Stephens et al. (2015) found increases in canopy cover over the past century and concluded that current goals for restoring forest canopy cover should be revised downward to reflect historical density estimates and increase the resilience of forest ecosystems to future disturbance. An investigation of Sooty Tern population declines on Ascension Island in the south Atlantic Ocean demonstrated an 84% decline in population size over three generations of the species and suggested upgrading the species' conservation status to "Critically Endangered" (Hughes et al. 2017).

3.4. Looking back, looking forward: historical ecology and climate change

Fifty-seven papers (26%) mentioned the potential impacts of climate change on their study system such as changes in temperature (15 papers) and drought (11 papers). Of these, 25 papers (<12% of all papers coded) contained at least one recommendation that explicitly addressed a dimension of ongoing or projected climate change. Recommendations included both traditional and explicitly future-oriented strategies, including protecting and restoring biological structure and heterogeneity (e.g., Lydersen et al. 2013, Tucker et al. 2016) and native species and ecosystems (e.g., Clavero et al. 2017); restoring abiotic environmental conditions and processes and prioritizing restoration where supported by these conditions (e.g., Paalvast and Van der Velde 2014), and targeting areas likely to provide suitable habitat in the future (e.g., Danneyrolles et al. 2017).

The question of how to prioritize ecosystem management activities in the context of climate change has received increasing attention over the past decade, with a number of reviews aimed at helping guide ecosystem management (e.g., Mawdsley et al 2009, Heller and Zavaleta 2009, Lawler 2009, Hansen et al. 2010, Stein et al. 2013). While our focus here is broader (i.e., on general ecosystem management rather than climate change adaptation), many of the approaches prevalent in historical ecology studies are also emphasized by the climate change adaptation literature. This is particularly true of landscape- and ecosystem-scale recommendations, such as increasing connectivity, expanding protected areas, mitigating or reducing non-climate stresses to ecosystems, and adaptive management and monitoring (see Appendix C for additional detail).

While there is substantial overlap in recommendations between the two bodies of literature, there are also apparent points of divergence (figure 6). Some approaches gaining prevalence in the climate change adaptation sphere, based on a recent analysis of recommendations (McLaughlin et al. *in prep*), are rare or absent in the historical ecology literature. These include explicitly future-oriented approaches such as translocation beyond the species' current range (e.g., Adams-Hosking et al. 2011, Şekercioğlu et al. 2012), targeting genotypes adapted to future conditions (e.g., Li et al. 2014, Zheng et al. 2015), and protecting genotypic and phenotypic diversity (e.g., Gray et al. 2014, Abbott et al. 2017). Many of the approaches least well represented by the historical ecology literature are at the species or population level, perhaps reflecting the large spatial scales of many studies and the challenge of obtaining historical data at smaller ecological scales. Conversely, emphases in historical ecology such as protecting and restoring around habitat remnants, protecting abiotic conditions and processes, and human stewardship of ecosystems (e.g., via traditional management practices) are less well represented in the climate change adaptation literature.

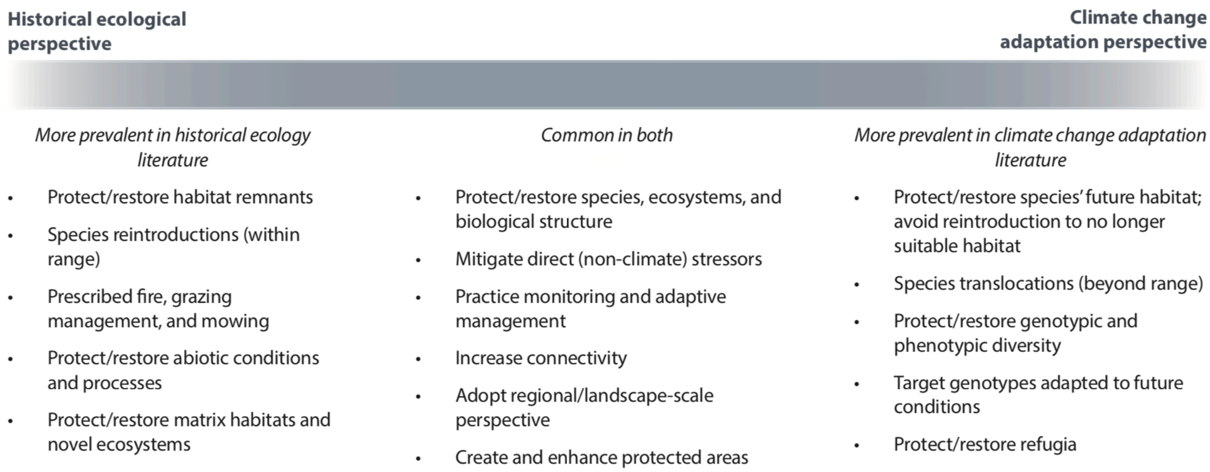

Figure 6. Conceptual comparison of example recommendations prevalent in the historical ecology literature (left), climate change adaptation literature (right), and in the top ten recommendations of both (center). Comparison is based on this paper plus synthesis of a number of reviews of the climate change adaptation literature (cf. Heller and Zavaleta 2009, Lawler et al. 2009, Mawdsley et al. 2009, Hansen et al. 2010, Groves et al. 2012, Stein et al. 2013, and McLaughlin et al. *in prep.*)

4. Conclusion

Here we present the first quantitative analysis of the global historical ecology literature across ecosystems, with a focus on the management recommendations generated by this body of research. Perhaps not surprisingly, many of the most common recommendations were associated with preserving or recovering former conditions or functions, such as protecting habitat remnants or reintroducing species within their former ranges. However, papers also made a range of other recommendations including the importance of ecosystem management in highly modified and human-dominated ecosystems, prioritizing people in landscape stewardship, and taking a larger, landscape-scale perspective. In addition, a substantial number of studies contained surprising recommendations that challenged status quo management. These results suggest that the broad temporal—and frequently spatial—scales adopted by historical ecology studies, coupled with a unique set of sources and approaches, equips the historical ecologist with a distinct perspective that can be challenging to acquire from short-term ecological studies and can be conducive to spurring new ideas and insights about ecosystem characteristics, processes, and potential.

A focus on the past is sometimes framed as standing in contrast or opposition to future-oriented management. “Backward looking” goals are cast as a desire to return to former ecosystem states, increase ecological integrity, and resist change, while “forward looking” goals are focused on restoring functions, increasing resilience to change, and embracing novelty (e.g., Seastedt et al.

2008, Heller and Hobbs 2014, Miller and Bestelmeyer 2016). We believe that this is a false dichotomy. Recommendations in the historical ecology literature are generally aligned with those fields such as climate change adaptation more traditionally conceived of as "forward looking." Far from aiming to restore a stable or pristine wilderness, historical ecology provides insights that cultivate a sense of ecosystems in their specific social and environmental contexts, and emphasizes the importance of people—now and in the past—in shaping and stewarding the natural world. It emphasizes the importance of habitat fragments and other areas of persistence, not as a return to the past, but as repositories of biodiversity and resilience, often linked to relatively stable abiotic conditions and processes. And it accentuates that historical and novel ecosystems are not two ends of a spectrum, as commonly portrayed, but occur side by side in complex, hybrid landscape mosaics superimposed at a variety of scales (cf. Hobbs et al. 2014).

That said, there are also clear directions for future research in historical ecology to enhance the field's applicability and representativeness. Our findings underscore key research gaps, in particular the paucity of studies focused on Asia, Central/South America, and Africa. In addition, we highlight the relative lack of research on aquatic ecosystems. The predominance of studies analyzing forests undoubtedly influenced recommendation rank; additional research could help provide more ecosystem-specific insights about the types of strategies and actions recommended.

Our research also suggests several opportunities for further synthetic research of the historical ecology literature. First, while we only examined journal articles available through Web of Science in the present study, additional valuable analyses are available in government documents, monographs, book chapters, and reports; inclusion of these studies would enhance understanding of the recommendations emerging from historical ecology. Second, it is unclear how the characteristics of papers that include explicit recommendations for management compare to the broader body of historical ecology literature (many of which do not include recommendations); future research could elucidate how the articles reviewed here related to the broader field in terms of study spatial and temporal scale, ecosystem and geographic context, and other dimensions. Third, it is unknown how these results would differ from a random sampling of management recommendations from conservation-focused papers from the same time frame; a next step would be to compare recommendations from the historical ecology and broader field of conservation to assess differences in the type and prevalence of recommendations from the two bodies of literature. Finally, it would be valuable to catalog the key system attributes quantified across historical ecology studies that have been used to identify management recommendations; this would provide insight into the types of historical information most useful and relevant for ecosystem management.

Our results also suggest an opportunity for historical ecology to more explicitly address environmental change. While many of the historically informed management strategies and targets suggested in the literature are likely to be appropriate in the future, there is no guarantee that this will be the case, and historical ecologists should be encouraged to explicitly address future changes in climate and disturbance regimes and explore the potential impact on appropriate management approaches. Fundamentally, however, we stress that insights generated from historical perspective are an essential component of developing future-oriented approaches to ecosystem management: approaches that are dynamic, creative, and novel yet rooted in place and past.

5. Acknowledgments

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Supplemental Material A: Search Term

TS = ((historic* NEAR/1 ecolog* OR "land cover change*" OR "landscape change*" OR ecosystem NEAR/2 change* OR ecologic* NEAR/2 change* OR vegetation NEAR/2 change* OR "ecosystem trajector*" OR "ecologic* trajector*" OR "landscape trajector*" OR "land cover" NEAR/1 trajector* OR "land use" NEAR/1 trajector* OR "ecolog* history" OR "landscape history" OR "past vegetation" OR historic* NEAR/2 population* OR "land use change*" OR "historic* condition*" OR "habitat loss" OR "habitat gain" OR "habitat change*" OR "land cover transition*" OR "historic* vegetation" OR composition* NEAR/2 change* OR "historic* change*" OR "historic* abundance" OR "past ecosystem*" OR "range of variability" OR shifting NEAR/1 baseline* OR "historic* baseline*" OR "baseline condition*" OR "long term ecolog*" OR "past land cover" OR "past land use" OR "historic* landscape" OR "historic* land cover" OR "historic* land use" OR "past landscape*" OR "landscape transformation*" OR "ecosystem trend*" OR "reference condition*" OR "land use history" OR "long term history" OR "change analys?s" OR "original vegetation" OR "cover change" OR former NEAR/1 abundance* OR past NEAR/2 abundance* OR change* NEAR/2 abundance* OR "historic* timescale*" OR "restoration baseline*" OR "conservation baseline*") AND (histor* OR centur* or decad* OR "multi-decad*" OR "long-term" OR "long term" OR "long* time" OR past OR "pre-European" OR "European settlement" OR presettlement OR pre-settlement OR preindustrial OR pre-industrial OR trajector* OR reconstruct* OR "1?0 year*" OR "2?0 year*" OR "3?0 year*" OR " 16?0*" OR " 17?0*" OR " 18?0*" OR "shifting baseline" OR "historic* baseline") AND ("historic* data" OR archiv* OR "historic* map*" OR "historic* photo*" OR aerial* OR "historic* survey*" OR "historic* document*" OR "historic* source*" OR "historic* approach*" OR "historic* record*" OR "historic* investigation" OR "multi-proxy" OR library OR museum OR "historic* reconstruction*" OR chart* OR "cadastral map*" OR "survey note*" OR "general land office" OR "reference condition*" OR "historic* evidence" OR "historic* inventory" OR "land survey*" OR logbook* or "historic* anecdote*" OR baseline*) AND (adaptation OR planning OR strategy OR conservation OR conserve OR restoration OR restore OR management) NOT (paleo* OR palaeo* OR archaeo* OR archeo* OR Pleistocene)) OR TS = (("historic* baseline*" OR "conservation baseline*" OR "restoration baseline*" OR "shifting baseline*" OR "historic* ecology")

Supplemental Material B: List of Coded Papers

1. Al-Abdulrazzak D, Pauly D. 2017. Reconstructing historical baselines for the Persian/Arabian Gulf Dugong, Dugong dugon (Mammalia: Sirena). Zoology in the Middle East 63: 95–102.
2. Alexander KE, Leavenworth WB, Cournane J, Cooper AB, Claesson S, Brennan S, Smith G, Rains L, Magness K, Dunn R, Law TK, Gee R, Jeffrey Bolster W, Rosenberg AA. 2009. Gulf of Maine cod in 1861: Historical analysis of fishery logbooks, with ecosystem implications. Fish and Fisheries 10: 428–449.
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11. Barry S, Fellers G. 2013. History and status of the California red-legged frog (*Rana Draytonii*) in the Sierra Nevada, California, USA. Herpetological Conservation and Biology 8: 456–502.
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13. Beller EE, Downs PW, Grossinger RM, Orr BK, Salomon MN. 2015. From past patterns to future potential: using historical ecology to inform river restoration on an intermittent California river. Landscape Ecology 3: 581-600.
14. Benchetrit J, McCleave JD. 2016. Current and historical distribution of the American eel Anguilla rostrata in the countries and territories of the Wider Caribbean. ICES Journal of Marine Science 73: 122–134.
15. Berger J. 2008. Undetected species losses, food webs, and ecological baselines: A cautionary tale from the Greater Yellowstone Ecosystem, USA. Oryx 42: 139–142.
16. Bergès L, Avon C, Arnaudet L, Archaux F, Chauchard S, Dupouey JL. 2016. Past landscape explains forest periphery-to-core gradient of understorey plant communities in a reforestation context. Diversity and Distributions 22: 3–16.
17. Bergès L, Feiss T, Avon C, Martin H, Rochel X, Dauffy-Richard E, Cordonnier T, Dupouey JL. 2017. Response of understorey plant communities and traits to past land use and coniferous plantation. Applied Vegetation Science 20: 468–481.
18. Bertolo LS, Lima GTNP, Santos RF. 2012. Identifying change trajectories and evolutive phases on coastal landscapes. Case study: São Sebastião Island, Brazil. Landscape and Urban Planning 106: 115–123.
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Supplemental Material C: Citations for Climate Change Adaptation Recommendations

Citations are listed if the recommendation is emphasized in the article. For Heller and Zavaleta (2009) and McLaughlin et al. (*in prep*) where recommendations are ranked, citations are listed if the recommendation was included within the top 10 list of ranked recommendations.

Recommendation	**Citations**
Protect/restore species, ecosystems, and biological structure	Lawler 2009, Mawdsley et al. 2009, Groves et al. 2012, McLaughlin et al. *in prep*
Mitigate direct (non-climate) stressors	Lawler 2009, Mawdsley et al. 2009, Heller and Zavaleta 2009, Hansen et al. 2010, Stein et al. 2013, McLaughlin et al. *in prep*
Practice monitoring and adaptive management	Lawler 2009, Mawdsley et al. 2009, Heller and Zavaleta 2009, Hansen et al. 2010, Stein et al. 2013, McLaughlin et al. *in prep*
Increase connectivity	Lawler 2009, Mawdsley et al. 2009, Heller and Zavaleta 2009, Groves et al. 2012, Stein et al. 2013, McLaughlin et al. *in prep*
Adopt regional/landscape-scale perspective	Heller and Zavaleta 2009, Stein et al. 2013, McLaughlin et al. *in prep*
Create and enhance protected areas	Lawler 2009, Mawdsley et al. 2009, Heller and Zavaleta 2009, Hansen et al. 2010, Stein et al. 2013
Protect/restore species' future habitat; avoid reintroduction to no longer suitable habitat	McLaughlin et al. *in prep*
Species translocations (beyond range)	Lawler 2009, Mawdsley et al. 2009, Heller and Zavaleta 2009, Stein et al. 2013, McLaughlin et al. *in prep*
Protect/restore genotypic and phenotypic diversity	Stein et al. 2013, McLaughlin et al. *in prep*
Target genotypes adapted to future conditions	Stein et al. 2013, McLaughlin et al. *in prep*
Protect/restore refugia	Mawdsley et al. 2009, Groves et al. 2012, Stein et al. 2013, McLaughlin et al. *in prep*

Chapter 3: From Savanna to Suburb: Effects of 160 Years of Landscape Change on Carbon Storage in Silicon Valley, California

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Abstract
Landscape changes such as urbanization can dramatically affect the provision of ecosystem services. For example, while cities have been shown to store substantial amounts of carbon in soils and vegetation, we have little information from long-term studies about how contemporary carbon storage in urban areas compares to carbon storage in the natural ecosystems that characterized these landscapes prior to urbanization. We used historical archival sources and land cover data to quantify and map historical tree carbon storage in the now-urban Santa Clara Valley, California, USA prior to substantial Euro-American modification (ca. 1850) and to analyze change in the amount and distribution of carbon storage over the past ca. 160 years. We estimate that total tree carbon storage in the study area was ~784,000 to 2.2 million Mg (13.6-38.1 Mg C/ha) when the region was characterized by oak savanna and woodland habitats compared to ~895,000 Mg C (15.5 Mg C/ha) today. This represents a non-significant gain of 14% to a significant loss of 60% depending on scenario. We also demonstrate changes in the spatial distribution of carbon on the landscape, as losses in carbon storage in areas of former oak woodland were partially offset by gains in carbon storage in historical habitat types that historically had few or no trees. This challenges the hypothesis that aboveground carbon storage increases with urbanization in Mediterranean-climate ecosystems due to irrigation and tree planting. Our study demonstrates the utility of using pre-1900s historical sources to reconstruct changes in ecosystem services such as carbon storage over century time scales.

Keywords: ecosystem services; carbon storage; historical ecology; landscape history; land-cover/land-use change, urban ecosystems; urban forestry

1. Introduction

The conversion of ecosystems and landscapes to urban land cover is a major driver of both local and global environmental change (Grimm et al., 2008). The extent of urban areas worldwide increased 40-fold from 1700 to 2000 (Ellis, Goldewijk, Siebert, Lightman, & Ramankutty, 2010) and is expected to triple again by 2030 (Seto, Guneralp, & Hutyra, 2012), with dramatic impacts on the ability of a landscape to provide key ecosystem services. For example, urbanization affects biogeochemical cycles (Pataki et al., 2011), carbon storage (Seto et al., 2012), biological diversity (Aronson et al., 2014), habitat extent and distribution (Groffman et al., 2014), and the provision of ecosystem services both within cities and outside their borders (Eigenbrod et al., 2011). At the same time, there is also increasing recognition of the value of ecosystems in urban areas to provide benefits such as carbon storage, climate and air quality regulation, flood control, and recreational and mental health benefits (cf. Haase et al., 2014; McDonnell & MacGregor-Fors, 2016).

For example, trees are a significant contributor to aboveground carbon storage in cities, as demonstrated by a multitude of studies (e.g., Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011; Hutyra, Yoon, & Alberti, 2011; Strohbach & Haase, 2012; Nowak, Greenfield, Hoehn, & Lapoint, 2013; Raciti, Hutyra, & Newell, 2014; Reinmann, Hutyra, Trlica, & Olofsson, 2016). However, assessments of contemporary carbon storage in cities are rarely compared to carbon storage in the former natural ecosystems that characterized these landscapes prior to urbanization. Many studies that quantify the impacts of land-use conversion and urban expansion on carbon storage (e.g., Hutyra, Yoon, Hepinstall-Cymerman, & Alberti, 2011; Pasher, McGovern, Khoury, & Duffe, 2014; Jiang, Deng, Tang, Lei, & Chen, 2017) focus on late 20th and early 21st century change in already modified landscapes that do not necessarily reflect former conditions, while other studies assume urban land uses store no carbon (e.g., Eigenbrod et al., 2011; Sallustio, Quatrini, Geneletti, Corona, & Marchetti, 2015; Li, Zhao, Thinh, & Xi, 2018). Space-for-time substitutions that compare urban carbon storage to surrounding natural ecosystems (e.g., Golubiewski, 2006; McHale, Hall, Majumdar, & Grimm, 2017) suggest temporal trends, but do not quantify site-specific change over time. (Note that while carbon storage in urban soils can be considerable, most of these studies quantify carbon stored in trees and aboveground vegetation only or use coarse land use/land cover based proxies for soil organic carbon; see section 4.3 for a discussion of soil carbon.) To our knowledge, no studies have examined temporal changes in carbon storage in urban areas extending before 1900. As a result, the impact of urbanization on carbon storage over century time scales, as well as how urban carbon storage compares to pre-settlement conditions, is not well understood.

In mesic climates where pre-settlement conditions were characterized by dense forest cover, long-term carbon storage change may be readily apparent, as aboveground carbon storage likely decreased over time as forested areas were cleared. In Seattle, for example, Hutyra et al. (2011b) found a ~40% loss in aboveground tree carbon stocks with urban expansion onto forested landscapes from 1986-2007, and in Boston Raciti et al. (2014) found mean aboveground tree carbon storage in the city was a quarter of that in nearby forested lands. However, in arid, semi-arid, and Mediterranean-climate ecosystems, many former grassland, savanna, and shrubland ecosystems have experienced increases in tree cover due to planting and increased water availability, making expected trends in carbon storage less clear. For example, Golubiewski (2006) showed increases in carbon storage (including soil organic carbon and aboveground herbaceous and woody vegetation) per unit area in Colorado suburbs compared to semi-arid native grassland ecosystems due to increases in woody vegetation with urbanization. However, McHale et al. (2017) showed that carbon storage in woody urban vegetation (trees and shrubs, including tree roots) per unit area in Phoenix, Arizona was lower than that in surrounding desert ecosystems as native shrubs were replaced by urban trees. For this reason, additional research is needed to understand carbon storage change in such systems.

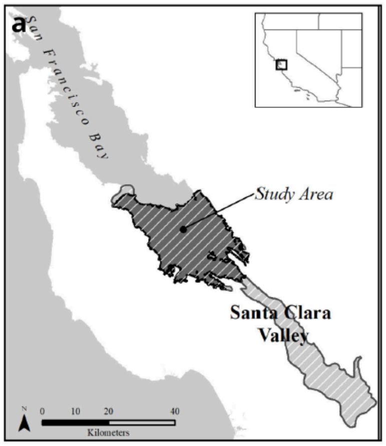
While the value of documenting change over time in ecosystem service provision has long been recognized, the use of historical datasets to reconstruct ecosystem services over time remains uncommon (Tomscha et al, 2016). Recent research has analyzed decadal-scale changes in ecosystem services in mountain ecosystems (Vigl, Schirpke, Tasser, & Tappeiner, 2016), forested ecosystems (Sutherland, Bennett, & Gergel, 2016), and agricultural landscapes (Jiang, Bullock, & Hooftman, 2013). Such reconstructions are valuable to analyze patterns of loss and gain, identify land-use legacy effects on service provision, understand tradeoffs and synergies between services across the landscape, identify the drivers underpinning changes in service provision, and understand landscape potential to provide ecosystem services in the future (cf. Renard, Rhemtulla, & Bennett, 2015; Tomscha & Gergel, 2015; Bürgi, Silbernagel, Wu, & Kienast, 2015). However, reconstructions that quantify and map spatio-temporal dynamics in ecosystem services over century time scales are still rare, particularly in urban and urbanizing landscapes.

Here, we use a case study from Santa Clara Valley, California, USA to (1) calculate historical tree carbon storage, (2) estimate change in tree carbon storage from pre-settlement conditions to the current urban landscape, and (3) examine the spatial distribution of carbon storage over time. We focus on tree carbon storage only (including both aboveground and belowground root biomass), hereafter referred to for simplicity as "carbon storage." By "historical" we refer to conditions in Santa Clara Valley as they existed, on average, prior to and during the early decades of Euro-American settlement (1770s-1850s, referred to here as "ca. 1850" for simplicity). Our aim is to analyze the impacts of urbanization on carbon storage in Mediterranean-climate ecosystems such as those found in Santa Clara Valley.

2. Methods

2.1. Study Area

The study area covers approximately 579 km^2 of Santa Clara Valley (also known as Silicon Valley), located south of San Francisco Bay in California's central coast ranges (Fig. 1) in the western USA. The region is characterized by a typical Mediterranean climate with cool, wet winters and warm, dry summers, and receives an average of 250-500 mm precipitation annually. Major Euro-American landscape modifications began in the late 18th century with the establishment of the Mission Santa Clara and Pueblo of San José in 1777. Since that time, Silicon Valley has experienced a series of rapid changes in land-cover/land-use regimes, from management by indigenous Ohlone communities prior to establishment of the Pueblo and Mission to grazing and ranching, intensive agriculture, and suburban and urban development (Grossinger, Striplen, Askevold, Brewster, & Beller, 2007). Today, the region is almost entirely urbanized, with just under half (44%) of land area in residential land uses, an additional 25% in commercial and industrial land uses, and 21% in transportation corridors. Open space composes only 9% of total area. It is inhabited by approximately 1.6 million people and includes San José, the 10th largest city in the United States (U.S. Census Bureau, 2010).



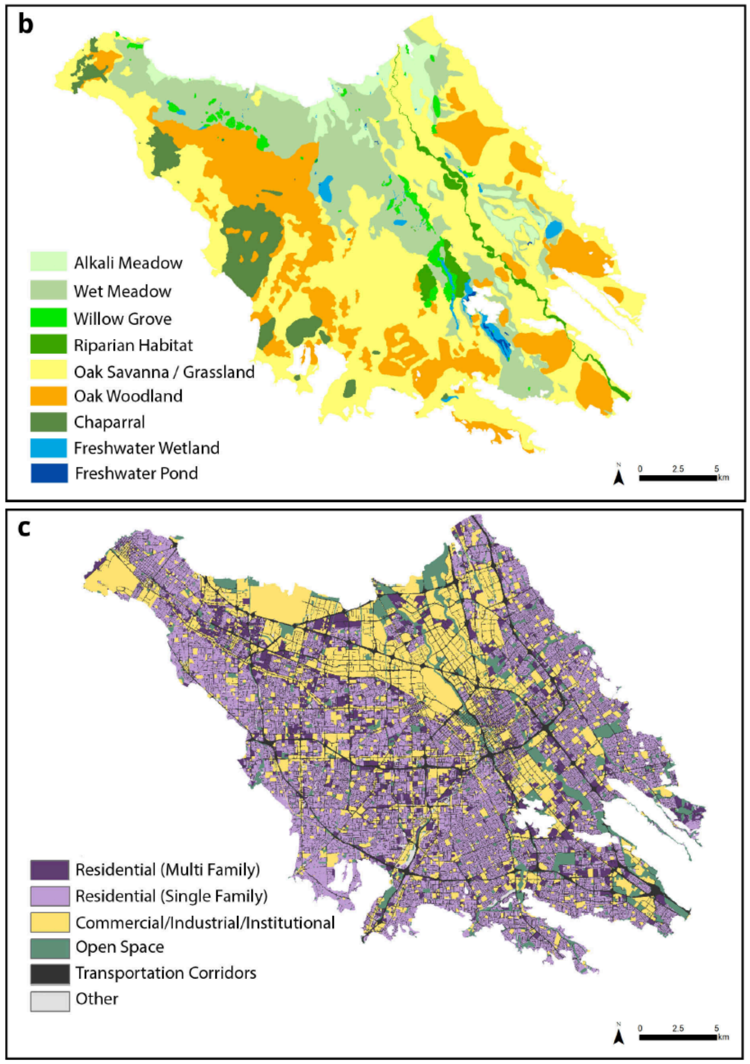


Figure 1. Study area location in the Santa Clara Valley, California (a), historical habitat type (b), and modern land use (c). Note that historical and modern tidal marshlands fringing the San Francisco Bay are excluded from the study area; also note the oak savanna classification (10-25% tree cover; FGDC 1997) likely also includes some areas of grassland with occasional oaks (0-10% tree cover). (Historical habitat type from Grossinger et al. 2006 and Beller et al. 2010; modern land use mapping from CalFire 2015.)

Prior to agricultural intensification in the late 19th and early 20th centuries, oak savannas and woodlands (collectively referred to here as “oak lands”) dominated by the deciduous valley oak (*Quercus lobata*) were the defining ecological feature of the valley (Beller, Salomon, & Grossinger, 2010). Early European explorers described the valley as the *“Llano de los Robles”*, or Plain of the Valley Oak, and described a landscape “very thickly grown with oaks of all sizes” (Font 1776, in Bolton, 1930). The open, park-like character of these oak lands, commented on by early observers (e.g., Vancouver, [1798] 1984), was likely heavily shaped by native residents who used fire to manage vegetation growth in oak woodlands (Mensing, 2006). Valley oaks, endemic to California, provide critical habitat for a diverse range of native mammals, birds, and other species (Davis, Baldocchi, & Tyler, 2016). Because of their association with sheltered valleys with fertile soils and high water tables, valley oak ecosystems have been disproportionately affected by agricultural development and urbanization (Griffin, 1973). Today, valley oak woodlands cover only 2.7% of California and compose only ~1% of all oak woodland habitats across the state (Allen-Diaz, Bartolome, & McClaran, 1999; Gaman & Firman, 2006).

2.2. Historical Data Sources

We used a variety of qualitative and quantitative sources to reconstruct historical carbon storage. We drew heavily on sources compiled as part of two previous historical ecology studies that produced land cover maps of the study area ca. 1850 (Grossinger et al., 2006, Grossinger et al., 2007, and Beller et al., 2010). These efforts used multi-source triangulation across several hundred maps, land surveys, paintings, narrative accounts, photographs, and other historical archival sources spanning the 18th to 20th centuries to produce maps of land cover prior to significant Euro-American impact (see Grossinger et al., 2006, Grossinger et al., 2007, and Beller et al., 2010 for more details on the methods used to create these land cover maps). Historical land cover maps include the distribution of oak savanna and woodland as well as other terrestrial and aquatic ecosystems (see Fig. 1). They were used in the present effort to estimate the amount of each habitat type historically, calculate change in land use/land cover over time, and analyze the spatial distribution of ca. 1850 carbon storage.

These efforts also assembled a wide array of archival sources that we used to support the present analysis, including maps, narrative descriptions, land surveys, landscape photographs, and aerial imagery spanning from the first Spanish explorers' accounts in 1769 to the mid-20th century (Fig. 2). In particular, the Public Land Survey field notes of the General Land Office (GLO) were a key source for reconstructing oak land composition and structure. The GLO survey, which surveyed public land across a grid of 36 mi^2 (94 km^2) townships divided into square mile (2.6 km^2) sections, was initiated in 1785 by the U.S. Continental Congress' Land Ordinance and reached Santa Clara Valley in 1851. The GLO recorded land use/land cover, along with species, diameter, and distance from the survey point for witness trees encountered at section corners and along survey lines. Spatial coverage is limited in Santa Clara Valley due to pre-existing private Mexican land grant holdings that cover approximately three-quarters of the study area; these areas were not as comprehensively surveyed as public land. However, GLO surveys still provide some of the earliest descriptions of landscape and vegetation following European contact (Bourdo, 1956). GLO survey notes spanning from 1851-1888 were transcribed and brought into a GIS environment using methods adapted from the Forest Landscape Ecology Lab at the University of Wisconsin-Madison (cf. Sickley, 2001).

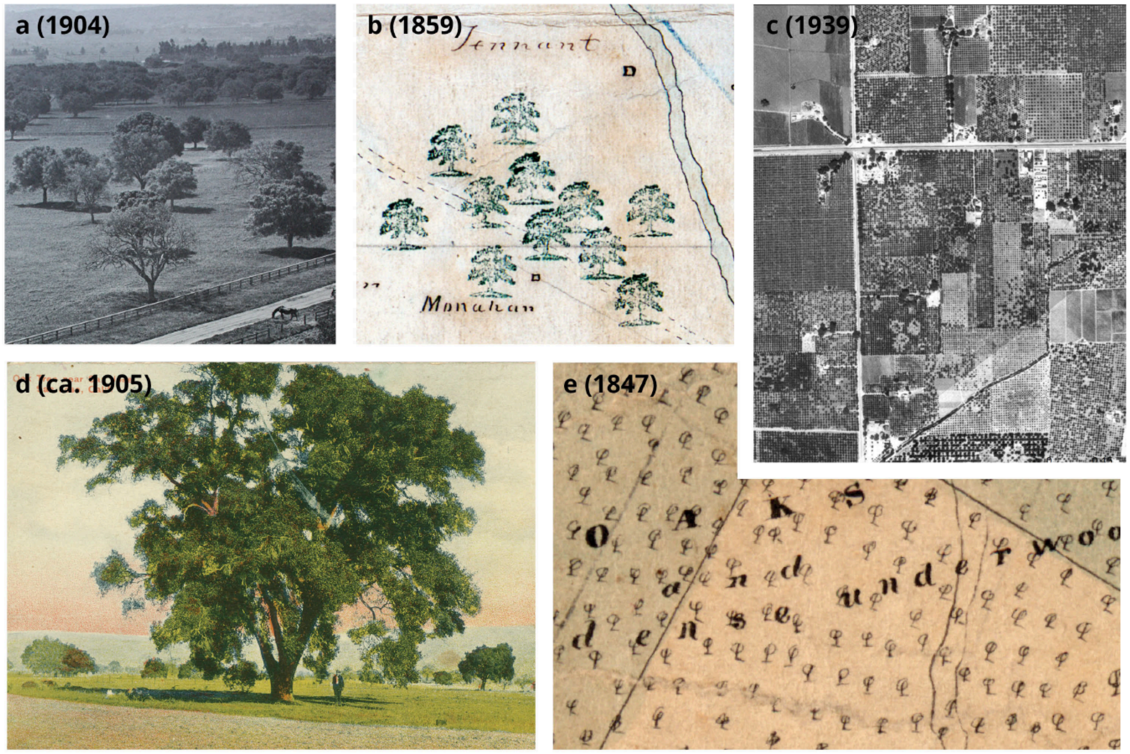


Figure 2. Examples of historical sources showing oak ecosystems in Santa Clara Valley, including landscape photographs (a), maps (b, e), aerial imagery (c), and postcards (d). (a: courtesy of the Palo Alto Historical Association; b: courtesy of The Bancroft Library, UC Berkeley; c: courtesy of Science & Engineering Library Map Room, UC Santa Cruz; d: courtesy of California Room, San José Public Library; e: courtesy of The Bancroft Library, UC Berkeley)

2.3. Reconstruction of Historical Oak Land Characteristics

We reconstructed historical oak savanna and woodland composition and structure using information from historical datasets and analog modern ecosystems. These characteristics formed the basis for estimating and comparing per hectare biomass and carbon storage for each habitat type. The extent of each oak habitat was derived from previously produced historical land cover maps (Grossinger et al., 2006; Beller et al., 2010).

To reconstruct tree species composition, we extracted witness trees surveyed by the GLO Public Land Survey that occurred on areas mapped as former oak lands. We removed riparian trees (primarily California sycamore, *Platanus racemosa*) from this dataset, including both trees explicitly described as riparian by GLO surveyors and hydrophilic species mapped alongside former stream channels. (Riparian carbon storage was estimated separately; see section 2.4.) We also removed undifferentiated (no species listed), non-native, and likely planted trees from the dataset.

We used GLO data to reconstruct tree diameter distributions for the three oak species found in the study area: valley oak (*Quercus lobata*), live oak (*Q. agrifolia*), and black oak (*Q. kelloggii*). We created probability distribution functions of tree diameters for valley oak (n = 177) by fitting the GLO witness tree diameter data to gamma distributions, which provided the best fit according to the small-sample-size-corrected Aikike Information Criterion metric (AICc). For live oak, we combined GLO diameter data from our study area with GLO data from adjoining portions of southern Santa Clara Valley (Whipple, Grossinger, & Davis, 2011) to provide a larger sample size of individuals (n = 65). A two-sample Kolmogorov-Smirnov test comparing live oak diameter across the two regions showed no significant difference (p-value = 0.60). For live oak, Weibull and gamma distributions provided equivalent fits according to the AICc; gamma was selected for consistency across species. We used the live oak diameter distribution for black oak as well in our analysis given the low number of black oak individuals surveyed in the study area (n = 13) and the absence of significant differences between surveyed black oak and live oak diameter distributions (based on a Tukey's HSD test, p-value = 0.94). Evidence for bias in GLO surveys due to surveyor preferences and survey instructions suggests that surveyors may have avoided sampling the largest and smallest trees (Bourdo, 1956; Manies, Mladenoff, & Nordheim 2001). While a wide range of tree sizes were sampled by surveyors in Santa Clara Valley (3"-80"), it is unknown whether bias exists in the survey data (Whipple et al., 2011). The probability distribution functions developed by fitting witness tree data to gamma distributions were chosen to better account for these very small and large trees (following Rhemtulla, Mladenoff, & Clayton, 2009; see de Lima, Batista, and Prado 2014 for a discussion of gamma distributions in forestry).

We also used GLO data to reconstruct stand densities (oaks per ha) for oak savanna and woodland. We used the Morisita (1957) method for estimating stand density from bearing tree data, which has been shown to be more robust than other plotless density estimators in areas with small sample sizes and large-scale population non-randomness (cf. Bouldin, 2008; Cogbill et al., 2018). After removing survey points in riparian areas or with fewer than two bearing trees (the minimum requirement for the Morisita formula), we assembled a total of 77 survey points. We converted the recorded distances from chains and links into meters, then calculated the number of trees per hectare for each survey point in the study area.

While the Morisita formula is recognized to be superior to other density estimates for small, nonrandom populations, it is still potentially problematic given the heterogeneous spatial structure of oak woodland habitats and the low sample size of GLO survey points (Hanberry et al., 2011). Further, the small sample size was insufficient to derive distinct estimates for oak woodland versus oak savanna. To mitigate this issue, we complemented GLO survey data with estimates from ancillary sources of information on oak land stand density. Additional historical sources included early narrative descriptions of the study area and quantitative analyses of stand density from adjoining areas and other valley oak ecosystems. We also surveyed the literature for estimates from studies in contemporary ecosystems across California (mostly coastal valleys) and derived estimates from modern aerial imagery of comparable remnant valley oak woodlands (see Table 1). These sources were used in addition to the GLO to derive a range of low and high stand density estimates for valley oak lands.

Table 1. Valley oak savanna and woodland stand densities compiled from historical and contemporary sources.

Reported Density (trees/ha)	Oak Habitat Type (Savanna or Woodland)	Location (Year)	Citation	Source Type
0.57-3.5	Not stated	Santa Ynez Valley (1989)	Brown & Davis, 1991	Aerial imagery and field observations
0.7-24	Mix	Santa Clara Valley (ca. 1850-1880)	present study	Historical GLO survey data
1.19	Savanna	Segdwick (2002)	Sork et al., 2002	Aerial imagery and field surveys
1.48	Savanna	Sedgwick (1944)	Sork et al., 2002	Aerial imagery
1.8-3.7	Savanna	Southern Santa Clara Valley (ca. 1850-1870)	Whipple et al., 2011	Historical GLO survey data
8	Not Stated	Santa Clara Valley (1897)	Westdahl, 1897a	Historical map
12	Not Stated *("included very sparsely populated and disturbed stands")*	Hunter Liggett (1971)	C. Fieblkorn (cited in Griffin, 1976)	Field survey
Average 13.6, highest 29.2	Mix (*does not include densest woodlands*)	Sedgwick Reserve, Santa Ynez Valley (1943)	Mahall, Davis, & Tyler, 2005	Aerial imagery
>25	Woodland	Santa Clara Valley (ca. 1867-1874)	Cooper, 1926	Historical narrative account

25-35	Woodland	Upper San Antonio and Nacimiento valleys (1976)	Griffin, 1976	Field survey
48.9	Woodland	Southern Santa Clara Valley (ca. 1850-1870)	Whipple et al., 2011	Historical GLO survey data
~1-50	Mix	Oak Grove Park, Stockton (2019)	present study	Aerial imagery

2.4. Estimation of Historical Carbon Storage

We used a benefits transfer approach (i.e., extrapolation of ecosystem services across a region based on land cover; Eigenbrod et al., 2010) to calculate carbon storage for one hectare of oak savanna and oak woodland habitat based on reconstructed tree species composition, diameter distribution, and stand density (including a low and high stand density estimate for both oak savanna and woodland). This created four stand densities: low-density oak savanna, high-density oak savanna, low-density oak woodland, and high-density oak woodland. We focused on historical tree carbon only for comparability to modern urban forestry-focused carbon storage estimates (Bjorkman et al., 2015; McPherson et al., 2017).

For each of the four stand densities, we calculated the number of trees per hectare generated from low and high stand density estimates based on a search of the literature (see Table 1). Estimates from the literature ranged from ~1 tree/ha for oak savanna to ~50 trees/ha for oak woodland; in consultation with valley oak woodland experts (Frank Davis, pers. comm.) we used stand density estimates of 1-10 trees/ha for oak savanna and 20-50 trees/ha for oak woodland for our analysis. We then used a Monte Carlo simulation approach to repeatedly sample (1,000 times for each of the four stand densities) from the reconstructed GLO species composition distribution and diameter probability distributions to calculate mean carbon storage and standard deviation for each hectare of habitat. Tree species were assigned to each individual by sampling from the GLO-derived tree species composition distribution, and then diameters were assigned by sampling from the probability distributions for each species. We then used species-specific allometric equations developed by the U.S. Forest Service for the iTree Eco v6 tool to calculate whole tree biomass and convert to carbon using a ratio of 0.5 (iTree, 2019). Equations used by iTree were acquired and calculated in R in order to perform the Monte Carlo simulations. Per-hectare estimates were multiplied by the area of each habitat type to scale to the full study area.

Oak savanna and woodland comprised the large majority (95%) of tree-dominated land cover in the study area historically. However, approximately 21 km^2 of extensive riparian habitats were also documented along streams and in areas of high groundwater that supported dense stands of willow (*Salix spp.*), cottonwood (*Populus fremontii*), sycamore (*Platanus racemosa*), box elder (*Acer negundo*), and other species. Given the absence of robust historical surveys documenting the composition, structure, and stand density of these habitats, we used modern data on carbon storage for comparable habitats in California to estimate carbon storage per hectare for riparian areas. Modern data were derived from carbon storage estimates for natural regeneration (i.e., unplanted) riparian forest plots (Matzek, Stella, & Ropion, 2018). Riparian carbon estimates did not account for smaller riparian areas alongside smaller stream channels, as they were not mapped by previous efforts.

To analyze spatial trends in historical carbon storage across Santa Clara Valley, we converted vector maps of historical land cover to 30-m pixels using majority vector to raster assignment, using the modern carbon raster map as a template to ensure spatial matching across pixels. We then assigned carbon storage estimates to each pixel by habitat type. Non-tree habitat types (e.g., chaparral and wetlands; see Fig. 1) were assigned a carbon storage value of zero. We developed maps for three scenarios: a "low" carbon storage scenario (using the low stand density estimates for oak savanna and woodland of 1 tree/ha and 20 trees/ha, respectively), a "high" carbon storage scenario (using the high stand density high estimates for oak savanna and woodland of 10 trees/ha and 50 trees/ha, respectively), and a "mean" carbon storage scenario (derived by calculating the mean of high and low carbon storage scenario estimates).

2.5. Carbon Storage Change Analysis

We used summary statistics and zonal statistics in GIS to analyze change over time in carbon storage from ca. 1850 to the present day. We compared historical land cover to modern land use (CalFire 2015) to analyze changes in land-use/land-cover change and carbon storage. Modern carbon storage was derived from a statewide analysis that used tree data (e.g., tree species and diameter at breast height) from field plots coupled with maps of urban tree canopy derived from high-resolution (1-m) National Agricultural Imagery Program (NAIP) aerial imagery to calculate whole tree carbon storage in urban areas across California (Bjorkman et al., 2015; see also McPherson et al., 2017). This effort mapped carbon storage across the landscape per 30-meter pixel (the resolution of urban land-use mapping), estimated by climate zone and land-use type. Biomass for each tree was calculated using urban-based allometric equations, then carbon storage was assessed using the U.S. Forest Service's CUFR Tree Carbon Calculator (https://www.fs.usda.gov/ccrc/tools/tree-carbon-calculator-ctcc, see Bjorkman et al., 2015 and McPherson et al., 2017 for additional information on methods). For each of the three historical carbon storage scenarios, we quantified change in carbon storage over time by 30-meter pixel from historical (ca. 1850) to current (2013) conditions, using the modern carbon map as a template to ensure spatial matching. Changes in carbon storage were analyzed for the entire study area and by municipality.

3. Results

3.1. Land Use/Land Cover Patterns and Change

Historically two-thirds of the study region was covered by oak savanna (44% area) and oak woodland (22% area). Wet/alkali meadow covered an additional one-quarter (24%) of total area; the remaining 10% supported chaparral, riparian habitats, and perennial wetlands. The region experienced a near-complete transformation of former terrestrial and aquatic habitats over the past ca. 160 years due to agriculture and urban development. Exceptions include scattered oaks that have persisted in the suburban matrix and areas of riparian habitat along major waterways captured as "open space" in the modern land use mapping. Former oak savanna and oak woodland habitats have primarily been converted to low-density residential land uses (39% of former oak lands), transportation corridors (22%), and commercial/industrial land uses (21%) (Fig. 3).

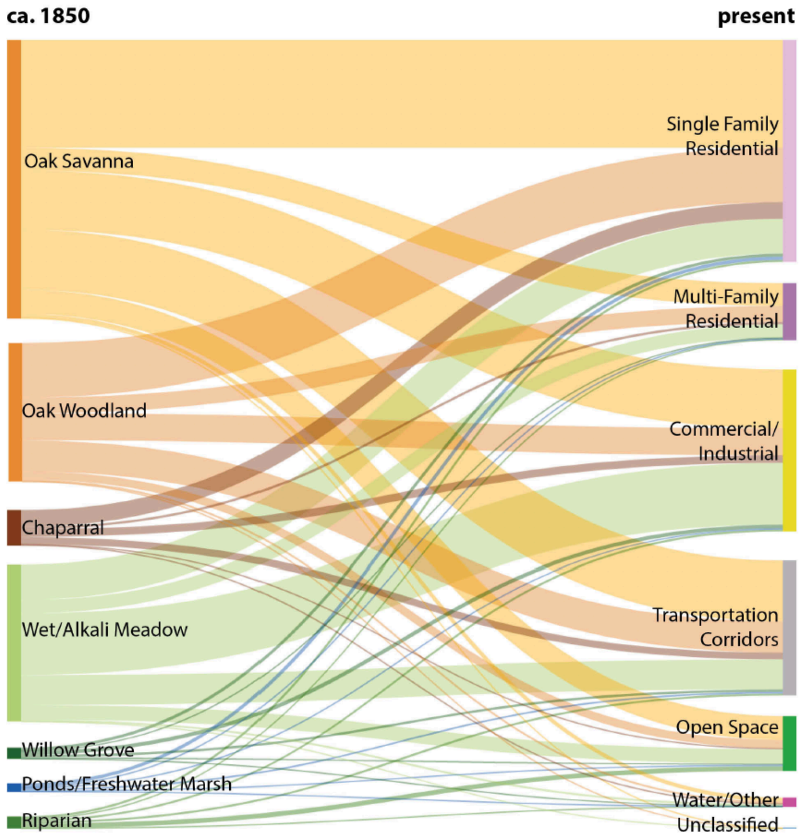


Figure 3. Land cover/land use transformation in Santa Clara Valley, ca. 1850 to present day (ca. 2013). The thickness of each line corresponds to the total area that has undergone each transformation.

3.2. Historical Oak Land Composition and Structure

A total of 341 witness trees were surveyed by the GLO between 1851-1888. Sixty-eight percent of these trees (233 trees, excluding riparian and non-native species) occurred on areas mapped as oak savanna/woodland; 85% of all valley oaks occurred on areas mapped on oak savanna/woodland. The 233 trees included 152 valley oak (*Q. lobata*), 38 live oak (*Q. agrifolia*), 13 black oak (*Q. kelloggi*), 28 undifferentiated oak (presumed valley oak; cf. Spotswood et al. 2016), and 2 wild cherry (*Prunus ilicifolia*). Since wild cherry composed <1% of the total documented population, we excluded them from subsequent analyses.

Using these data, we estimated a savanna/woodland composition of approximately 77.9% valley oak, 16.5% live oak, and 5.6% black oak. This overall species composition was corroborated by ancillary qualitative descriptions of Santa Clara Valley oak lands, such as descriptions of "white [valley] oak intermixed occasionally with live oak" (Campbell, 1861). Limited areas were dominated by live oak woodland rather than valley oak woodland (e.g., Palo Alto; Cooper, 1926); however, we lacked quantitative information to consistently resolve oak land composition at this level of detail. Mean diameter ranged from 50.0 +/- 7.1 cm SE for black oak to 57.4 +/- 5.1 cm SE for live oak and 65.4 +/- 2.5 cm SE for valley oak.

In the study area, stand densities calculated from GLO survey data for oak lands ranged from 0.7-24 trees/ha (10^{th}-90^{th} percentiles). This is comparable to estimates of 1.8-48.9 trees/ha from GLO survey data in southern Santa Clara Valley adjoining the study area (Whipple et al., 2011). A ca. 1870 textual account of oak woodland in the study area described "unbroken" oak forest averaging 25 or more trees per hectare (Cooper, 1926). These local historical estimates are comparable to overall density ranges expected for contemporary valley oak woodland of ~15-100 trees/ha (Davis et al., 2016), along with estimates from valley oak habitats in other California valleys which ranged from <1 tree/ha (Brown & Davis, 1991) to ~50 trees/ha (Whipple et al., 2011; Table 1).

3.3 Historical Carbon Storage

Based on the reconstructed composition and structure for oak savanna and woodland, we estimated approximately 12.6 Mg C/ha (range 2.3-22.9) in oak savanna and 80.5 Mg C/ha (range 45.9-115.0) in oak woodland. Carbon storage in riparian habitats was estimated at 83.2 Mg C/ha (95% CI 74.2-92.5; Matzek et al., 2018). Based on these estimates, we calculate total carbon storage across the study area of approximately 1.5 million Mg C (range 784,000 to 2.2 million). The majority (68%) of this represents carbon stored in oak woodland habitats (mean 1.0 million Mg C; range 575,000-1.4 million), followed by oak savanna (mean 317,000 Mg C; range 57,900-577,000) and riparian habitat types (mean 169,000 Mg C; range 151,000-188,000).

3.4 Carbon Storage Change over Time

Total tree carbon storage in the contemporary landscape is estimated to be 895,000 Mg C (Bjorkman et al., 2015). Compared to the mean and high historical carbon storage scenarios, this represents a decrease in carbon storage of ~40-60% since the mid-1800s (Fig. 4). Compared to the low carbon storage scenario, this represents a modest and non-significant gain of 14%. Mean contemporary carbon storage is 15.5 Mg C/ha, on the low end of estimates for historical carbon storage averaged across the study area (mean 25.8 Mg C/ha; range 13.6-38.1 Mg C/ha).

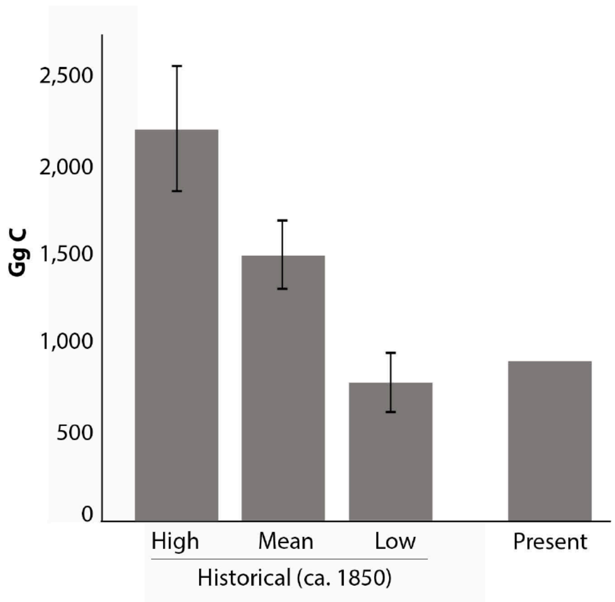


Figure 4. Total tree carbon storage (Gg C) in Santa Clara Valley from ca. 1850 to present. Error bars represent propagated error based on the standard deviations of savanna and woodland stand densities weighted by area.

The spatial distribution of carbon on the landscape has also changed over this time. In total, thirty-six percent of the landscape experienced a loss of carbon storage across all three scenarios, while 32% experienced gains (Fig. 5). While areas of former oak woodland lost carbon storage in all scenarios, these losses were partially offset by gains in carbon storage in areas with few or no trees historically, such as wet/alkali meadows and chaparral (Fig. 6). Trends in carbon change in oak savanna habitats were more variable, with net gains in carbon storage estimated in the low and mean historical carbon storage scenarios but net losses estimated in the high historical carbon storage scenario. These changes have resulted in a more homogeneous distribution of carbon in the landscape: for example, areas that formerly supported chaparral, oak savanna, and oak woodland habitats today exhibit no significant difference in per-hectare carbon storage. In addition, the extensive wet and alkali meadowlands that historically fringed the San Francisco Bay in low-lying areas today support large numbers of trees.

In addition, spatial trends in change in carbon storage varied by city (Table 2) and land cover/land use change type. Many cities that have relatively low carbon storage per hectare today (e.g., Sunnyvale, Mountain View, and San Jose; see Fig. 1) formerly supported substantial areas of oak woodland, and experienced a loss in carbon storage across all scenarios. Conversely, cities that support high per-hectare carbon storage today (e.g., Palo Alto, Los Altos, and Los Gatos) but that historically included substantial areas of wet/alkali meadow and chaparral experienced a gain in carbon storage across all scenarios (note these calculations exclude upland portions of each city outside the study area).

Patterns also emerged when comparing carbon storage change across land cover/land use change types. For example, conversion of oak savanna to residential land use generated an increase carbon across all scenarios, while conversion of oak savanna to commercial/industrial land use and transportation corridors generated gains only in the low historical carbon storage scenario, and losses of carbon storage in the mean and high historical carbon storage scenarios. Conversion of oak woodland generated decreases in carbon storage across all scenarios for all major land cover/land use change types, including residential, commercial/industrial, and transportation corridors.

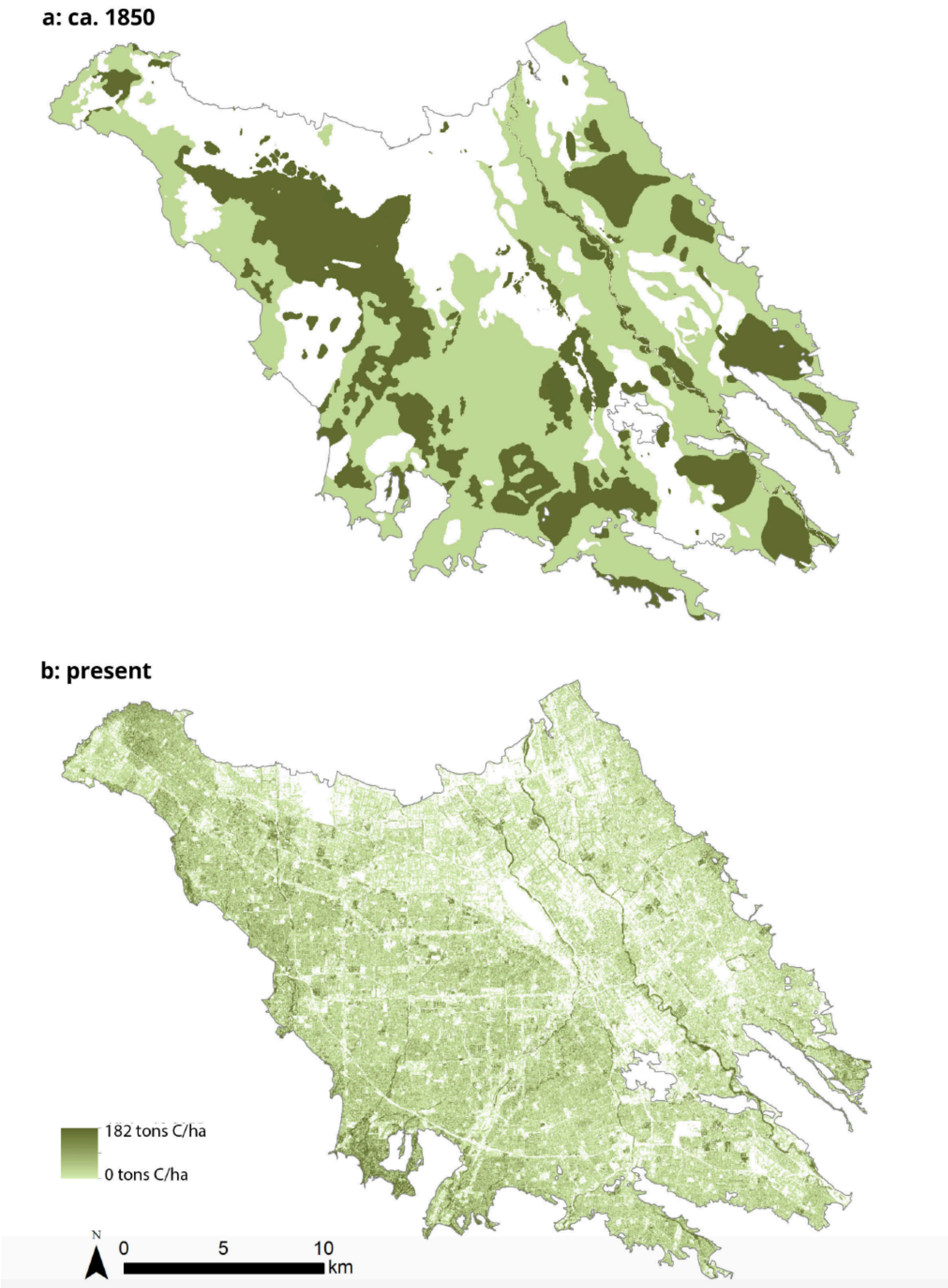


Figure 5. Tree carbon storage in Santa Clara Valley ca. 1850 (a) and present day (b) per 30 meter grid cell. Historical carbon storage is derived from the mean scenario; modern carbon storage is from Bjorkman et al. (2015).

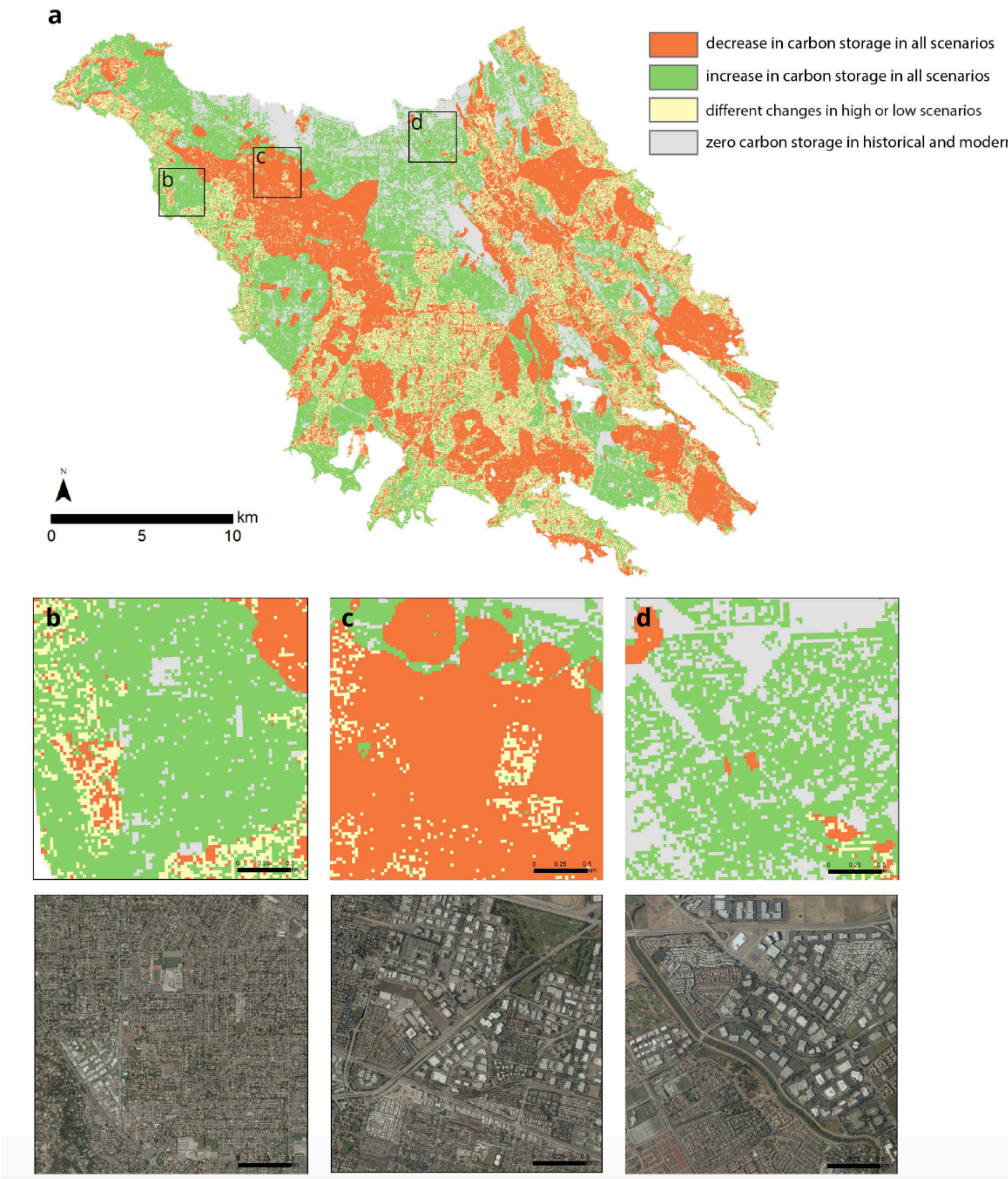


Figure 6. Net change in tree carbon storage in Santa Clara Valley (a), ca. 1850 to present (calculated as the difference in carbon storage over time per 30 meter grid cell). Spatial patterns varied across the valley, including areas of overall gain in suburbs occupying former chaparral and oak savanna along the hills (b), areas of overall loss in former oak woodland (c), and areas of no carbon storage (in both historical and modern) and gain in low-lying areas that formerly supported seasonal wetlands (d). (Aerial imagery courtesy of NAIP 2010)

Table 2. Historical and modern carbon storage and change by city. (Area is total area of each city within study area; total carbon storage ca. 1850 is based on the mean historical density scenario. Change over time range is based on low and high density scenarios.)

City	Area (ha)	C storage (Gg C)		Net C storage change (thousand metric tons C)	Change type
		Modern	Ca. 1850		
Campbell	1,580	26.4	41.9	-15.5 (-39.6 to 8.5)	Unclear
Cupertino	2,189	40.0	35.2	4.9 (-13.4 to 23.1)	Unclear
Los Altos	1,499	42.9	23.9	19.0 (4.2 to 33.8)	Gain
Los Altos Hills	49	2.6	0.62	1.9 (1.4 to 2.4)	Gain
Los Gatos	1,315	37.7	22.5	15.2 (0.04 to 30.4)	Gain
Milpitas	2,669	20.4	28.5	-8.2 (-24.6 to 8.2)	Unclear
Monte Sereno	66	3.8	0.83	3.0 (2.3 to 3.7)	Gain
Mountain View	2,858	46.9	102.1	-55.2 (-97.1 to -13.2)	Loss
Palo Alto	2,384	59.1	33.2	26.0 (8.1 to 43.7)	Gain
San Jose	29,397	392.7	841.9	-449.2 (-842.3 to -56.6)	Loss
Santa Clara	4,709	52.7	66.0	-13.2 (-45.5 to 19.1)	Unclear
Saratoga	1,884	63.5	44.7	18.8 (-5.4 to 43.0)	Unclear
Sunnyvale	4,878	66.1	206.9	-140.8 (-227.9 to -53.2)	Loss

4. Discussion

Here we use an array of historical and contemporary sources to calculate historical carbon storage ca. 1850 and change over the past ca. 160 years in Santa Clara Valley. Historical carbon storage is estimated to be 12.6 +/- 10.3 Mg C/ha in oak savanna and 80.5 +/- 34.5 Mg C/ha in oak woodland. These estimates are in line with estimates of contemporary carbon storage in

California tree-dominated ecosystems (64 Mg C/ha; Gonzalez, Battles, Collins, Robards, & Saah, 2015) and riparian forest (83.2 Mg C/ha; Matzek et al., 2018). We documented a significant loss of approximately half of former tree carbon storage in Santa Clara Valley over the past ca. 160 years in the mean and high historical carbon storage scenarios, and no significant change in the low historical carbon storage scenario. Large decreases in carbon storage in former oak woodland areas appear to have driven overall declines in carbon storage over this time period. However, these declines were partially offset by increases in carbon storage through the expansion of urban forest canopy into former areas of few or no trees, including former areas of chaparral in upslope portions of the valley and former wetland areas. This analysis is overall suggestive of considerable losses in carbon storage over this period, despite the large variance in historical carbon storage estimates driven by uncertainties in oak ecosystem stand densities.

In the following section, we discuss three dimensions of our findings in greater detail: the effects of land-use change on carbon storage, the challenges and uncertainties in using historical datasets to reconstruct ecosystem services such as carbon storage, and implications of our research for managing for carbon storage in the urban landscape.

4.1 Effects of Past Land-Use Change on Carbon Storage

Historical datasets have rarely been used to document long-term changes in carbon storage, and we are not aware of other studies that use historical archival data to quantify the effects of urbanization on carbon storage over century time scales. However, our findings are broadly consistent with long-term carbon change studies from landscapes that experienced agricultural intensification. In the United Kingdom, for example, Jiang et al. (2013) found no significant change from 1930-2000 in carbon storage with agricultural intensification, as carbon lost through agricultural conversion of grassland and other land-use types was offset by increases in woodland area. In a reconstruction of above-ground carbon storage across the state of Wisconsin from 1850-2000, Rhemtulla et al. (2009) estimated losses of nearly three-quarters of forest carbon storage by peak agriculture in the 1930s, followed by substantial recovery with reforestation to two-thirds of former carbon storage. While we did not investigate early 20^{th} century, agricultural-era carbon storage in Santa Clara Valley given the lack of available land-use/land-cover maps and tree survey data from this time period to assist with interpretation of aerial imagery, we would expect to see similar trends in our study area. Given the intensive agriculture that characterized the turn-of-the-century era, it is likely that this period similarly represents a low point in carbon storage in Santa Clara Valley after clearing of the oak lands but prior to widespread urban expansion and development of the urban forest. Future efforts to estimate carbon storage during this era would shed light on these trajectories.

Our spatially explicit reconstruction of carbon storage change across Santa Clara Valley also suggests a more uniform distribution of carbon storage across the landscape over the past two centuries. Our analysis shows large spatial variability in the distribution of carbon storage on the landscape historically: ca. 1850, between two-thirds and three-quarters of carbon was concentrated in the oak woodlands that covered less than one-quarter of the total area, while large areas of seasonally flooded meadow were devoid of trees. Carbon lost from oak woodlands as trees were cut was offset by carbon gained in former meadowlands and other areas with few or no trees that are now part of the urban forest. Our findings are similar to Rhemtulla et al. (2009), who also documented homogenization of above-ground carbon storage over time across the state of Wisconsin as carbon storage decreased in formerly forested areas due to logging and increased in former savannas due to settlement and fire suppression. However, our findings contrast with other studies that have found development of carbon storage and other ecosystem service "hotspots" over time as service provision is concentrated into small areas while decreasing across the overall landscape (e.g., Jiang et al., 2013; Blumstein & Thompson, 2015).

4.2. Challenges in Reconstructing Long-Term Changes in Ecosystem Services

Our analysis highlights both the potential utility of historical records in quantifying long-term ecosystem service change, along with the array of challenges and uncertainties inherent to such efforts. The quantification of historical carbon storage and change over time was complicated by limitations on historical data availability, in addition to known issues with land cover proxy-based methods for estimating ecosystem services (cf. Eigenbrod et al., 2010) and the relative coarseness of the climate zone and land-use based modern carbon storage estimates at 30-m resolution available for the region.

In particular, the limited availability of early quantitative, comprehensive, and spatially explicit historical data on valley oak stand density translated into large variations in our carbon storage estimates and contributed to uncertainty in the overall change in carbon storage over time. This data scarcity also necessitated the use of simplistic categories of "woodland" or "savanna" to estimate stand density. In many cases, the distinction between areas mapped as woodland or savanna was confirmed by multiple observers. For example, a large (>45 km^2) feature known as "the Roblar" was described by numerous maps, descriptions, and surveys as a continuous and distinct body of timber found on the region's coarse loamy soils (Beller et al. 2010). However, oak woodlands exhibit characteristic heterogeneity in structure across scales (Whipple et al., 2011, Davis et al., 2016), and there would have been large variability in stand density both within and across habitat types at the landscape scale that we were unable to capture here.

This heterogeneity also limited the utility of the GLO surveys for density reconstruction. While GLO data have been used for estimation of stand structure and carbon storage across a broad array of forested systems (e.g., Radeloff, Mladenoff, He, & Boyce, 1999; Rhemtulla et al., 2009; Goring et al., 2016), the low number of GLO survey points with bearing trees coupled with the clustered spatial distributions of trees in Santa Clara Valley meant we could not rely on GLO data alone for robust stand density estimations, as has been done in temperate forested ecosystems (cf. Hanberry et al., 2011 and Cogbill et al., 2018 for a discussion of sample size and density estimates based on GLO data).

In our case, the high levels of uncertainty associated with historical datasets were compounded by the early and widespread transformation of valley oak habitats across California. Many California alluvial valleys formerly supported valley oak habitats; these rich, fertile lands were rapidly transformed into ranchland, agriculture, and settlements beginning in the 19^{th} century (Griffin, 1973; Allen-Diaz et al., 1999). In Santa Clara Valley, it was noted as early as the 1860s that the oak woodlands were "a good deal destroyed since the Americans came" (Fernandez, 1864). By the end of the 19^{th} century, observers described that "the forrest [sic] of oaks in the vicinity of Mountain View is being rapidly cleared and orchards planted instead" (Westdahl, 1897b) and that only a "stray one or two trees in many fields" and a few remnant oak groves remained "of all the great belts of woods that originally…swept down the whole plain of the

Santa Clara valley" (Gates, 1895). An analysis of oak woodland change over time from southern Santa Clara Valley (to the south of our study area) estimated a 99% loss of oaks in woodland stands by the time of the first available aerial imagery in the 1930s (Whipple et al., 2011). As a result, there is a lack of modern analogs and field data from intact valley oak habitats in California valleys to underpin historical reconstructions of habitat characteristics and carbon storage. Further, since most of the density estimates derived from remnant habitats (see Table 1) post-date direct habitat modifications from ranching, agriculture, and development, many are likely to be underestimates of former stand densities—even those from the late 19th and early 20th centuries. This was acknowledged by many researchers: for example, Griffin (1976) estimated a stand density of 22-35 oaks/ha in valleys on the central California coast, but noted that densities were "speculated to be greater before ranching and other disturbances." While fire suppression or reduced fire frequency after Euro-American contact led to increases in oak savanna and woodland densities in many upland wildland settings (cf. Mensing, 2006), in settled coastal valleys reductions in densities from intensive grazing, fuel and charcoal production, and clearing for agriculture would have likely overshadowed any effects of fire suppression on oak densities (cf. Whipple et al. 2011).

For the present study, this meant that we were challenged by both an incomplete historical dataset and by modern analogs whose representativeness of historical conditions is unclear. However, it also underscores the value of harnessing data from early historical sources despite limitations, since such sources provide one of the few available glimpses into these landscapes prior to major impacts. Even studies that take advantage of historical aerial imagery—one of the earliest readily available historical sources, reaching back nearly 100 years—risk dramatic mischaracterization of earlier stand density, oak extent, and carbon storage given the extent of land cover transformations already realized by that time.

4.3. Application to Urban Planning and Ecosystem Management

The ecological value of reincorporating oaks within an urban setting has been recognized in Santa Clara Valley and in other California valleys (Whipple et al., 2011; Easterday, McIntyre, Thorne, Santos, & Kelly, 2016). In Santa Clara Valley, oaks are valuable for their ability to support native wildlife, improve regional connectivity, and withstand drought and other climate stressors compared to other common trees in the urban forest, among other benefits (Spotswood et al., 2016). Our findings suggest these efforts to "re-oak" Santa Clara Valley have the potential to contribute to ecosystem services benefits such as carbon storage as well. Mean carbon storage in the contemporary landscape is 15.5 Mg C/ha. This is comparable to whole tree carbon storage per unit land cover in other California urban areas such as Los Angeles (9.5 Mg C/ha), Sacramento (10.3 Mg C/ha), Oakland (11.0 Mg C/ha), and San Francisco (14.7 Mg C/ha) (Nowak et al., 2013). It is on the lower end of the mean historical carbon storage of 25.8 +/- 12.2 Mg C/ha, suggesting potential local capacity for increased carbon storage through urban forest management.

However, these opportunities are not evenly distributed across the landscape. In particular, different land cover/land use change types offer different opportunities for carbon storage. Fully 80% of former oak woodland habitats were found in Sunnyvale, Mountain View, and San Jose, three of the cities that today support some of the lowest urban forest canopy cover in Santa Clara County (Simpson & McPherson, 2007; CalFire, 2015). Each of these cities have goals to increase urban tree canopy by 1-5% to increase ecosystem service benefits (Xiao et al., 2013; Bernhardt & Swiecki, 2014; Davey Resource Group, 2015); we suggest that the locations of former oak woodland might provide opportunities to reintroduce oaks and increase canopy cover and carbon storage, where supported by current soil and groundwater conditions.

More broadly, there are opportunities through California's Cap-and-Trade Program to invest in projects across the state that reduce greenhouse gas emissions, including habitat restoration (Matzek, Puleston, & Gunn, 2015). However, there are relatively limited data on carbon storage in non-forest ecosystems in California such as savanna and woodland ecosystems (Gonzalez et al., 2015). This lack of available data on the potential carbon storage in intact California valley oak ecosystems presents a challenge to those wishing to take advantage of the state's climate investments program for oak woodland restoration efforts. By reconstructing carbon storage in intact valley oak habitats prior to the major modifications of the 19^{th} and 20^{th} centuries, our findings also provide insight into the carbon storage potential of restored oak savannas and woodlands in California valleys.

Here we have focused on only one dimension of one ecosystem service—changes in carbon stored in trees. A fuller accounting of other carbon pools, including other sources of aboveground carbon, dead wood, and soil organic carbon, are also important to more fully understand carbon storage change and inform management priorities. While the majority of aboveground carbon storage would have been concentrated in oak habitats historically, California chamise chaparral habitats (shrublands dominated by *Adenostoma fasciculatum*) store on the order of 14 Mg C/ha in aboveground carbon (Bohlman, Underwood, & Safford, 2018); including these habitats in our calculations would increase estimates of historical carbon storage in woody vegetation. Soil carbon storage in oak savanna, woodland, and other habitat types, while not accounted for in our analysis, can be considerable: California valley oak woodlands are estimated to store an additional 28 Mg C/ha (Gaman, 2008). Wetland soils also have the potential to store substantial amounts of carbon. In the western U.S., wetland soils have been estimated to store over 200 Mg C/ha (Nahlik & Fennessy, 2016); as a result, wetland conversion can result in the loss of significant amounts of soil organic carbon. However, it is not clear how these figures compare to organic soil carbon stored in Santa Clara Valley today, as organic carbon stored in urban soils can also be high (Edmondson, Davies, McHugh, Gaston, & Leake, 2012). For example, estimates for soil organic carbon storage in Oakland, California ranged from 33 Mg C/ha for areas covered by impervious surfaces to 144 Mg C/ha for residential areas (Pouyat, Yesilonis, & Nowak, 2006). As a result, the influence of including soil organic carbon in estimates of total carbon storage loss and future potential are unknown.

Finally, we stress that carbon storage is only one of the multitude of ecosystem services of management interest in urban areas. Changes in land use and tree species composition and structure over time in Santa Clara Valley influenced not only carbon storage, but also the provisioning of services such as shade, flood mitigation, nutrient and water retention, air quality, recreation, and biodiversity support. Quantifying and mapping changes in other ecosystem services will provide a better understanding of the tradeoffs and synergies between services both across the landscape and over time.

5. Conclusion

Our study demonstrates the utility of using pre-1900s historical sources to reconstruct historical carbon storage across the landscape and estimate change in carbon storage over century time scales. We show changes in tree carbon storage ranging from an insignificant gain of 14% to significant losses of 40-60% over the past ca. 160 years, depending on the selected scenario, and identify areas that have experienced losses and gains in tree carbon storage over this time. Our findings suggest that in Mediterranean-climate ecosystems with heterogeneous tree cover, gains in tree carbon storage in formerly treeless areas can be offset by losses in high-biomass former woodland areas. Similar to findings from McHale et al. (2017) in Phoenix, Arizona, this challenges the idea that carbon storage increases with urbanization in arid and semiarid environments due to irrigation and tree planting. Despite uncertainties and limitations inherent to using historical datasets, we suggest that there is significant value in generating first-order approximations of change over time in carbon and other ecosystem services. We hope our research can serve as a roadmap for applying similar methodology in other urban and urbanizing areas to quantify the magnitude, spatial patterns, and drivers of changes and to understand the landscape potential to provide services in the future.

6. Acknowledgments

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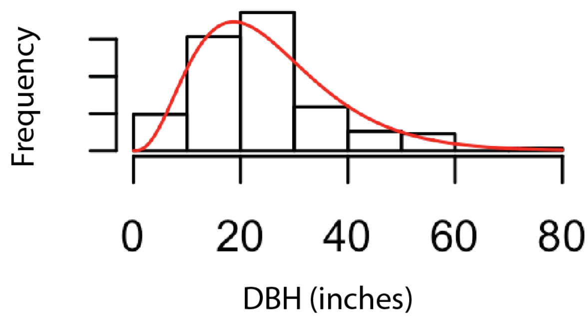
Supplemental Material A

Diameter distribution (DBH) for Valley oak and Live oak trees

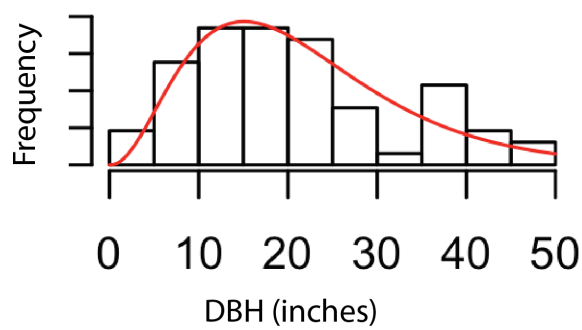
Parameters for gamma distribution

	Live oak	Valley oak
Shape	3.29	3.85
Scale	6.57	6.68
Threshold	0	0

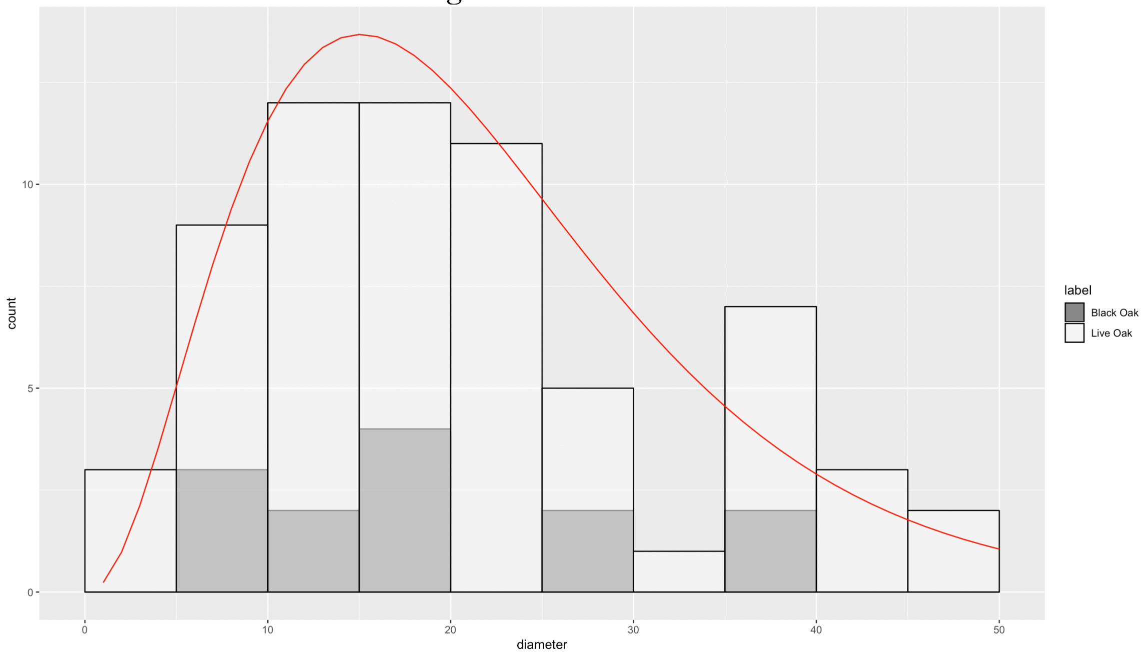
DBH with gamma distribution – Valley oak
Min-max DBH: 3-80"



DBH with gamma distribution – Live oak
Min-max DBH: 3-48"



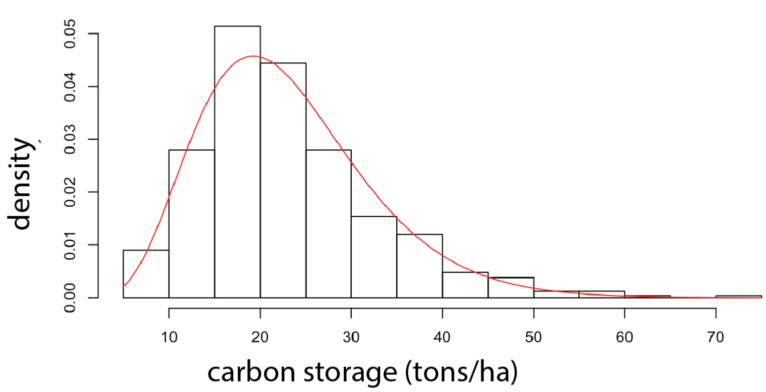
Live oak and black oak DBH with gamma distribution based on Live oak DBH data



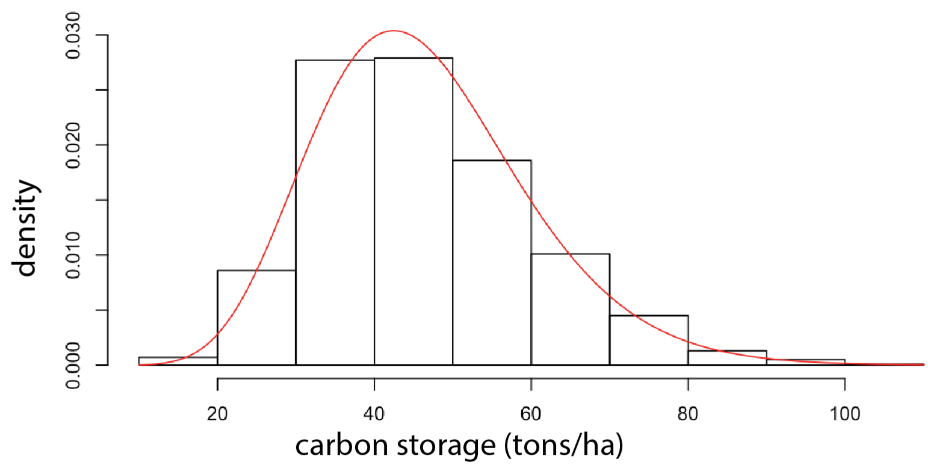
Black oak DBH in study area
Min-max DBH: 8-36”

DBH (in)	Count
0-5	0
6-10	3
11-15	2
16-20	4
21-25	0
26-30	2
31-35	0
36-40	2
Total	**13**

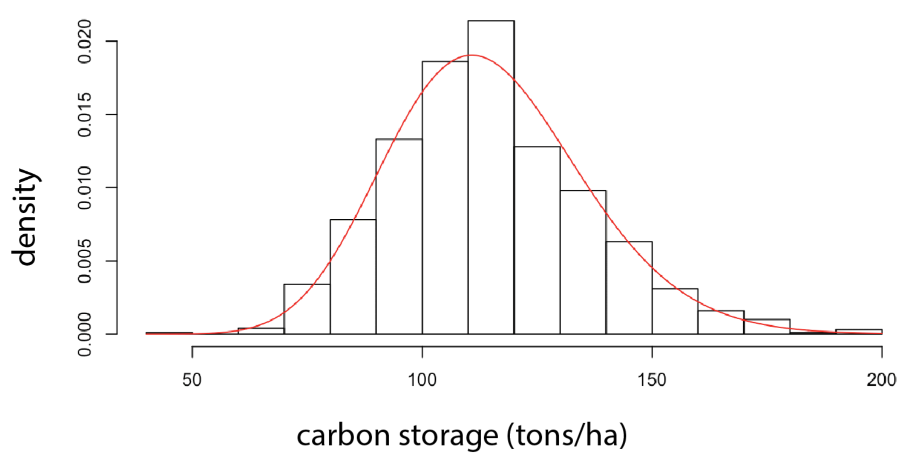
Monte Carlo simulation: distribution of 1,000 runs, 10 trees/ha
Gamma distribution (best fit) overlaid



Monte Carlo simulation: distribution of 1,000 runs, 20 trees/ha
Gamma distribution (best fit) overlaid



Monte Carlo simulation: distribution of 1,000 runs, 50 trees/ha
Gamma distribution (best fit) overlaid



Chapter 4: Building Ecological Resilience in Highly Modified Landscapes

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Abstract
Ecological resilience is a powerful heuristic for ecosystem management in the context of rapid environmental change. Significant efforts are underway to improve the resilience of biodiversity and ecological function to extreme events and directional change across all types of landscapes, from intact natural systems to highly modified landscapes such as cities and agricultural regions. However, identifying management strategies likely to promote ecological resilience remains a challenge. Here we present seven core dimensions to guide long-term and large-scale resilience planning in highly modified landscapes, with the objective of providing a structure and shared vocabulary for recognizing opportunities and actions likely to increase resilience across the whole landscape. We illustrate application of our approach to landscape-scale ecosystem management through case studies from two highly modified California landscapes, Silicon Valley and the Sacramento-San Joaquin Delta. We propose that resilience-based management is best implemented at large spatial scales and through collaborative, cross-sector partnerships.

Keywords: ecological resilience, landscape-scale management, landscape conservation, restoration, California

1. Building ecological resilience across whole landscapes

The concept of ecological resilience has emerged as a powerful heuristic for managing ecosystems and landscapes in the context of accelerating environmental change, uncertainty, and variability (Standish et al. 2014, Scheffer et al. 2015). While resilience-based ecosystem management has widespread appeal, the path forward is far from clear for those who wish to apply these concepts to real landscapes. Despite rapid advances in our understanding of the mechanisms of ecological resilience in recent years (*cf.* Oliver et al. 2015, Timpane-Padgham et al. 2017) and increasing recognition of the importance of landscape-scale management (e.g., Lindenmayer et al. 2008, Menz et al. 2013), little guidance exists on how to integrate resilience science into landscape conservation, restoration, and management activities.

Many of today's landscapes are heterogeneous mosaics of open space and relatively intact ecosystems alongside cities, suburbs, and agriculture (Hobbs et al. 2014). Such highly modified landscapes have the potential to support biodiversity, connect people with nature, and contribute to regional management goals (Scherr and McNeely 2008, Dearborn and Kark 2010, Hobbs et al. 2014). However, they can present a challenge to resilience-based ecosystem management, due to both legacies of human activities and land-use change (including habitat loss, fragmentation, and decreased biological diversity) and the complexities of coordinating across property boundaries, jurisdictions, and sectors. In this context, an understanding of the landscape attributes likely to confer ecological resilience is needed to help identify resilience-based management strategies and align site-scale plans and actions with landscape-scale goals.

Integrating considerations from landscape ecology, conservation biology, and other fields, we describe an emerging approach to managing for ecological resilience, both in highly modified systems and across whole landscapes. Our approach was developed to support the needs of local stakeholders, including government agencies, local non-profits, and a private company, who wished to incorporate ecological resilience into site-scale and regional ecosystem management activities. Stakeholders expressed a desire to integrate the ecological dimensions of resilience alongside other social and infrastructure considerations, both to support ecological goals and in recognition of the potential for greater ecological resilience to also promote social resilience and human health (e.g., tidal marsh restoration that also buffers communities from sea-level rise). Consequently, our aim is to clearly elucidate the *ecological* dimensions of resilience, with the goal of helping operationalize the concept to support on-the-ground ecosystem management. Since ecological resilience is only one facet of the broader concept of resilience in social-ecological systems (Walker and Salt 2012), our approach is intended to be complementary to existing socio-ecological resilience frameworks (e.g., Resilience Alliance 2010, Biggs et al. 2012) by yielding additional specificity on what ecological resilience means in highly modified landscapes.

Here, we synthesize and simplify published literature into seven dimensions of landscape-scale ecological resilience, along with a set of key considerations for evaluating the current state of a landscape and identifying potential management strategies that could contribute to resilience. We then demonstrate application of our approach to identify ecological resilience goals and actions through case studies from two highly modified landscapes in California, USA: the predominantly agricultural Sacramento-San Joaquin Delta and urban Silicon Valley. Finally, we illustrate how ecological resilience insights derived from this approach are being integrated into landscape planning and implementation through partnerships with a diverse array of stakeholders.

2. Identifying mechanisms of landscape resilience

While many researchers and practitioners alike are concerned with resilience, the peer-reviewed literature often does not translate to applications on the ground. We conducted a qualitative review of the peer-reviewed literature to extract landscape attributes to consider in assessing and targeting landscape-scale ecological resilience, hereafter referred to as "landscape resilience" (Beller et al. 2015). We define landscape resilience as the ability of a landscape to sustain desired biodiversity and ecological functions over time in the face of climate change and other anthropogenic and natural stressors. "Desired biodiversity" includes native taxa, nearby species whose ranges may shift in the future, and non-native species that support desired ecological functions or ecosystem services; "natural stressors" include both episodic events such as fire, flood, or drought in addition to prolonged stressors and directional change.

We drew on both empirical and theoretical studies to synthesize key dimensions of ecological resilience identified in the literature. We included studies that explicitly linked to resilience as well as those that were found to support components of resilience, such as community reassembly or the ability of habitats to be self-sustaining. Many landscape attributes were widely recognized to contribute to resilience, with numerous supporting empirical studies: for example, response diversity, functional redundancy, and connectivity between habitats). Other attributes, such as cross-scale interactions, had strong theoretical support but less robust empirical documentation of relationships to resilience. Still others were rarely studied or only indirectly related to resilience (e.g., abiotic processes such as flooding promote resource heterogeneity, which in turn is linked to resilience). (See supplemental material for additional detail.)
We organized attributes into seven broad dimensions that we suggest are relevant to managing for ecological resilience: setting, process, connectivity, diversity/complexity, redundancy, scale, and people, along with several core considerations within each category (box 1). We refined these dimensions during a two-day workshop in March 2016 that brought together the authors, a mix of academic and applied scientists interested in bridging the gap between resilience theory and practice.

Box 1. Seven dimensions of landscape resilience

These prompts are intended to provide a holistic yet concise set of key considerations to help evaluate the current state of a landscape and identify potential strategies to improve ecological resilience. We emphasize the value of the dimensions in conjunction rather than isolation; an assessment of the synergies and trade-offs between and among them can help prioritize actions and ensure key landscape attributes are not left out.

1. Setting: Geophysical, biological, and socio-cultural aspects of a landscape that determine constraints on and opportunities for resilience

- ☐ What elements of the <u>geophysical context</u> (geology, soils, and topography) support characteristic habitats, ecological diversity, and the local distribution of microclimates?
- ☐ What <u>biotic legacies</u> (e.g., intact soil structure, seed banks) are present? What are the dominant and rare/unique vegetative communities that characterize the landscape?

- ☐ How have land-use history and change influenced the landscape? Where are persistent processes, structures, habitats or populations (e.g., high groundwater, remnant habitat patches, locally adapted populations) that might represent features or areas of high resilience? Are there novel features (e.g., managed wetlands, green infrastructure, novel habitat types) that might similarly support resilience in highly modified conditions?

2. Process: Movement of energy and materials that create and sustain landscapes through physical, biological, and chemical drivers

- ☐ What are the characteristic abiotic processes (e.g., flooding, groundwater recharge, fire, sediment transport) or biotic processes (e.g., movement and gene flow, adaptation and evolution, food-web dynamics) that produce resource heterogeneity, maintain habitats, shape habitat structure, accelerate recovery after disturbance, and/or create opportunities for wildlife?
- ☐ What are key biotic-abiotic feedbacks that might enable recovery and persistence of habitats (e.g., sediment-vegetation interactions)?

3. Connectivity: Linkages between habitats, processes, and populations that enable movement of materials and organisms

- ☐ Where are opportunities to preserve or create structural and functional linkages between habitat patches that support exchange of materials; physical processes; and wildlife ability to avoid unfavorable conditions, make use of new resources, reestablish after disturbance, and exchange genes?
- ☐ How might the spatial configuration of habitat decrease the sensitivity of populations to disturbance, facilitate movement, or hasten recovery (e.g., connectivity across physical gradients in temperature, moisture, or salinity)?
- ☐ Where might isolation or disconnectivity be important to minimize the spread of undesirable disturbance, invasion, or disease?

4. Diversity/Complexity: The variety and arrangement of biotic and abiotic landscape elements that provide a range of options for wildlife

- ☐ What is a locally appropriate variety of landscape features, including a diversity of habitat types, abiotic heterogeneity (e.g., topography, groundwater, and soils), within-habitat heterogeneity (e.g., refugia)?
- ☐ Where is within- or between-species variability present in functional traits and genotypic/phenotypic traits for key species or populations?
- ☐ Which key species display diversity in life history that might promote variable responses to disturbance?

5. Redundancy: Multiple similar or overlapping elements or functions within a landscape that provide insurance against loss of key functions or features

- ☐ Where are opportunities to increase structural redundancy for key features (i.e., multiple discrete habitat patches or structures)?
- ☐ Where might distinct populations of priority species be supported to provide population redundancy?
- ☐ Which target species might support similar or overlapping ecological functions? (functional redundancy)

6. Scale: Spatial and temporal extent at which population, community, and ecosystem dynamics to occur

- ☐ What spatial scale of key features (e.g., habitat patches) is necessary to accommodate biotic and abiotic processes and sustain key populations?
- ☐ What is the temporal scale at which ecological processes needed to sustain key habitats, species, and functions occur? What time horizon is appropriate for planning for changing conditions?
- ☐ Which cross-scale dynamics (e.g., organisms in the same functional group using landscapes at different spatial scales) might enhance the resilience of a function to perturbation? How do landscape-scale factors influence local-scale dynamics?

7. People: The individuals, communities, and institutions that shape and steward landscapes

- ☐ How does traditional/local knowledge across a range of communities and cultures provide insight into desirable and place-based landscape management priorities?
- ☐ How can public participation and engagement with local communities guide planning and goal-setting, facilitate integration of ecological considerations with other needs, and help build broad stakeholder support, partnerships, and investments in ecosystems?
- ☐ Which policies, land uses, and jurisdictions might influence the goals and actions that are feasible and desirable for a specific site?
- ☐ How do lessons from adaptive management and stewardship, including monitoring, research, and pilot projects, inform future management goals and actions and help plan for uncertainty and surprises?

3. Applying the landscape resilience approach in highly modified California landscapes

Although the resilience literature we reviewed focuses largely on intact landscapes, we illustrate application of the seven dimensions of ecological resilience outlined in box 1 in two highly modified California landscapes that typify the challenges confronting land managers: Silicon Valley and the Sacramento-San Joaquin Delta (figure 1). Each landscape contains heterogeneous land-use mosaics, with areas of protected open space and ecological restoration embedded within and adjacent to areas that are intensively developed or managed for agriculture. Threats in these regions include sea-level rise, increased temperatures, and increased frequency and severity of storms and droughts (Franco et al. 2011), in addition to continued urbanization and development. These case studies illustrate the process of systematically applying each dimension to identify a suite of landscape management objectives and recommendations likely to support ecological resilience across both urban and agricultural landscapes, and provide examples of early adoption of these recommendations.

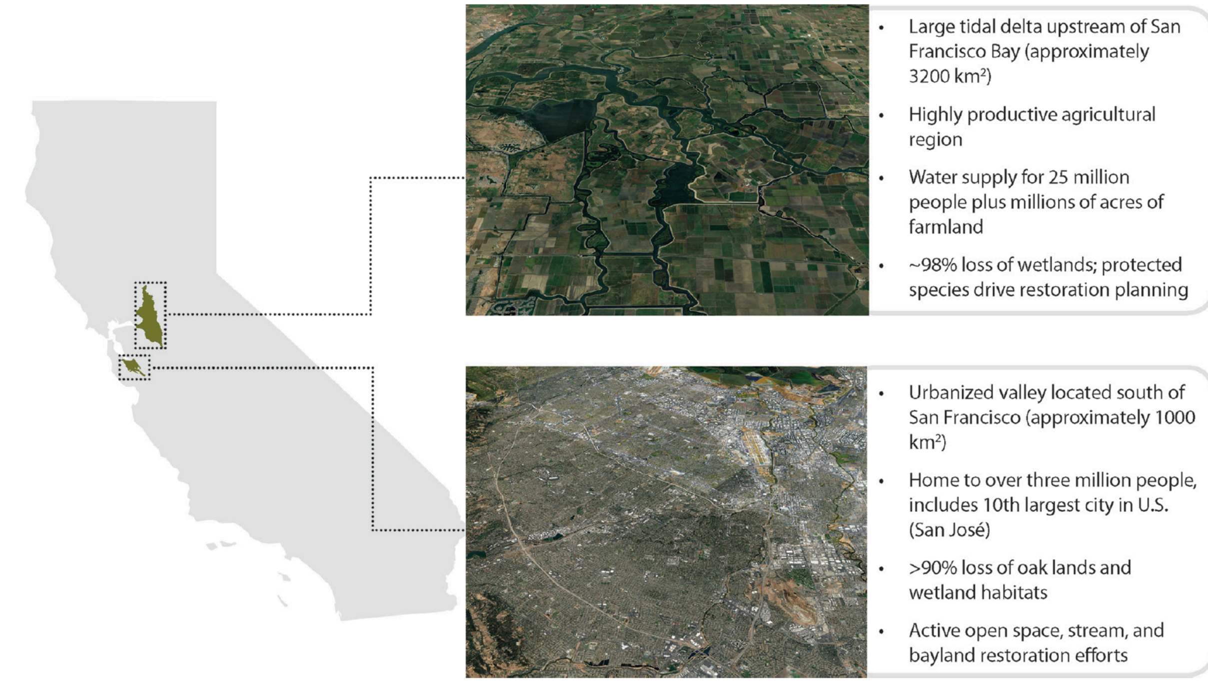

Figure 1. Map of California case studies. The two case studies focus on two heavily modified and iconic landscapes in California, the agricultural Sacramento-San Joaquin Delta and urban Silicon Valley.

For each case study, a suite of ecological management objectives (resilience "of what?", *sensu* Carpenter et al. 2001) were developed in consultation with local science advisors and stakeholders. Objectives targeted specific processes and functions, such as groundwater recharge or beneficial flooding, or elements of biodiversity such as oak woodland species or anadromous fish. The seven dimensions were then used to identify specific recommendations likely to support the resilience of each ecological objective over time.

In each location, we used detailed regional-scale assessments of ecological history and landscape change as a first step to analyze Setting and Process (see box 1) and guide development of objectives and recommendations. These analyses helped underpin an understanding of the whole portfolio of landscape management options across the spectrum of ecosystem alteration, from the historical to the novel (Hobbs et al. 2017). This included persistent features (such as remnant habitat patches with intact flooding regimes) that could serve as restoration nodes, forgotten features (e.g., habitats with >90% loss) that might guide restoration, and areas where changed conditions and land-use legacies might make such targets infeasible or more novel elements desirable (e.g., areas with land subsidence or urban fill). Such historical context is valuable for analyzing contemporary landscape processes, dynamics, and potential (the "way things work" rather than the "way things were"; Safford et al. 2012), and are expected to remain important in setting ecological restoration goals in the future (Higgs et al. 2014). It is particularly useful in heavily transformed and rapidly changing regions, where discerning persistence and change can be otherwise challenging (Grossinger et al. 2007).

3.1. Case Study 1: Silicon Valley

Silicon Valley is a densely populated urban landscape located south of San Francisco Bay in California. The region has retained significant natural habitat along urban creeks, in wetlands fringing the Bay, and in open space and working landscapes in the adjacent mountains. These habitats continue to support a diverse suite of native wildlife, including several federally listed species (ICF International 2012). Ongoing activities such as the South Bay Salt Pond Restoration Project, tree planting efforts by local non-profits, and green infrastructure to improve water quality provide opportunities to enhance landscape resilience across sectors and ecosystems. The "Resilient Silicon Valley" project was initiated to help integrate ecological resilience considerations into these and other efforts by using the seven dimensions of landscape resilience (box 1; initially developed for this project) to identify shared objectives and recommendations for the region.

Landscape resilience objectives for the region were developed in concert with the project technical advisory committee (twelve scientists from agency, non-profit, private, and academic settings) and vetted by representatives from local environmental organizations. We drew upon a wealth of contemporary and historical data, including landscape reconstructions and change analyses (Grossinger et al. 2007, Beller et al. 2010), land use/land cover data, and environmental and biological datasets to assist in making objectives appropriate for the local geography and social context (figure 2). Some objectives were already broadly recognized as regionally important: for example, the objective of restoring tidal systems able to migrate upslope and adapt to rising sea levels, with the goals of contributing to regional primary productivity and providing long-term habitat for endemic marsh species such as salt marsh harvest mouse *(Reithrodontomys raviventris)* and Ridgway's rail *(Rallus obsoletus)*, anadromous and estuarine fish, and waterbirds (Goals Project 2015). Others were new: for example, re-establishment of oak ecosystems ("re-oaking") on the urbanized valley floor was identified as a regional objective given their iconic status and dramatic (>99%) loss in Silicon Valley (Whipple et al. 2011), their drought tolerance and adaptiveness to projected future conditions, and their foundational role in supporting native wildlife such as acorn woodpeckers *(Melanerpes formicivorus)*.

For each regional management objective, the landscape resilience dimensions were systematically reviewed to identify key existing or potential landscape attributes likely to contribute to resilience of the desired feature or function (see supplemental material for the worksheet used in this exercise). For example, recommendations for the tidal marsh objective generated from consideration of each dimension included: augmenting sediment delivery to tidal marshes to support accretion that offsets sea-level rise via re-connection of creeks (Process), restoration of estuarine-terrestrial transition zone habitat upslope of tidal wetlands to support wildlife movement around the Bay perimeter (Connectivity), restoration of marshes and migration space at multiple sites to provide several population reserves of endemic marsh species to diversify risk (Redundancy), preservation of topographic heterogeneity within tidal wetland habitats to provide high-water refugia (Diversity/Complexity), and creation of accommodation space to anticipate landward migration of tidal marshes with sea-level rise over long time frames (Scale). (See table 1 for an additional example targeting "re-oaking" the urbanized valley floor).

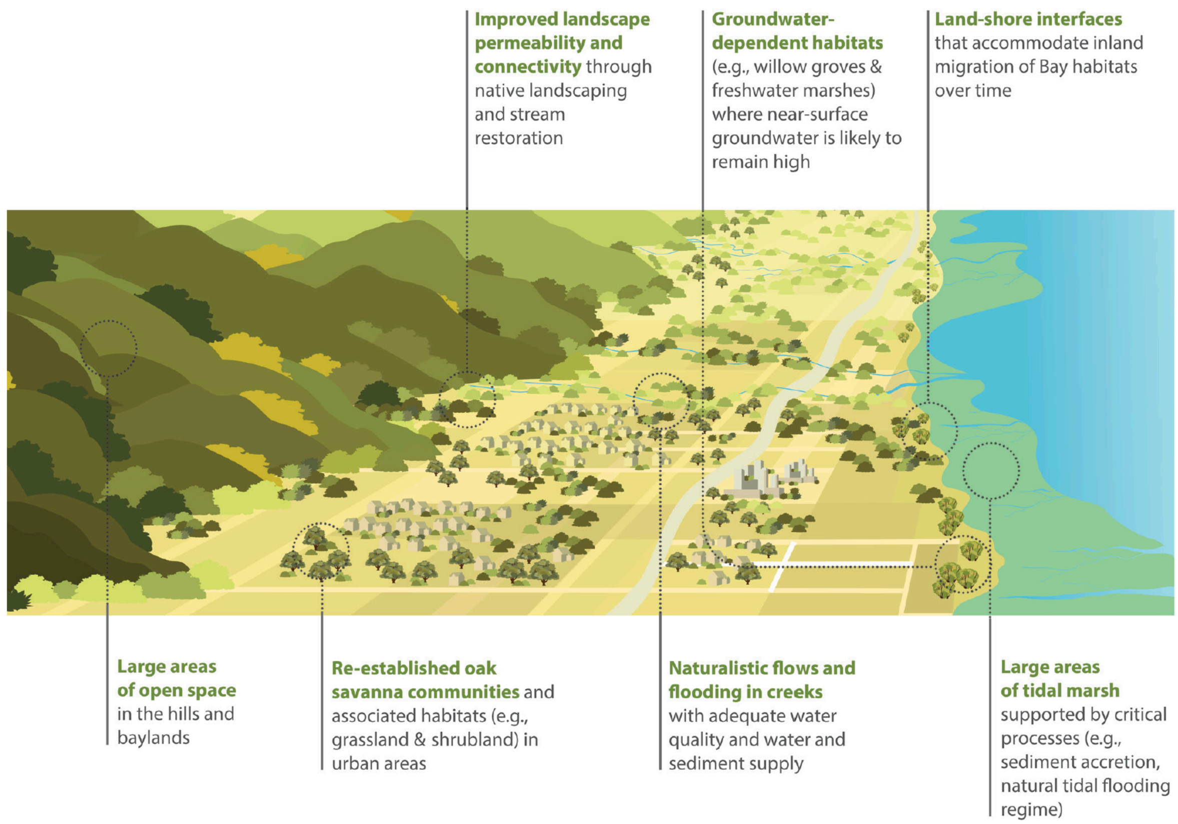

Figure 2. Examples of Silicon Valley landscape resilience objectives (cf. Robinson et al. 2015). Figure by Maria Dillman and Bonfire Communications.

Table 1. Example recommendations for the goal of reintroducing oak ecosystems into the urban landscape, based on the landscape resilience dimensions.

Dimension	Recommendation
Setting	Evaluate past and present soil types and how site conditions have been modified by soil removal and compaction. Plant native oaks for which compaction is minimal and root volumes are sufficient to support large trees. Preserve older heritage oaks as a source population for locally adapted genotypes (*geophysical context, biotic legacies*)
Process	Plant Valley oaks for which reliable access to groundwater is likely. Avoid locations in which surrounding turf or other landscaping requires irrigation during the dry season. (*abiotic process, biotic–abiotic feedback loops*)
Connectivity	Plant Valley oak trees close enough together to support pollination of trees and create connectivity for oak specialist wildlife. Plant oaks in nodes (16–20 acres) to increase functional connectivity between oaks within nodes, and coordinate planting across the urban landscape to enable wildlife movement among nodes. (*structural and functional links, spatial configuration*)
Diversity/complexity	Add oak understory vegetation that blooms across seasons, adding floral resources, vertical structure, and habitat complexity. Use existing large trees to support a diversity of wildlife such as cavity nesting birds. Plant multiple oak species to decrease risk of mortality from pest outbreaks and stabilize acorn crop production across years. Trial use of oak genotypes native to southern California to promote drought tolerance. (*within-habitat heterogeneity, species life-history diversity, genotypic variability*)
Redundancy	Create multiple nodes of oak planting (16–20 acres) centered around large trees. Plant multiple individuals of each oak species within nodes to facilitate pollination and support acorn production. (*structural redundancy, population redundancy*)
Scale	Encourage oak planting at the landscape scale (e.g., city or county scale) to maximize the capacity for supporting native biodiversity in cities. (*spatial scale*)
People	Create multiple pathways of implementation for oak planting, including engaging the public and landowners through incentive and outreach programs, and integration of oak planting guidelines into programs and plans (e.g., urban forestry Master Plans). (*participation and engagement; policies, land use, and jurisdictions*)

The Resilient Silicon Valley project is beginning to serve as a shared foundation and catalyst for implementation across sectors of environmental management, spanning water resources and flood control, open space and parks, green infrastructure and stormwater, urban landscaping and forestry, and creek and wetland restoration. For example, Silicon Valley's regional water agency used project recommendations to inform development of objectives and performance metrics for their One Water Plan, an integrated approach to managing for water supply, flood protection, and stream stewardship at the watershed scale. Similarly, early adoption of project guidance on tree planting and other urban greening activities to support oak ecosystems is currently taking place in multiple locations (box 2).

Box 2: "Re-Oaking" Silicon Valley

Once we developed recommendations for supporting resilient oak ecosystems in Silicon Valley (Spotswood et al. 2017; see table 1), we translated them into specific management actions achievable across different sectors. This translation is a challenge in an urban setting, where numerous entities are responsible for managing urban vegetation to achieve a variety of goals beyond ecological resilience (e.g., urban forestry goals that include using trees to sequester carbon and provide shade). We worked with local partners, including urban planners, landscape architects, and open space and urban forestry non-profits, to refine recommendations stemming from the landscape resilience dimensions into useable guidelines, and to identify ways that recommended actions could be achieved through their ongoing activities. This involved using site-specific data and local knowledge to identify locations physically and socially suitable for oak planting, along with locations where changing conditions following development (e.g., due to soil modification and compaction) has made conditions less suitable for oaks.

A number of local entities are currently implementing the re-oaking guidance. For example, two local urban forestry and ecological restoration non-profits (Canopy and Grassroots Ecology) are working together to pilot the creation of "oak nodes": areas containing at least 20 trees within around 20 acres that are designed to increase functional connectivity for oak populations and oak-associated wildlife (see table 1). Nodes being planted in East Palo Alto and Palo Alto span across property boundaries and include plantings in public spaces such as street trees, local parks, and a church, along with volunteer-led outreach to private residents about re-oaking in target neighborhoods. Similarly, Google is working with landscape architects to integrate re-oaking guidance into their campus planning (figure 3), and the Santa Clara Valley Open Space Authority, a regional open space agency, is developing a guidance document to encourage integration of re-oaking into their urban open space granting program.

Figure 3. Newly planted valley oaks on Google's campus in Sunnyvale, California. To date, over 200 oak trees have been planted on campus. (Photograph: Erica Spotswood)

3.2. Case Study 2: Sacramento-San Joaquin Delta

The landscape resilience dimensions were incorporated into a restoration visioning project underway in the Sacramento-San Joaquin Delta, a highly productive agricultural area at the heart of California's Central Valley and the linchpin of the state's critical water infrastructure. Although the Delta is a highly altered ecosystem, it is home to endemic threatened and endangered species such as Delta smelt *(Hypomesus transpacificus)* and giant garter snake *(Thamnophis gigas)*. A push over the past decade toward large-scale wetland restoration in the Delta created a need for a landscape resilience visioning process that was met by the "Delta Landscapes" project. The project used analyses of landscape change and ecological function over the past two centuries (Whipple et al. 2012, SFEI-ASC 2014) to develop an approach to regional ecosystem restoration that aimed to achieve ecological goals and build resilience to climate change and other stressors in the context of water supply and agricultural considerations (SFEI-ASC 2016).

The Delta Landscapes project was already underway when the landscape resilience dimensions were developed, so ecological objectives had already been set. Objectives included support for several wildlife guilds (e.g., marsh wildlife and native fish) and other ecological functions (e.g., a productive food web). Recommended actions to take on the landscape to create resilience for these functions were developed by applying each landscape resilience dimension in the context of the contemporary Delta and the changes the region has experienced over time, including substantial modifications to its channel network, extreme wetland loss (98%), changes in freshwater and tidal flows, and transformative invasions by aquatic weeds and predatory fish (SFEI-ASC 2014, 2016).

For example, a key ecological objective for the Delta is support for native fish populations, which have been severely impacted by these changes to the physical and biological aspects of the ecosystem. The landscape resilience dimensions were systematically reviewed to produce management recommendations for supporting native fish populations in the context of sea level rise and other climate change impacts, with a focus on increasing food supplies and places to hide from predators and reducing physiological stress and mortality from entrainment (figure 4). For the native fish support objective, recommendations for Setting and Process related principally to restoring beneficial fluvial and tidal flows and flooding across land surfaces and in channels to create and maintain habitats that favor native fish. In consideration of Redundancy, recommendations included restoring and enhancing multiple migratory routes for anadromous species through the Delta to provide alternatives that might vary in suitability as conditions change. For Scale, suggestions included restoring marshes in patches large enough to support formation of complex dendritic channel networks in the marshes (500 hectares or more; SFEI-ASC 2016). These channel networks are also critical for addressing Diversity/Complexity, since multiple-order tidal channel networks create habitat heterogeneity in both space and time, including variation in water depth, velocity, turbidity, and structural complexity along the edge of the banks due to live vegetation, debris, and slumps. For Connectivity, recommendations included spacing restored marshes in close enough proximity to allow salmon smolt to move between them in one day (~15-20 km based on observed daily migration rates; Michel et al. 2012). This connectivity would enable the fish to rest and feed in marsh areas in between movements down the channel mainstem, which has high water velocities, non-native predators, and few refuge areas. For People, recommendations included fish-friendly farming practices such as reduced pesticide application and cultivation of rice to maintain agricultural production and provide novel floodplain habitat that fish can access for growth and rearing.

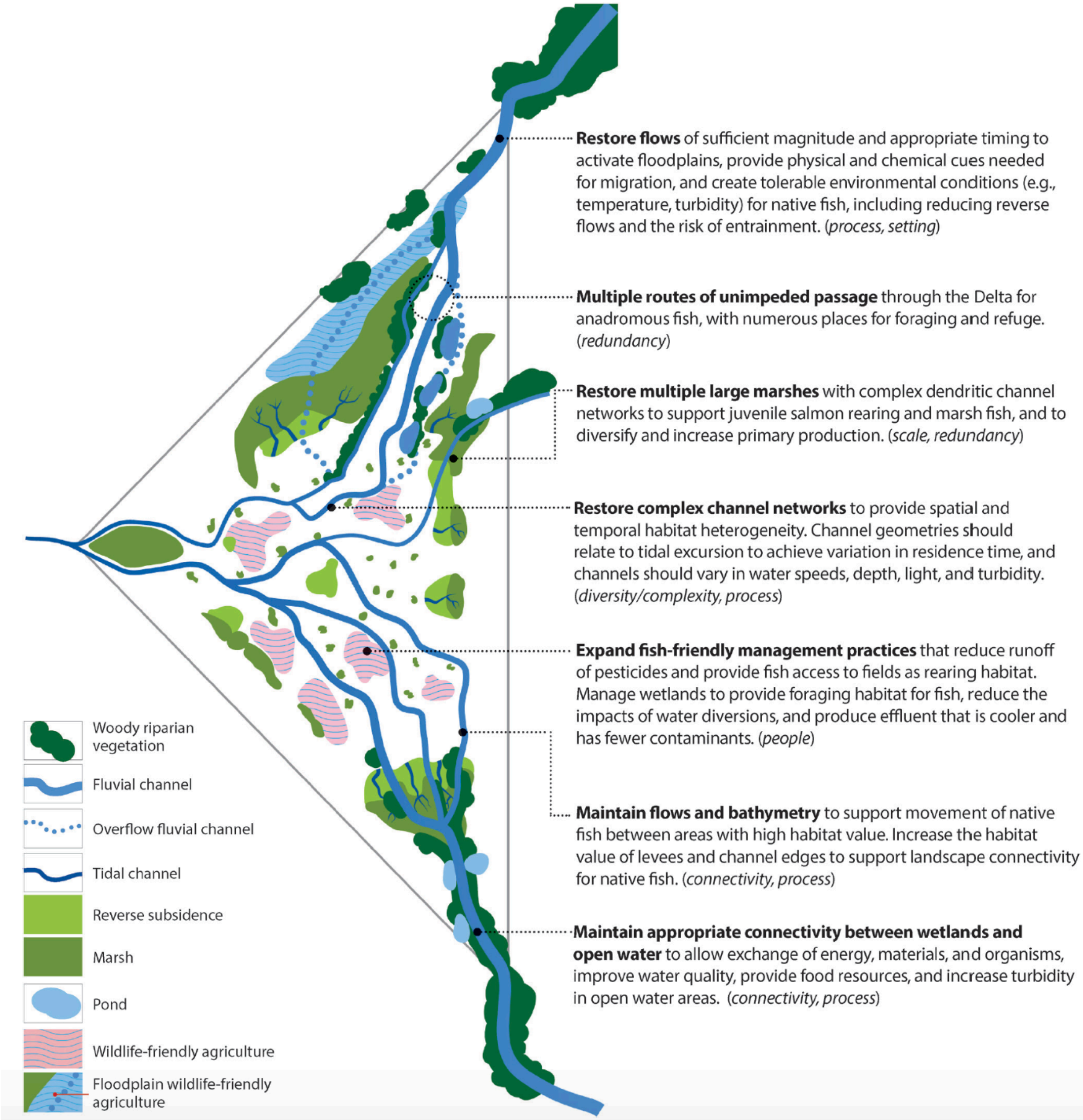

Figure 4. Recommendations for native fish support in the Sacramento-San Joaquin Delta. Goals for supporting native fish in the Delta focused on both resident estuarine and anadromous fish, including the endemic delta smelt and Chinook salmon. Here we illustrate examples of recommendations for increasing the resilience of native fish support across the Delta. Similar recommendations and conceptual models were produced for other wildlife support goals, including marsh birds and mammals, riparian wildlife, and waterbirds (see SFEI-ASC 2016).

These and other recommendations from the Delta Landscapes project are being incorporated into a variety of regional planning efforts, providing a landscape-scale and resilience-based approach that stands in contrast to a more traditional single-species management approach. For example, recommendations have informed amendments to the Delta Plan, a comprehensive, long-term regional management plan that sets legally enforceable regulations aimed at improving water supply reliability and ecosystem health while preserving and enhancing the Delta's unique agricultural, cultural, and recreational characteristics. Recommendations have also been directly incorporated into the Delta Conservation Framework, a collaborative effort involving federal, state, and local agencies and the Delta stakeholder community, designed to guide regional conservation actions through 2050 (Sloop et al. 2017). Delta Landscapes concepts and recommendations are also informing subregional, stakeholder-driven restoration planning efforts: for example, the Central Delta Corridor Partnership, composed of representatives from public agencies that own large tracts of land in the Delta, is considering if the parcels under their control could be restored to support a coherent network of large, functionally connected marshes as per Delta Landscapes specifications.

4. The value and challenge of planning for landscape resilience

This project advances the practice of resilience-based management by providing a structured approach and shared vocabulary for identifying, organizing, and harnessing potential opportunities and actions likely to increase landscape resilience, particularly in highly modified landscapes. The case studies suggest that systematic consideration of the seven dimensions can yield new insights into actions and strategies likely to promote landscape resilience (table 2). In Silicon Valley, for example, consideration of the dimensions generated a new ecological objective not previously considered (oak ecosystems), helped identify existing features likely to contribute to oak ecosystem resilience (e.g., heritage trees, areas with reliable access to groundwater), and suggested previously unrecognized opportunities to further improve resilience (e.g., recommendations for managing stand density, composition, and structure). In the Delta, our approach led to a heightened focus on the large-scale hydrologic processes needed to create and maintain resilient wetlands in landscape configurations that would increase survivorship, growth and reproduction of native fish. In both cases, we found this approach has helped spur regional alignment and incorporation of resilience science across sectors. In Silicon Valley, this has catalyzed a number of local implementation projects led by a variety of stakeholders from public agencies, non-profit groups, and other sectors, while in the Delta coordination has occurred through incorporation of guidelines into policies and programs, such as the Delta Plan Ecosystem Amendment, Delta Conservation Framework, and Central Delta Corridor Partnership.

The case studies also highlight the importance of a regional or landscape focus in planning for ecological resilience. This is due partly to practical considerations, since implementation of many of the strategies derived through this process requires coordination across stakeholders and sites to align site-scale actions with landscape-scale objectives and outcomes, as illustrated by the creation of large oak "nodes" in Silicon Valley, or the restoration of a functional corridor >50 km long for native fish in the Delta. In addition, we suggest a landscape perspective is required to distinguish undesirable site-scale ecological change (e.g., habitat conversion that does not contribute to regional goals) from desirable site-scale transformation (i.e., adaptation that contributes to broader-scale goals). This increases managers' ability to allow for dynamic change at the patch or site scale as conditions change and places support different functions and species over time. At the same time, it emphasizes actions that "keep every cog and wheel" (Leopold 1949) at the landscape level by promoting persistence and recovery of desired functions and features. In the Delta, for example, areas restored to non-tidal marsh or terrestrial habitat types in the near term may transition to tidal marsh as sea level rises, while in Silicon Valley some forested areas may become shrublands under future climates. The lost habitat acreage would be of less concern if, in a larger planning context, non-tidal marshes and forests are being tracked and restored elsewhere if necessary. In the context of landscape resilience goals, these transformations can help ensure desired habitat types are maintained in the landscape even as their distributions shift, with minimal loss of support for key functions and biodiversity.

Table 2. Example landscape resilience objectives, recommendations, and implementation efforts.

		
Case study location	Silicon Valley	Sacramento–San Joaquin Delta
Resilience of what?	Oak ecosystems	Native resident and anadromous fish populations
Resilience to what?	Heat, drought, and urban context	Water temperatures and highly altered, channelized ecosystem
Example objective	Promote oak ecosystems in urban context in which supported by soil type and groundwater levels and with community support for their establishment	Support native resident and anadromous fish for which natural flooding processes can be reestablished within an agricultural landscape and where water supply infrastructure impacts allow
Example recommendation	Create multiple nodes of oak planting (16–20 acres) centered around large trees	Restore multiple routes of unimpeded passage through the Delta for anadromous fish, with numerous places for foraging and refuge
Example implementation effort	Work with local nonprofits to incorporate oak planting recommendations into tree planting and restoration efforts	Work with farmers to expand fish-friendly management practices such as fish-compatible rice farming and reducing pesticide application and runoff

Photograph: Kehoe CC BY 2.0 (left), Shira Bezalel (right).

Since these efforts are still in their early stages, evidence is not yet available to assess the impact of this approach on landscape management outcomes. However, we hypothesize that implementing actions that address the dimensions of resilience comprehensively and in combination will improve the ability of these landscapes to sustain desired biodiversity and ecological functions in response to stressors. In Silicon Valley, for example, planting a diversity of native oak species and trialing use of oak genotypes native to southern California is likely to provide differential response to drought. This in turn will improve oak persistence and stabilize wildlife populations that depend on oaks, such as acorn woodpeckers and scrub jays, by providing more consistent acorn crops across years. Planting a diversity of drought-adaptive understory vegetation can help increase availability, diversity, and temporal stability of floral resources available for native bees and other pollinators, buffering populations when resources are limiting. Similarly, creation of large patches of tidal marsh coupled with creek realignment to increase sediment transport to and deposition on the marsh plain (and decrease sediment accumulation in the channels) will better equip tidal marshes to keep pace with sea-level rise while also decreasing flood risk in the lower reaches of creeks (figure 5). In the Delta, we expect that implementation of the recommendations would foster the resilience of native fish to increasing water temperatures by providing areas for individuals to escape periodic warm water conditions (e.g., maintaining deepwater habitats that provide cold water refuge in the summer) and by creating habitat in areas less likely to experience high temperatures in the future (e.g., wetlands in the North Delta). In addition, restoration of many large, connected habitat patches across a broad temperature gradient in the Delta would support large, diverse fish populations, promoting adaptation to warming waters.

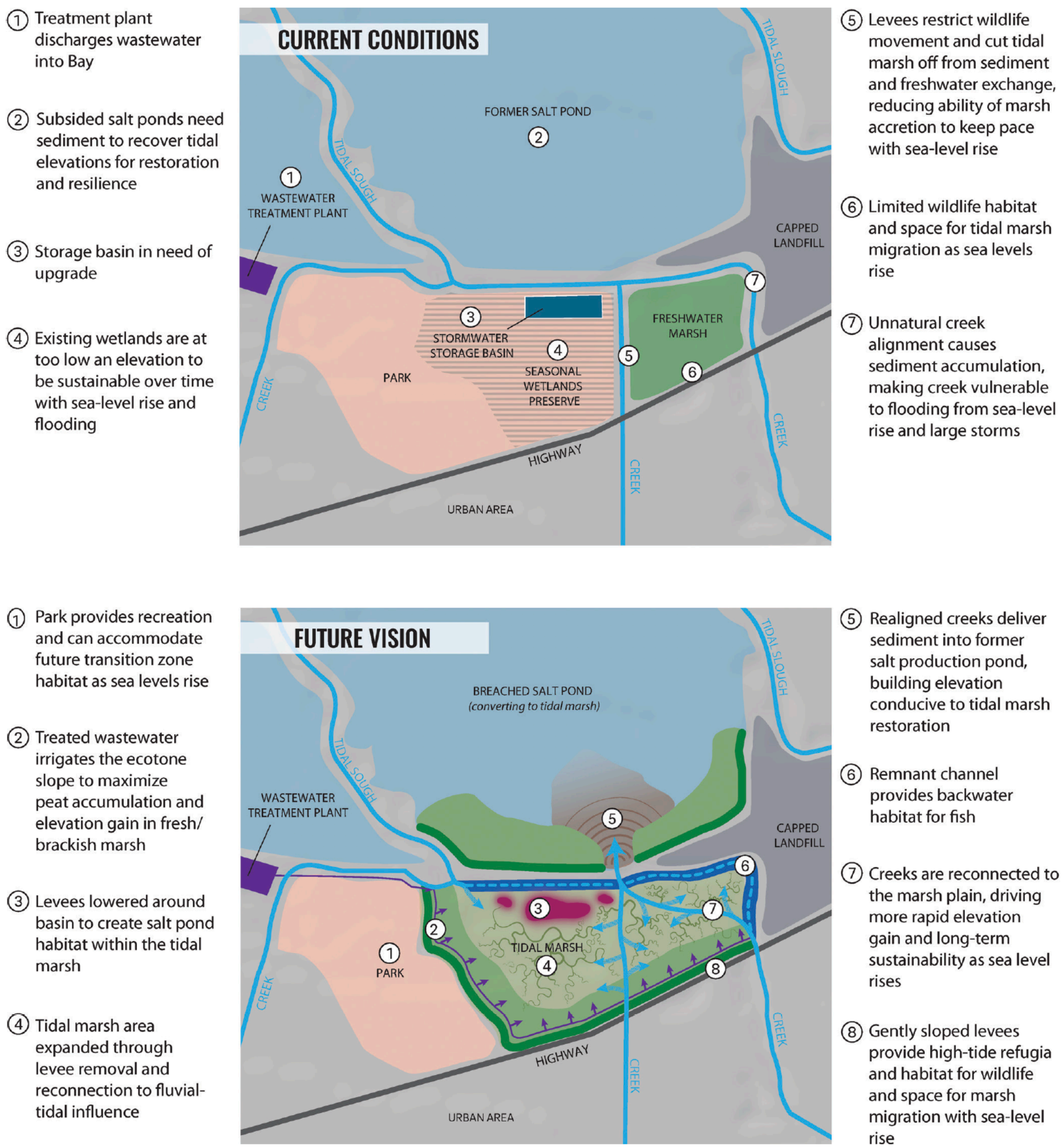

Figure 5. Application of the landscape resilience dimensions to an example Silicon Valley landscape adjoining San Francisco Bay, illustrating the difference between current landscape condition and challenges to resilience management (top) and management recommendations generated through the landscape resilience approach (bottom). Figure by Katie McKnight and Scott Dusterhoff.

Implementing this approach is not without challenges and limitations. We found that some landscape attributes (box 1), while widely cited in literature as contributors to resilience, were challenging to operationalize in the absence of targeted studies detailing how they apply to particular functions, sites, or systems: for example, cross-scale interactions and functional redundancy). Further, quantifying resilience remains broadly challenging (Quinlan et al. 2015, Newton 2016). In addition, while many management actions will contribute to multiple dimensions, others will involve trade-offs: for example, linking habitat patches can increase connectivity and promote species movement, but keeping them isolated can promote diversity and redundancy while limiting the spread of diseases and invasions. The relative significance of landscape resilience dimensions will vary by location, and no single plan will be able to address them all.

In applying the landscape resilience approach to real geographies, we found that the process benefits from coordination and buy-in across partner institutions and requires substantial resources—space, labor, funding, expertise, and time. The case studies in Silicon Valley and the Delta each included original historical ecological reconstructions and landscape change analysis, drew on more than thirty regional expert science advisors in total, and spanned several years. Implementation will extend for many more years, and must be integrated into broader planning efforts that incorporate goals beyond ecological resilience, including social resilience goals, economic considerations, and other factors that influence ecosystem management (e.g., public preferences, safety, maintenance, and existing policies and regulatory frameworks). We therefore suggest our approach may be best suited for regional-scale, programmatic planning through processes involving multiple stakeholders. Nevertheless, individual land and resource managers may find the dimensions helpful as a starting point for qualitatively assessing potential existing sources of resilience, opportunities to improve resilience, and key knowledge gaps.

Chornesky et al. (2015) suggest that climate change adaptation efforts require four elements we also consider relevant to landscape resilience planning: usable scientific information, practical steps to sustain ecosystem functions and adaptive capacity, a venue for collaborative planning, and mechanisms to encourage collective and individual action. Initial work to date in both Silicon Valley and the Delta has primarily centered on the first two elements (i.e., translation of relevant scientific information into practical guidelines) while beginning to establish processes that encourage collective planning and action. In Silicon Valley, for example, outreach by forestry non-profits and others to motivate homeowners to plant oaks has been essential to adoption of the resilience recommendations. In the Delta, we recognized the need to communicate project recommendations through numerous stakeholder presentations and meetings to diverse audiences. For example, we held a workshop to generate feedback from stakeholders (including landowners, regulators, restoration practitioners, and government agency staff) that resulted in consideration of these recommendations in the context of specific projects and ongoing conservation efforts. However, future efforts would be strengthened by further broadening the array of stakeholders to include other members of the public, including homeowners, farmers, local residents, and environmental advocates. The success of this approach will be contingent on early, sustained and active engagement with these stakeholders to integrate ecological resilience goals with other considerations (e.g., a homeowner's desire to maintain a backyard lawn or landscape with edible or beautiful non-native plants) and build widespread support for and adoption of plans. This must happen not only through inclusive educational and outreach activities, but also via public participation and collaboration in landscape planning and management processes.

We have endeavored to provide guidance that may help accelerate planning and actions for landscape resilience in the face of uncertainty—in future climate regimes, ecosystem response, the success of potential interventions, and our understanding of ecological resilience mechanisms themselves. Undoubtedly, these ideas and approach will be refined over time as they are tested across diverse landscapes, and as resilience science evolves. Our hope is that a systematic, landscape-scale, and collaborative approach will accrue greater cumulative benefits to resilience management activities, and ultimately better equip landscapes to sustain biodiversity and function into the future.

5. Acknowledgments

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Supplemental Material A

Summary of seven dimensions of landscape resilience, along with examples of each from the peer-reviewed literature.

Dimension	What is it?	What are the components?	Examples of how it contributes to resilience
Setting	Aspects of a landscape that determine potential constraints on and opportunities for resilience	• Geophysical context • Biotic legacies • Land-use history and trajectories	• Serpentine soils enable more native species to persist than elsewhere in heavily invaded California grasslands, and may facilitate recovery from disturbance (Harrison 1999, Fernandez-Going et al. 2012) • Intensive land-use practices such as heavy grazing and bulldozing inhibit recovery of some forest patches in

			the tropics (Chazdon 2003, Cramer et al. 2008).
Process	Physical, biological and chemical drivers, events and processes that create and sustain landscapes over time	• Abiotic processes • Biotic processes • Biotic/abiotic feedbacks	• Seed dispersal can promote and accelerate recovery after disturbances such as fire and agricultural abandonment (Chazdon 2003) • Plant/soil feedbacks can enable recovery and persistence via dynamic interactions between plants, microbial diversity and nutrient releases into soils (Miki et al. 2010)
Connectivity	Linkages between habitats, processes, and populations that enable movement of materials and organisms	• Functionally and structurally linked habitat patches • Spatial configuration; connections across habitats and physical gradients • Isolation and disconnectivity	• Spatial configurations of woodland habitat that facilitate increased connectivity decrease the sensitivity of butterfly populations to extreme drought and hasten recovery (Oliver et al. 2013) • Habitat connectivity between mangroves and coral reefs in Australia increases coral reef resilience to algal growth by creating mobile links for herbivorous fish to graze (Olds et al. 2012)
Diversity/ Complexity	The variety and arrangement of biotic and abiotic landscape elements that provide a range of options	• Variety of landscape features/habitat types • Within-habitat heterogeneity • Diversity in species life history • Genotypic and phenotypic variability	• Regional topographic heterogeneity can increase resilience of perennial grassland populations to drought in Australia (Godfree et al. 2011) • Genotypic diversity in eelgrass in the Baltic Sea improves community recovery to extreme heat (Reusch et al. 2005)

Redundanc y	Multiple similar or overlapping elements or functions within a landscape that provide insurance against loss	• Structural redundancy • Population redundancy • Functional redundancy	• Functional redundancy and response diversity contribute to resilience in coral reefs (Nyström 2006) • Isolated habitats or populations are less vulnerable to catastrophic losses from perturbations such as fire, disease, or invasion (Levin and Lubchenco 2008)
Scale	Spatial and temporal extent that allow population, community, and ecosystem dynamics to persist and coexist	• Spatial scale • Temporal scale • Cross-scale dynamics and interactions	• Large habitat patches contribute to resilience of butterfly populations in UK woodlands by reducing population sensitivity and thus hastening recovery after perturbation (Oliver et al. 2013) • Organisms in the same functional group often have different body sizes, creating discontinuities in scale that minimize niche overlap between species within functional groups while enhancing functional redundancy (Nash et al. 2014)
People	The individuals, communities, and institutions that shape and steward landscapes	• Local knowledge • Participation and engagement • Policies, land use, and jurisdictions • Adaptive management and stewardship	• Community engagement through outreach and education help build broad stakeholder support, partnership, and investment enhancing the ability of restoration and conservation activities to be resilient (Biggs et al. 2012) • Adaptive management and stewardship that emphasizes flexibility and learning can enable landscapes to more effectively respond to uncertainty and unpredictable surprises (Gunderson 2000, Tompkins and Adger 2004)

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Supplemental Material B

Example worksheet used to help develop potential conservation, restoration, and management recommendations based on the landscape resilience dimensions.

Resilience objective: ____

	Landscape attribute	**Current conditions and potential opportunities**
Setting	Geophysical context	
	Biotic legacies	
	Land-use legacies	
Process	Abiotic processes	
	Biotic processes	
	Biotic-abiotic feedbacks	
Connectivity	Structural and functional linkages	
	Spatial configuration	
	Isolation and disconnectivity	
Diversity/ Complexity	Variety of landscape features/habitat types	
	Within-habitat heterogeneity	
	Genotypic/phenotypic variability	
	Life history diversity	

	Landscape attribute	Current conditions and potential opportunities
Redundancy	Structural redundancy	
	Population redundancy	
	Functional redundancy	
Scale	Spatial scale	
	Temporal scale	
	Cross-scale dynamics	
People	Local knowledge	
	Participation and engagement	
	Policies, land use, and jurisdictions	
	Adaptive management and stewardship	

Chapter 5: Conclusions and Directions for Future Research

1. Managing for multifunctionality in complex landscapes

The past decade has shown increasing recognition of the importance of managing at the scale of the landscape to support multiple goals around biodiversity conservation, ecosystem service provision, and enhancing resilience (e.g., Lindenmayer et al. 2008, Parrott and Meyer 2012, Menz et al. 2013). Yet today's landscapes are heterogeneous mosaics of land uses and ecosystems, with differing histories, ownership, and management goals (Hobbs et al. 2014). Areas of open space, remnants of former habitat, and populations of endangered species sit alongside—and not infrequently, within—rangelands, croplands, and cities.

Such human-modified and human-dominated landscapes are a crucial component of biodiversity conservation and ecosystem management (Miller and Hobbs 2002, Koh and Gardner 2010). Developing successful management strategies in these complex places will require reconciliation of multiple, often conflicting goals and priorities and the ability for landscapes to be "multifunctional"—that is, to concurrently support desired multiple ecosystem services and other desired benefits (Mastrangelo et al. 2014). It will likely require integration of approaches that draw on a variety of frameworks, from the conservation of habitat remnants and restoration of historical ecosystems to embracing novel goals, targets, and approaches (Kueffer and Kaiser-Bunbury 2014). The challenge then becomes understanding what anchors ecosystem management in these landscapes, and in an increasingly changing and dynamic environment. How do we situate management strategies within their landscape context—in the particulars of a given place, from cultural legacies to geophysical processes—while remaining adaptable, creative, and forward-looking?

The goal of this dissertation was to tackle these questions by exploring the value of a long-term, historical perspective in landscape management across a range of management goals, land-use contexts, and geographic scales. In the preceding chapters, I show that history continues to be a cornerstone of ecosystem management, despite past and ongoing transformations in land use and climate in human-dominated landscapes and other highly modified ecosystems. I demonstrate that the changes experienced by highly modified ecosystems do not undermine the value of a historical perspective. In fact, history is arguably more important than ever in this context, where rapid change has obscured ecological memory and understanding. As observed by Sanderson (2019), scholars of American history do not study past wars in order to recreate the battles, but rather to better understand the context and drivers of the event and gain insights into our current situation and lessons learned for the future. Similarly, historical ecology is a tool not to recreate the past, but to provide new insights into current conditions and inform future potential.

Below, I summarize key findings and implications from my research and highlight potential areas of future research.

2. Key findings and implications

1. History can inform multiple dimensions of landscape management – not just biodiversity conservation.

While historical ecological analyses have most commonly been used to guide biodiversity conservation and ecosystem restoration activities, my research highlights the importance of expanding the scope of these efforts to include a broader array of management considerations. In Chapter 3, I show how historical documents provide a unique opportunity to estimate changes in ecosystem services such as carbon storage over century time scales in an urban region, offering insights into the impacts of land-cover and land-use transformation on these services over time. My research suggests opportunities to increase carbon storage in the current Silicon Valley landscape in areas that have experienced substantial loss in tree cover over time. It also provides insight into the carbon storage potential of California valley oak woodlands more broadly, relevant to supporting Cap-and-Trade Program investments in oak habitat restoration in other regions across the state. In Chapter 4, I demonstrate that a historical perspective provides important context for planning for ecological resilience by informing regionally appropriate objectives, strategies, and actions for resilience management.

2. Insights from historical ecology can transcend the case study.

Historical ecology has traditionally been a largely place-based discipline, oriented around the local case study. Idiosyncratic source availability and the time-intensive nature of historical research make historical ecology research difficult to scale. Variations in land-use history, geophysical context, climate, and other environmental and cultural factors contribute to the "distance decay" problem: that is, the similarity in ecosystem characteristics between two places decreases with increasing distance between them (White and Walker 1997, Swetnam et al. 1999). The implication is that ecosystems and landscapes are all unique, and that drawing connections and deriving relevant insights across locations can present a challenge. As a result, the value of history has largely been centered around its ability to provide locally relevant insights and foster a connection to place (e.g., Higgs et al. 2014).

My research suggests that in addition, historical ecology can provide more generalizable insights about ecosystem trajectories and management recommendations across regions. In Chapter 2, I synthesize recommendations across the global corpus of historical ecology research. I show emerging patterns in the management recommendations made by the global historical ecology literature across ecosystems and locations, for example in the value of both habitat remnants and novel ecosystems, the role of people in shaping and stewarding ecosystems, and the value of managing across scales. This is consistent with a recent push in human-environment geography and land-use change studies to link insights from local case studies to global insights through meta-analysis and synthesis studies to derive more nuanced understanding of the drivers, magnitude, and impacts of global environmental change (e.g., van Vliet et al. 2016, Margulies et al. 2016, Magliocca et al. 2018).

3. Historical ecology can revise or challenge our understanding of desirable future states.

Historical ecology has been recognized for its ability to provide new and often surprising insights that can adjust how we manage species and ecosystems (McClenachan et al. 2015). My research affirms this. In Chapter 3, for example, my finding of likely significant loss of approximately half of Silicon Valley's tree carbon storage ca. 1850 to present challenges the hypothesis that aboveground carbon storage increases with urbanization in Mediterranean-climate ecosystems due to irrigation and tree planting. In Chapter 2, I suggest that such surprising or counterintuitive insights are prevalent across geographies and ecosystems: I determine that about one-quarter of historical ecology studies worldwide contain management recommendations identified by the authors as having revised or challenged status quo management. The prevalence of such recommendations emphasizes the value of a historical perspective in shifting our understanding of desirable management goals, strategies, and targets.

4. Past and future-oriented perspectives are complementary, not contradictory.

I argue that development of forward-looking management strategies in these complex and dynamic landscapes requires moving beyond the often-invoked choice between "historical" versus "novel" ecosystem management goals. Historically anchored goals are often cast as "backward looking", shaped by a desire to return to former ecosystem states, increase ecological integrity, and resist change. This focus on the past is often framed as standing in contrast to "forward looking" goals that are focused on restoring functions, increasing resilience to change, and embracing novelty. The work presented here underscores that this is a false dichotomy. Historical and novel ecosystems are not two ends of a spectrum, but occur side by side in complex, hybrid landscape mosaics superimposed at a variety of scales (cf. Hobbs et al. 2014, Barnosky et al. 2017). In Chapter 2, I show that recommendations in the historical ecology literature are generally complementary to those from the "forward looking" field of climate change adaptation. Similarly, in Chapter 4 I show the value of a historical perspective in setting goals for ecological resilience planning by identifying persistent features that could serve as restoration nodes, forgotten features that might guide restoration, and areas where changed conditions and land-use legacies might make such targets infeasible or more novel elements desirable.

Despite this alignment, ecosystem management goals centered around a historical perspective and those that prioritize resilience or adaptation to climate change are rarely co-evaluated. Based on my research, I suggest this is a missed opportunity, and that integrating these approaches is likely to yield better outcomes for management. This includes both a more explicit integration of past and ongoing changes in climate and disturbance regimes into historical ecological analyses, as well as more consistent inclusion of historical ecology assessments in the ecological resilience and climate change adaptation literature to understand the drivers, patterns, and consequences of ecological persistence and change across the landscape.

3. Future research directions

This research aims to encourage scientists, managers, and policymakers in human-dominated landscapes to integrate a long-term historical perspective into what landscape management looks like in these places, as a complement to an understanding of current conditions and potential future changes—not as a prescription, but as a guide. A few key directions for future research would continue to strengthen the integration of history into multi-benefit landscape management.

First, this research points to the importance of continuing to advance the integration of historical sources into ecosystem service analyses and decisionmaking processes. In Silicon Valley, future research should include a more comprehensive accounting of historical landscape carbon storage (including soil organic carbon and aboveground pools in grasses and wetlands) along with quantitative assessments of other ecosystem services such as sediment and stormwater management, food production, and freshwater provision. Research should also include estimates of service provision at additional time periods, particularly ca. 1930-1940 during the pre-World War II agricultural era. These additional analyses would provide a better understanding of temporal trajectories in individual ecosystem services along with synergies and trade-offs among services across time and space (e.g., Qiu and Turner 2013, Renard et al. 2015). A more detailed assessment of contemporary tree carbon storage, for example based on field data (e.g., tree surveys) and high-resolution remote sensing datasets, would also refine assessments of carbon change over time. Future research could also include an assessment not just of the changing capacity of the landscape to provide ecosystem services over time, but also of the changing recognition of and demand for ecosystem services over time. Such an assessment could be completed using historical written records, census data, and maps and surveys (cf. Bürgi et al. 2015, Tomscha et al. 2016). Beyond Silicon Valley, additional research into ecosystem trajectories in Mediterranean-climate and semi-arid environments that combines historical and contemporary sources would shed further light onto aboveground carbon storage dynamics with urbanization in such places.

In addition, this current research effort investigates three key aspects of ecosystem management in parallel – managing for ecological restoration, ecological resilience, and ecosystem services. However, successful multi-benefit management requires understanding the synergies and trade-offs between management goals in a given landscape. In agricultural contexts, for example, agricultural ecosystems can provide significant ecosystem services in addition to crop production, including pest control, biodiversity support, pollination, and carbon sequestration, yet such ecosystems can also engender disservices such as loss of wildlife habitat, nutrient runoff, and sedimentation of streams (Power 2010). In urban systems, trade-offs often exist between biodiversity goals and ecosystem service provision: for example, non-native species may provide more limited wildlife habitat but offer increased ecosystem services such as carbon storage, shade, or aesthetic value (Dearborn and Kark 2010). Evaluation of all three considerations in the same place through an integrated analysis is a key next step in developing true multi-benefit approaches to management that capitalize on “win-win” opportunities for achieving multiple desired outcomes while minimizing trade-offs between management goals (Parrott and Meyer 2012). While a temporal perspective has been shown to be critical in understanding these trade-offs and synergies (Tomscha and Gergel 2015, Renard et al. 2015), such research is rarely performed.

Finally, my research suggests the potential value of additional meta-analysis and synthesis studies in the field of historical ecology to investigate drivers of ecosystem change, system response to environmental and anthropogenic stressors and disturbances, and map pathways to impact for historical data in ecosystem management. For example, future studies synthesizing research across the field of historical ecology could examine examples of how historical ecology has influenced ecosystem management and identify the ecological metrics used by such studies to understand ecosystem change and inform decision-making.

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