Building Ecological Resilience in Highly Modified Landscapes

ERIN E. BELLER, ERICA N. SPOTSWOOD, APRIL H. ROBINSON, MARK G. ANDERSON, ERIC S. HIGGS, RICHARD J. HOBBS, KATHARINE N. SUDING, ERIKA S. ZAVALETA, J. LETITIA GRENIER, AND ROBIN M. GROSSINGER

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. In this article, 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

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). Although 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, because of 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 nonprofits, 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. Because ecological resilience is only one facet of the broader concept of resilience in socioecological systems (Walker and Salt 2012), our approach is intended to be complementary to existing socioecological resilience frameworks

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(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: 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.

Identifying mechanisms of landscape resilience

Although 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 nonnative species that support desired ecological functions or ecosystem services; *natural stressors* include both episodic events such as fire, flood, or drought and 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 the 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 or complexity, redundancy, scale, and people, along with several core considerations within each category (box 1). We refined these dimensions during a 2-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.

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.

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 the setting and the process (see box 1) and to 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 in which 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).

Box 1. Seven dimensions of landscape resilience.

These prompts are intended to provide a holistic but 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.

Setting: Geophysical, biological, and sociocultural aspects of a landscape that determine constraints on and opportunities for resilience

What elements of the *geophysical context* (geology, soils, and topography) support characteristic habitats, ecological diversity, and the local distribution of microclimates?

What *biotic legacies* (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?

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) and *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 feedback loops* that might enable recovery and persistence of habitats (e.g., sediment–vegetation interactions)?

Connectivity: Links between habitats, processes, and populations that enable movement of materials and organisms

Where are opportunities to preserve or create *structural and functional links* 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?

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), and 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?

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)*

Scale: Spatial and temporal extent at which population, community, and ecosystem dynamics 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?

Box 1. Continued.

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?

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?

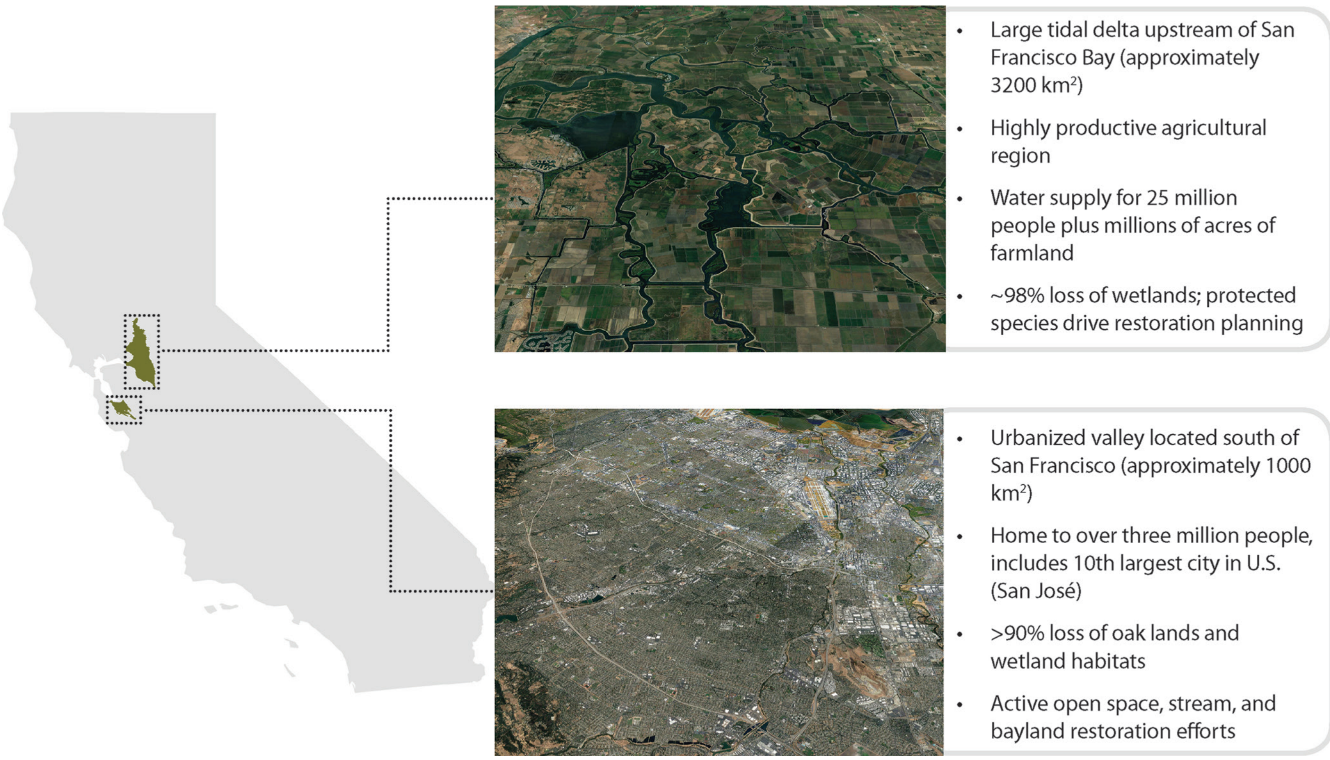

Figure 1. Map of California case studies. The two case studies focus on two heavily modified and iconic landscapes in California, the agricultural Sacramento–San Joaquin Delta and urban Silicon Valley.

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 nonprofits, 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, nonprofit, private, and academic settings) and vetted by representatives from local environmental organizations. We drew on a wealth

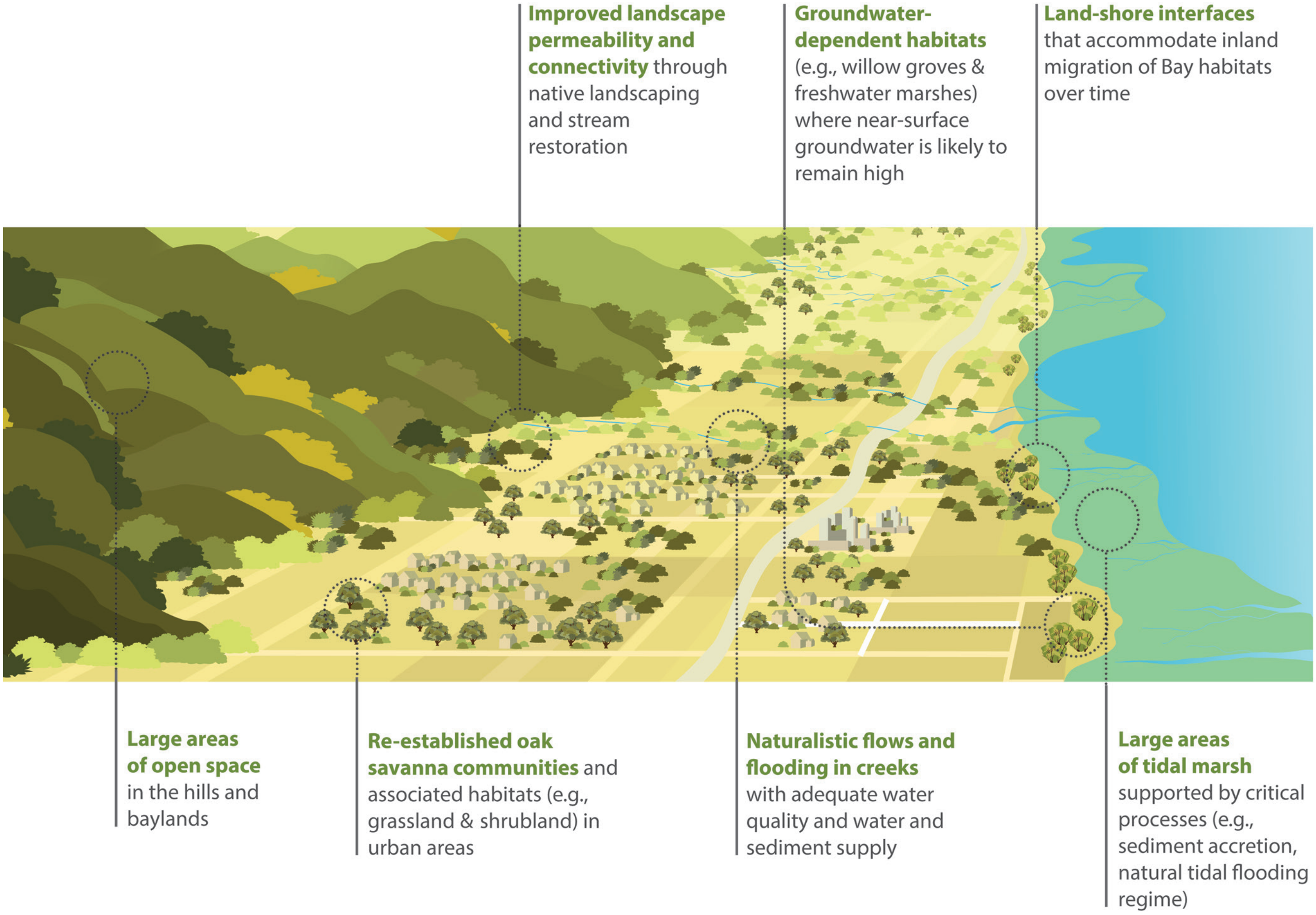

Figure 2. Examples of Silicon Valley landscape resilience objectives (cf. Robinson et al. 2015). Figure by Maria Dillman and Bonfire Communications.

of contemporary and historical data, including landscape reconstructions and change analyses (Grossinger et al. 2007, Beller et al. 2010), land use and land cover data, and environmental and biological data sets 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, the reestablishment of oak ecosystems "reoaking" on the urbanized valley floor was identified as a regional objective given their iconic status and dramatic (over 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 the supplemental material for the worksheet used in this exercise). For example, the 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 reconnection 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* or *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 reoaking the urbanized valley floor).

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,

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*)

green infrastructure and stormwater, urban landscaping and forestry, and creek and wetland restoration. For example, Silicon Valley's regional water agency used the project's 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).

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 (hereafter referred to as the 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 affected 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, the 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

Box 2. Reoaking Silicon Valley.

Once we developed recommendations for supporting resilient oak ecosystems in Silicon Valley, or "reoaking" (Spotswood et al. 2018; 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 nonprofits, to refine the 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., because of soil modification and compaction) has made conditions less suitable for oaks.

A number of local entities are currently implementing the reoaking guidance. For example, two local urban forestry and ecological restoration nonprofits (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 reoaking in target neighborhoods. Similarly, Google is working with landscape architects to integrate reoaking 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 reoaking 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)

channel networks in the marshes (500 hectares or more; SFEI-ASC 2016). These channel networks are also critical for addressing "diversity/complexity" (how the dimension is written in Box 1), because 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 because of live vegetation, debris, and slumps. For connectivity, the recommendations included spacing restored marshes in close enough proximity to allow salmon smolt to move between them in a day (approximately 15–20 kilometers, a figure 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, nonnative predators, and few refuge areas. For people, the recommendations included fish-friendly farming practices such as reduced pesticide application and cultivation of rice to

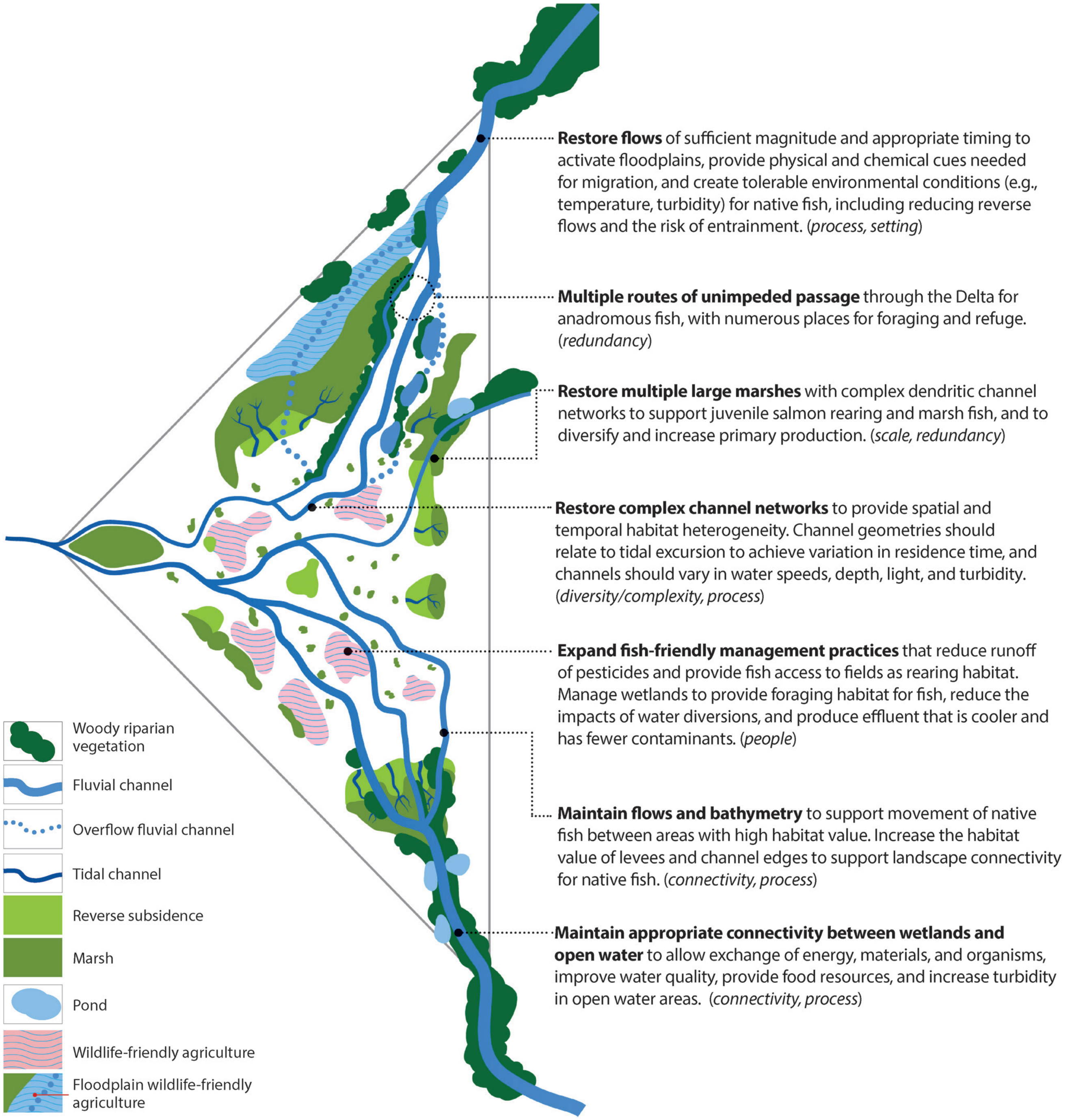

Figure 4. Recommendations for native fish support in the Sacramento–San Joaquin Delta. Goals for supporting native fish in the Delta focused on both resident estuarine and anadromous fish, including the endemic Delta smelt and Chinook salmon. This figure illustrates examples of recommendations for increasing 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).

maintain agricultural production and provide novel floodplain habitat that fish can access for growth and rearing.

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, the recommendations have informed amendments to the Delta Plan, a comprehensive, long-term regional management plan that sets legally enforceable regulations

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).

aimed at improving water supply reliability and ecosystem health while preserving and enhancing the Delta's unique agricultural, cultural, and recreational characteristics. The 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 whether the parcels under their control could be restored to support a coherent network of large, functionally connected marshes as per Delta Landscapes specifications.

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 (urban 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, nonprofit groups, and other sectors, whereas in the Delta, coordination has occurred through incorporation of guidelines into policies and programs, such as the Delta Plan Ecosystem Amendment, the Delta Conservation Framework, and the 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, because 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 nontidal marsh or terrestrial habitat types in the near term may transition to tidal marsh as sea level rises, whereas 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, nontidal 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.

Because 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 northern 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.

Implementing this approach is not without challenges and limitations. We found that some landscape attributes (box 1), although widely cited in the 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. Furthermore, quantifying resilience remains broadly challenging (Quinlan et al. 2015, Newton 2016). In addition, although 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 and colleagues (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 nonprofits 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 the project's 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

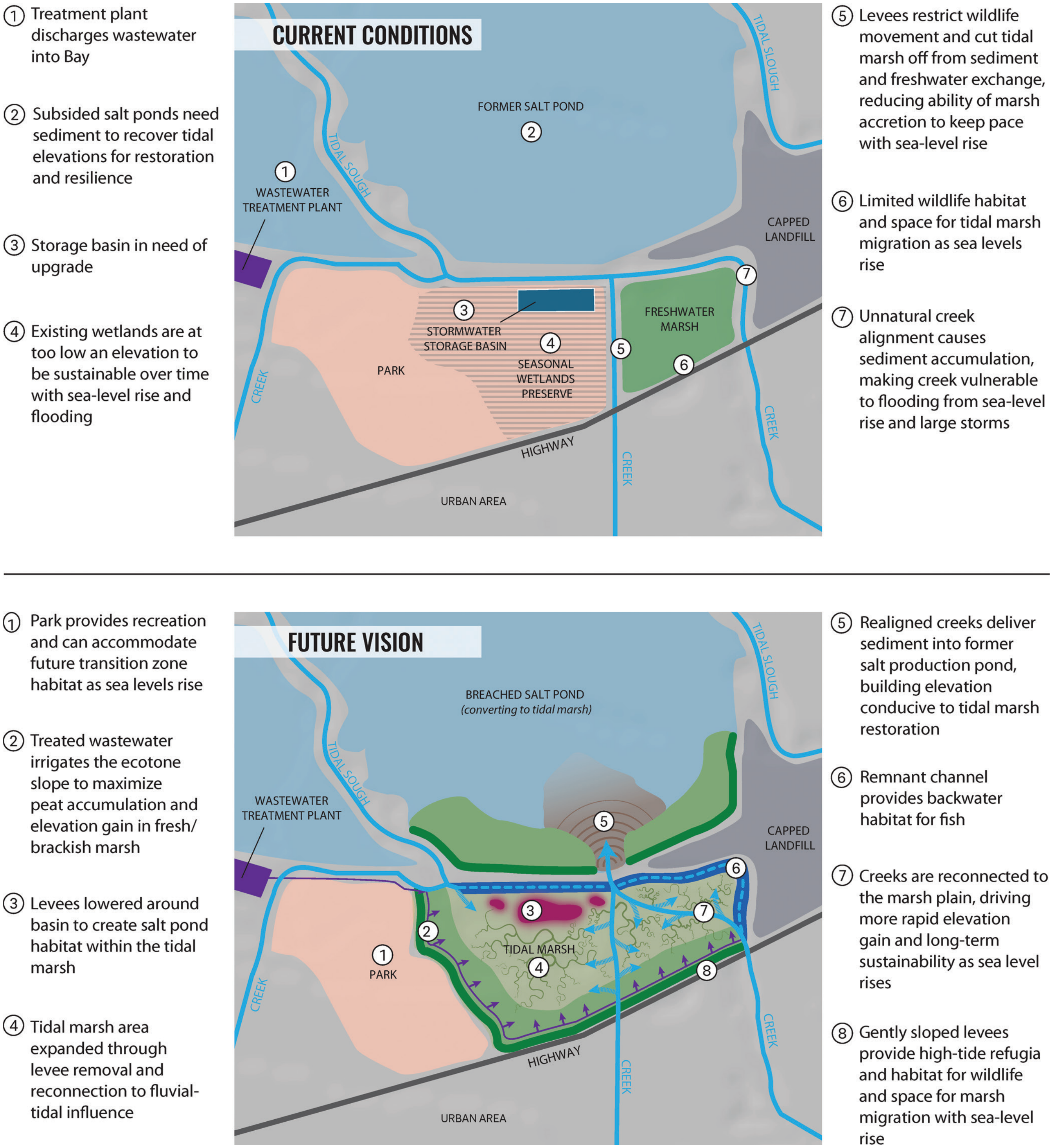

Figure 5. Application of the landscape resilience dimensions to an example Silicon Valley landscape adjoining San Francisco Bay, illustrating the difference between current landscape condition and challenges to resilience management (top) and management recommendations generated through the landscape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

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.

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Supplemental material

Supplemental data are available at *BIOSCI* online.

References cited

Beller EE, Salomon MN, Grossinger RM. 2010. Historical vegetation and drainage patterns of western Santa Clara Valley. San Francisco Estuary Institute.

Beller EE, Robinson A, Grossinger R, Grenier L. 2015. Landscape Resilience Framework: Operationalizing Ecological Resilience at the Landscape Scale. San Francisco Estuary Institute.

Biggs R, Schlüter M, Biggs D, Bohensky EL, BurnSilver S, Cundill G, Dakos V, Daw TM, Evans LS, Kotschy K. 2012. Toward principles for enhancing the resilience of ecosystem services. Annual Review of Environment and Resources 37: 421–448.

Carpenter S, Walker B, Anderies JM, Abel N. 2001. From metaphor to measurement: Resilience of what to what? Ecosystems 4: 765–781.

Chornesky EA, Ackerly DD, Beier P, Davis FW, Flint LE, Lawler JJ, Moyle PB, Moritz MA, Scoonover M, Byrd K, Alvarez P, Heller NE, Micheli ER, Wiess SB. 2015. Adapting California's ecosystems to a changing climate. BioScience 65: 247–262.

Dearborn DC, Kark S. 2010. Motivations for conserving urban biodiversity. Conservation Biology 24: 432–440.

Franco G, Cayan DR, Moser S, Hanemann M, Jones MA. 2011. Second California Assessment: Integrated climate change impacts assessment of natural and managed systems. Climatic Change 109: 1–19.

Goals Project. 2015. The Baylands and Climate Change: What We Can Do. California State Coastal Conservancy.

Grossinger RM, Striplen CJ, Askevold RA, Brewster E, Beller EE. 2007. Historical landscape ecology of an urbanized California valley: Wetlands and woodlands in the Santa Clara Valley. Landscape Ecology 22: 103.

Higgs E, Falk DA, Guerrini A, Hall M, Harris J, Hobbs RJ, Jackson ST, Rhemtulla JM, Throop W. 2014. The changing role of history in restoration ecology. Frontiers in Ecology and the Environment 12: 499–506.

Hobbs RJ, Higgs E, Hall CM, Bridgewater P, Chapin FS, Ellis EC, Ewel JJ, Hallett LM, Harris J, Hulvey KB. 2014. Managing the whole landscape: Historical, hybrid, and novel ecosystems. Frontiers in Ecology and the Environment 12: 557–564.

Hobbs RJ, Higgs ES, Hall CM. 2017. Expanding the portfolio: Conserving nature's masterpieces in a changing world. BioScience. 67: 568–575.

ICF International. 2012. Final Santa Clara Valley Habitat Plan. San Francisco, California. http://scv-habitatagency.org/178/Santa-Clara-Valley-Habitat-Plan.

Leopold A. 1949. A Sand County Almanac, and Sketches Here and There: Outdoor Essays and Reflections.

Lindenmayer D, Hobbs RJ, Montague-Drake R, Alexandra J, Bennett A, Burgman M, Cale P, Calhoun A, Cramer V, Cullen P. 2008. A checklist for ecological management of landscapes for conservation. Ecology Letters 11: 78–91.

Menz MH, Dixon KW, Hobbs RJ. 2013. Hurdles and opportunities for landscape-scale restoration. Science 339: 526–527.

Michel CJ, Ammann AJ, Chapman ED, Sandstrom PT, Fish HE, Thomas MJ, Singer GP, Lindley ST, Klimley AP, MacFarlane RB. 2012. The effects of environmental factors on the migratory movement patterns of Sacramento River yearling late-fall run Chinook salmon (*Oncorhynchus tshawytscha*). Environmental Biology of Fishes 96: 257–271.

Newton AC. 2016. Biodiversity risks of adopting resilience as a policy goal. Conservation Letters 9: 369–376.

Oliver TH, Heard MS, Isaac NJ, Roy DB, Procter D, Eigenbrod F, Freckleton R, Hector A, Orme CDL, Petchey OL. 2015. Biodiversity and resilience of ecosystem functions. Trends in Ecology and Evolution 30: 673–684.

Quinlan AE, Berbés-Blázquez M, Haider LJ, Peterson GD. 2015. Measuring and assessing resilience: Broadening understanding through multiple disciplinary perspectives. Journal of Applied Ecology 53: 677–687.

Resilience Alliance. 2010. Assessing Resilience in Social–Ecological Systems: Workbook for Practitioners (revised version 2.0).

Robinson A, Beller E, Grossinger R, Grenier L. 2015. Vision for a Resilient Silicon Valley Landscape. San Francisco Estuary Institute.

Safford H, North M, Meyer MD. 2012. Climate change and the relevance of historical forest conditions. Pages 23–45 in M. North, editor. Managing Sierra Nevada forests. General Technical Report PSW-GTR-237. US Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

SFEI-ASC (San Francisco Estuary Institute-Aquatic Science Center). 2014. A Delta Transformed: Ecological Functions, Spatial Metrics, and Landscape Change in the Sacramento-San Joaquin Delta. San Francisco Estuary Institute-Aquatic Science Center. Report no. 729.

SFEI-ASC (San Francisco Estuary Institute-Aquatic Science Center). 2016. A Delta Renewed: A Guide to Science-Based Ecological Restoration in the Sacramento-San Joaquin Delta. San Francisco Estuary Institute-Aquatic Science Center. Report no. 799.

Scheffer M, Barrett S, Carpenter S, Folke C, Green A, Holmgren M, Hughes T, Kosten S, Van de Leemput I, Nepstad D. 2015. Creating a safe operating space for iconic ecosystems. Science 347: 1317–1319.

Scherr SJ, McNeely JA. 2008. Biodiversity conservation and agricultural sustainability: Towards a new paradigm of 'ecoagriculture' landscapes. Philosophical Transactions of the Royal Society B 363: 477–494.

Sloop C, Jacobs B, Logsdon R, Wilcox C. 2017. Delta Conservation Framework: A Planning Framework for Integrated Ecosystem Conservation toward Resilient Delta Landscapes and Communities by 2050 (Public Draft). California Department of Fish and Wildlife.

Spotswood E, Grossinger RM, Hagerty S, Beller EE, Robinson A, Grenier L. 2017. Re-Oaking Silicon Valley: Building Vibrant Cities with Nature. San Francisco Estuary Institute-Aquatic Science Center. Report no. 825.

Standish RJ, Hobbs RJ, Mayfield MM, Bestelmeyer BT, Suding KN, Battaglia LL, Eviner V, Hawkes CV, Temperton VM, Cramer VA. 2014. Resilience in ecology: Abstraction, distraction, or where the action is? Biological Conservation 177: 43–51.

Timpane-Padgham BL, Beechie T, Klinger T. 2017. A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. PLOS ONE 12 (art. e0173812).

Walker B, Salt D. 2012. Resilience Practice: Building Capacity to Absorb Disturbance and Maintain Function. Island Press.

Whipple AA, Grossinger RM, Davis FW. 2011. Shifting baselines in a California oak savanna: Nineteenth century data to inform restoration scenarios. Restoration Ecology 19: 88–101.

Whipple AA, Grossinger RM, Rankin D, Stanford B, Askevold RA. 2012. Sacramento-San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process. San Francisco Estuary Institute-Aquatic Science Center. Report no. 672.

Erin E. Beller (erin@sfei.org) is an environmental scientist at the San Francisco Estuary Institute and a PhD candidate in the Department of Geography at the University of California, Berkeley. Erica N. Spotswood is an applied ecologist, April H. Robinson is an environmental scientist, and J. Letitia Grenier and Robin M. Grossinger are senior scientists, at the San Francisco Estuary Institute. Mark G. Anderson is director of conservation science for The Nature Conservancy's Eastern US Region. Eric S. Higgs is a professor of environmental studies at the University of Victoria, in, British Columbia, Canada. Richard J. Hobbs is a professor and IAS Distinguished Fellow in the School of Biological Sciences at the University of Western Australia, in Perth. Katharine N. Suding is a professor in ecology and evolutionary biology at the University of Colorado, Boulder. Erika S. Zavaleta is a Howard Hughes Medical Institute Professor in the Department of Ecology and Evolutionary Biology at the University of California, Santa Cruz.