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Successes, Failures and Suggested Future Directions for Ecosystem Restoration of the Middle Sacramento River, California

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Keywords:

CALFED, Flow Regime, Geomorphology, Goals, Ecological Indicators, Monitoring, Restoration, River Processes, Sacramento River, Wildlife

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Abstract:

Large-scale ecosystem restoration projects seldom undergo comprehensive evaluation to determine project effectiveness. Consequently, there are missed opportunities for learning and strategy refinement. Before our study, monitoring information from California's middle Sacramento River had not been synthesized, despite restoration having been ongoing since 1989. Our assessment was based on the development and application of 36 quantitative ecological indicators. These indicators were used to characterize the status of terrestrial and floodplain resources (e.g., flora and fauna), channel dynamics (e.g., planform, geomorphology), and the flow regime. Indicators were also associated with specific goal statements of the CALFED Ecosystem Restoration Program. A collective weight of evidence approach was used to assess restoration success. Our synthesis demonstrates good progress in the restoration of riparian habitats, birds and other wildlife, but not in restoration of streamflows and geomorphic processes. For example, from 1999 to 2007, there was a > 600% increase in forest patch core size, and a 43% increase in the area of the river bordered by natural habitat > 500 m wide. Species richness of landbirds and beetles increased at restoration sites, as did detections of bats. However, degraded post-Shasta Dam streamflow conditions continued. Relative to pre-dam conditions, the average number of years that pass between flows that are sufficient to mobilize the bed, and those that are of sufficient magnitude to inundate the floodplain, increased by over 100%. Trends in geomorphic processes were strongly negative, with increases in the amount of bank hardened with riprap, and decreases in the area of floodplain reworked. Overall the channel simplified, becoming less sinuous with reduced overall channel length. Our progress assessment presents a compelling case for what needs to be done to further advance the ecological restoration of the river. The most important actions to be taken relate to promoting river meander and floodplain connectivity, and restoring components of the natural flow regime.

Supporting material:

Appendix A: Detailed Information on Individual Ecological Indicators

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Successes, Failures, and Suggested Future Directions for Ecosystem Restoration of the Middle Sacramento River, California

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ABSTRACT

Large-scale ecosystem restoration projects seldom undergo comprehensive evaluation to determine project effectiveness. Consequently, there are missed opportunities for learning and strategy refinement. Before our study, monitoring information from California's middle Sacramento River had not been synthesized, despite restoration having been ongoing since 1989. Our assessment was based on the development and application of 36 quantitative ecological indicators. These indicators were used to characterize the status of terrestrial and floodplain resources (e.g., flora and fauna), channel dynamics (e.g., planform, geomorphology), and the flow regime. Indicators were also associated with specific goal statements of the CALFED Ecosystem Restoration Program. A collective weight of evidence approach was used to assess restoration success. Our synthesis demonstrates good progress in the restoration of riparian habitats, birds and other wildlife, but not in restoration of streamflows and geomorphic processes. For example, from 1999 to 2007, there was a >600% increase in forest patch core size, and a 43% increase in the area of the river bordered by natural habitat >500 m wide. Species richness of landbirds and beetles increased at restoration sites, as did detections of bats. However, degraded post-Shasta Dam streamflow conditions continued. Relative to pre-dam conditions, the average number of years that pass between flows that are sufficient to mobilize the bed, and those that are of sufficient magnitude to inundate the floodplain, increased by over 100%. Trends in geomorphic processes were strongly negative, with increases in the amount of bank hardened with riprap, and decreases in the area of floodplain reworked. Overall the channel simplified, becoming less sinuous with reduced overall channel length. Our progress assessment presents a compelling case for what needs to be done to further advance the ecological restoration of the river. The most important actions to be taken relate to promoting river meander and floodplain connectivity, and restoring components of the natural flow regime.

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KEY WORDS

CALFED, flow regime, geomorphology, goals, indicators, monitoring, restoration, river process, Sacramento River, wildlife.

INTRODUCTION

For ecosystem restoration programs to receive ongoing support they must demonstrate success in achieving their stated objectives. Increasingly, policymakers are calling for proof of return on investment (Murdoch et al. 2007). The challenges of demonstrating success may be especially great for large-scale restoration programs. Their goals and objectives are often broadly stated, which can make progress assessments difficult. Typically, monitoring is of short duration and limited in scope, making comprehensive assessments problematic (Roni et al. 2008). This results in missed opportunities for learning, and reduces the effectiveness of future projects (Walters and Holling 1990; Holl and Cairns 2002). Also, the extensive geographical scale of large restoration programs often encompasses substantial environmental variation which can make it difficult to determine if observed patterns are caused by implemented actions or environmental factors.

Extensive investment and limited assessment characterize restoration efforts on the Sacramento River, in north-central California. Over the past two and a half decades, the CALFED Ecosystem Restoration Program (ERP) and other entities (e.g., California Wildlife Conservation Board, National Oceanographic and Atmospheric Administration—Fisheries, National Fish and Wildlife Foundation, and private corporations), have invested significant resources in conservation and restoration of terrestrial and aquatic resources in this area (CALFED 2000a). Yet, to date, comprehensive evaluations of the effectiveness of implemented actions have been limited. Isolated studies have been useful in examining the response of specific ecosystem components (e.g., Alpert et al. 1999; Griggs and Golet 2002; Holl and Crone 2004; Borders et al. 2006); however, integrated assessments of progress toward established goals have not been conducted. Unfortunately, this is not uncommon. In a review of U.S. river restoration efforts, Bernhardt et al. (2005) found that only 10% of projects had any form of assessment or monitoring, although the percentage may be higher for large projects than for small ones.

In a retrospective evaluation of ERP-funded restoration projects, Kleinschmidt and Jones & Stokes (2003) concluded that a lack of agreed-upon indicators and the absence of an overall framework for evaluation made it difficult to assess performance. They strongly recommended development and implementation of a multilevel framework for measuring performance, deemed necessary because the ERP had not yet adopted a way to evaluate performance at the program, project, or ecosystem levels. Layzer (2008) also noted that CALFED's approach to performance measurement was limited; "Even where measures were adopted... it was too difficult to get consensus on outcome-level metrics, so the program relented and measured outputs instead" (Layzer 2008, p 159-160). Outputs included parameters such as number of projects funded, total dollars spent, and acres of habitat planted (Kleinschmidt and Jones & Stokes 2003). Measuring only outputs resulted in an inability to demonstrate return on investment (Little Hoover Commission 2005), a failing that ultimately contributed to CALFED losing much of its funding (Layzer 2008). Even now, with enough time having passed to manifest the ecological responses, there has been little synthesis of information. Consequently, many of the restoration program's successes and failures have gone unrecognized, and the reasons underlying each remain obscure.

In this paper, we begin to fill this information gap by synthesizing a suite of quantitative ecological indicators (outcome-level metrics) to evaluate the success of restoration of the middle Sacramento River. Individual indicators developed and applied in our study characterize the status of terrestrial and floodplain resources (including flora and fauna) and channel dynamics (including planform, geomorphology, and flow regime parameters). They do not directly represent aquatic resources such as fish; however, they do characterize habitat elements and physical processes that are important to aquatic biota.

We evaluated restoration success in two complementary ways. Both involved evaluations of trend data derived from quantitative ecological indicators. First, indicators were associated with six broad ecosystem elements (e.g., terrestrial riparian habitats, fluvial and geomorphic processes), and second, they were aligned with specific goals of the CALFED Ecosystem Restoration Program (CALFED 2000a). In both instances the collective weight of evidence from the relevant indicators was used to assess success.

In conducting our indicator assessment we both collected new data and analyzed existing information. Because this system has been intensively studied, we had a wealth of previously collected data to draw from. Although information was not available on every attribute that might characterize a riparian restoration project, our set of indicators is robust, and the picture it presents of the status and trends of the Sacramento River riparian ecosystem is compelling. Our analysis identifies areas where significant progress has been made, and areas where it has not. Based on these findings, we identify specific actions to advance the restoration of the river in the years to come. Because many of the factors that have impeded the progress of restoration on the Sacramento River are common to other rivers, recommendations that we make for future emphasis may be applicable elsewhere.

BACKGROUND

Study Area and Anthropogenic Alterations

The Sacramento River is California's largest river, supplying approximately 80% of freshwater flowing into the Sacramento and San Joaquin River Bay–Delta (California State Lands Commission 1993). The 62,000 km^2 watershed is the single most important source of water for Californians, and provides critical habitat for a wide variety of species. Historically, the river was lined by approximately 325,000 hectares of riparian forest; however, over 95% of this habitat has been lost to logging, agriculture, urban development, flood control, and power generation projects (Katibah 1984). Levees and riprap further degrade the habitat by confining two-thirds of the river's linear extent. Channelization, bank protection, and the construction of Shasta Dam severely constrain the river's natural processes that promote habitat succession and regeneration. Cumulatively, these changes have greatly stressed the Sacramento River ecosystem leading to reduced wildlife populations and invasion and proliferation of non-native invasive species.

The watershed is under the influence of a Mediterranean climate that is strongly affected by El Niño Southern Oscillation and Pacific–North America teleconnection climatic patterns (Redmond and Koch 1991; Cayan et al. 1999). The watershed typically experiences hot, dry summers and variably wet winters, with periods of drought. Several large foothill storage reservoirs alter the natural flow regime in the Sacramento River. These were primarily designed to store spring snowmelt for farmland irrigation and municipal needs, and to dampen the largest winter flood peaks; however, they are also managed to provide hydropower and recreation, and to meet habitat needs of listed fish species. An analysis of the influence of these storage reservoirs on downstream hydrology is presented in Singer (2007).

This study focuses on the Middle Sacramento River (Figure 1). Situated between the towns of Red Bluff and Colusa (~161 river km), this is an alluvial stretch of the river that still has some riparian habitat and hydraulically connected floodplain. The bed of the river is dominantly gravel-bedded in this reach, transitioning to sand downstream of Colusa (Buer et al. 1989; Singer and Dunne 2001, 2004; Singer 2008, 2010). Below Colusa, levees entirely confine the river along its banks. The middle stretch contains the entire 4,142-ha U.S. Fish and Wildlife Service (USFWS) Sacramento River National Wildlife Refuge, as well as the 1,526-ha California Department of Fish and Wildlife (CDFW) Sacramento River Wildlife Area.

Riparian conservation and restoration efforts have primarily focused on this reach because the degradation that the river has experienced here is largely reversible. Farms (as opposed to human settlements) have replaced floodplain forests, and levees, where present, are often set back from the river by appreciable distances. Along some stretches of this historically meandering reach of the river, bank revetment (riprap) is absent and the natural processes of bank erosion and point bar deposition are still intact.

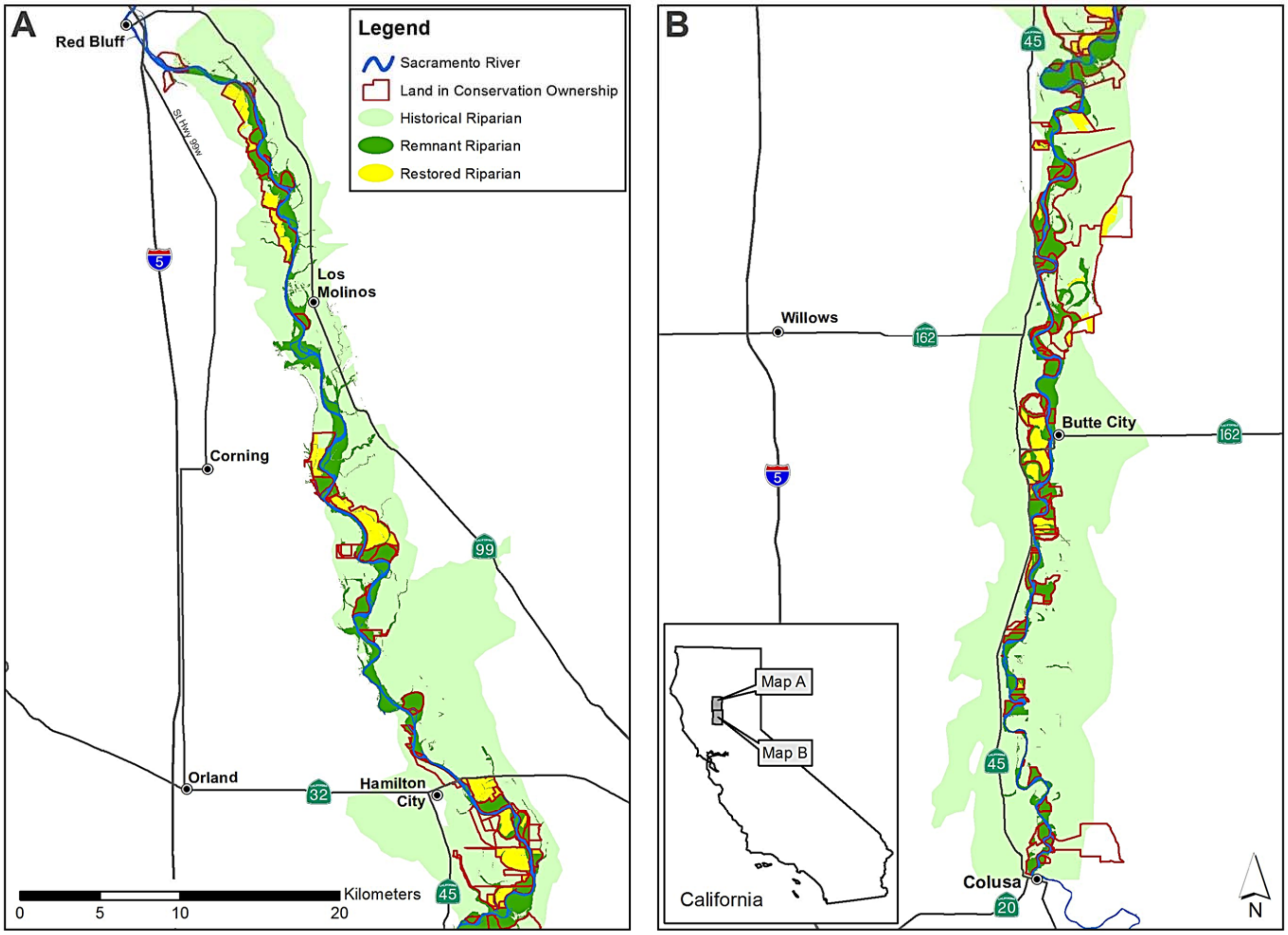

Figure 1 Map of conservation lands in the 161 river km Sacramento River Project area, located between the towns of Red Bluff and Colusa: (A) northern portion of the project area; (B) southern portion of the project area. Also shown are remnant and restored habitats and the historical riparian zone, drawn from an interpretation of the Holmes and Nelson (1916) soil map.

At-risk Species

The loss of riparian habitat along the Sacramento River has caused local extirpations and threatens the persistence of important native species. The most well-known imperiled species are anadromous fishes (e.g., salmonids and sturgeons); however, a suite of terrestrial taxa, including mammals, birds and insects are also at risk. Among the special-status mammals are rare and ecologically important bat species [e.g., the western mastiff bat (*Eumops perotis*) and yuma myotis (*Myotis yumanensis*)]. Several migratory birds have declined or have experienced range retractions, including the western yellow-billed cuckoo (*Coccyzus americanus occidentalis*), bank swallow (*Riparia riparia*), yellow-breasted chat (*Icteria virens*), yellow warbler (*Dendroica petechia*) and Swainson's hawk (*Buteo swainsoni*). Birds that no longer reproduce along the river include least Bell's vireo (*Vireo bellii pusillus*) and willow flycatcher (*Empidonax trailii*) (Gaines 1977; Shuford and Gardali 2008; Howell et al. 2010). The valley elderberry longhorn beetle (*Desmocerus californicus dimorphus*, VELB), is a federally threatened, endemic species of the Central Valley that is absent from large areas within its historical range (CALFED 2000b).

Restoration Vision for the Sacramento River Ecological Management Zone

The overall vision for the Sacramento River Ecological Management Zone is expressed in the CALFED Ecosystem Restoration Program Plan (CALFED 2000a):

> To improve, restore, and maintain the health and integrity of the Sacramento River riverine-riparian and tributary ecosystems to provide healthy conditions for sustainable fish and wildlife populations and the plant communities on which they depend.

As described in the plan, the path to achieving this vision is through preservation and restoration of erosional and depositional channel and floodplain-forming processes, riparian and wetland habitats, spawning gravel recruitment, and reducing the extent and influence of stressors. It includes goals of restoring elements of the natural flow regime in support of native species and communities. In addition to the overall vision for the ecological management zone, the Restoration Program Plan developed specific vision statements for the two ecological management units that comprise the Sacramento River Project area (Box 1).

Implemented Restoration

Although severely degraded, the Sacramento River is still one of the most diverse and extensive river ecosystems in California. It is composed of a rich, although fragmented, mosaic of aquatic habitats, oxbow lakes, sloughs, seasonal wetlands, riparian forests, valley oak woodlands, and grasslands. A striking feature of the Sacramento River is the potential for restoration that it presents. Recognizing this potential, and in an effort to restore habitat as well as viable populations of resident and migratory birds, VELB, anadromous fish, and other wildlife, government and non-government organizations have implemented a series of restoration programs[a] along the river.

The Nature Conservancy (TNC) began planting native woody trees and shrubs on Sacramento River floodplain lands in 1989 (Alpert et al. 1999), and in 2000, an understory component was added to the planting palette. Current restoration projects include up to 33 species (see Table 3 in Golet et al. 2008). In total, as of 2012, over 2,500 hectares of riparian habitat have been planted (Figure 2), compared to the 6,000 hectares called for under ERP Milestone 60 (USFWS et al. 2004). Sacramento River riparian restoration costs approximately $12,300 per ha (TNC, unpublished data). Thus over $30 million dollars were invested in restoration plantings over 23 years.

Monitoring of Ecosystem Response to Restoration on the Middle Sacramento River

Localized surveys confirm the success of restoring Sacramento River riparian habitats for wildlife (Holl and Crone 2004; Gardali et al. 2006; Gardali and Nur 2006; Small et al. 2007; Williams 2007, 2010; Golet et al. 2008, 2011, 2013; Gardali and Holmes 2011; McClain et al. 2011). However, previously implemented projects need more comprehensive assessment. This requires examining the ecosystem as a whole, including both restored and non-restored areas and the major physical processes (e.g., channel and floodplain processes) that drive ecosystem dynamics. The synthesis of indicator information presented in this paper provides an initial step in this direction.

METHODS

Ecological Indicators

To characterize the status of the riparian ecosystem and assess progress toward attaining ERP goals, we developed quantitative ecological indicators from data collected in remote sensing and field-based monitoring studies. A great variety of data were ana-

a The California State Legislature, in 1986, passed Senate Bill 1086, which mandated the development of a management plan to protect, restore and enhance riparian habitat along the Sacramento River and its tributaries. In response, the Sacramento River Conservation Area Forum (SRCAF) formed, and set as its primary goal the preservation of remaining riparian habitat and the reestablishment of a continuous riparian corridor from Red Bluff to Colusa (SRCAF 2003). The Nature Conservancy (TNC), and its agency partners (including the U.S. Fish and Wildlife Service, the California Dept. of Water Resources, the CA Dept. of Fish and Game, and the California Dept. of Parks and Recreation) have worked to implement many SRCAF conservation initiatives including horticultural restoration of the historical riparian floodplain. CALFED, the Wildlife Conservation Board, and the Central Valley Project Improvement Act's (CVPIA) Habitat Restoration Program supported riparian plantings, as well as the related expenses of land acquisition, restoration planning, research and monitoring. CALFED alone funded 2,300 hectares of habitat protection along the river between Red Bluff and Colusa (D. Burmester, CDFW, pers. comm.).

Box 1 Specific CALFED Ecosystem Restoration Program vision statements and interpretations for the two ecological management units that comprise the Sacramento River Project area (see Figure 1).

The Vision for the Red Bluff Diversion Dam to Chico Landing Ecological Management Unit:

> "To protect and expand the quantity and quality of the stream meander corridor; protect the associated riparian forest and allow it to reach maturity; to maintain flows that emulate the natural hydrology to the extent possible; and recover or contribute to the recovery of threatened, endangered, and special concern species. The existing meander belt should be protected and improved to sustain the riparian and riverine aquatic habitat component that is important habitat for riparian forest-dependent species, such as the yellow-billed cuckoo, other Neotropical migrant bird species, and the valley elderberry longhorn beetle."

In the interpretation of this vision statement, it is noted that restoring endangered species and species of special concern requires that water management activities be consistent with maintaining ecological processes. These include flows that emulate the natural hydrologic regime to the extent possible. Important considerations include flows needed to maintain natural stream meander processes, gravel recruitment, transport, deposition, and establishment and growth of riparian vegetation. It is further stated that the broad riparian corridors throughout the unit should be connected to support increased populations of Neotropical migrants. It is recognized that species such as the bank swallow will benefit from the restoration of processes that create and maintain habitat within this unit (CALFED 2000b).

The Vision for the Chico Landing to Colusa Ecological Management Unit:

> "To improve habitat and increase survival of many important fish and wildlife resources by preserving, managing and restoring a functioning ecosystem that provides a mosaic of varying riparian forest age classes and canopy structure; maintaining a diversity of habitat types, including forest and willow scrub, cut banks and clean gravel bars, oxbow lakes and backwater swales with marshes, and floodplain valley oak/sycamore woodlands with grassland understory; maintaining uninterrupted gravel transport and deposition; supporting a complexity of shaded and nearshore aquatic substrate and habitats with well-distributed instream woody cover and organic debris; setting back levees. Closing gaps in the shoreline riparian vegetation and nearshore aquatic habitat will be accomplished by several means. These include natural colonization or active restoration of expanded floodplain along channels. The continuance of natural river migration within its meander zone is essential to create and maintain most of these habitats."

The ERP calls for employing a mix of solutions to reduce the need for future additional bank protection or separation of the channel from its floodplain. One such solution is strategic levee setbacks. According to the program plan, in this unit, broad riparian corridors should be interconnected with narrower corridors that are not subject to fragmentation. These corridors should connect larger blocks of riparian habitat—typically larger than 20 ha—to support the river's natural cooling by convection currents of air flowing from the cool, humid forests and across the river water. The wider riparian corridors should generally be greater than 100 m wide to support Neotropical migrants, such as the yellow-billed cuckoo. Cavity nesting species, such as wood duck (*Aix sponsa*), and special-status species, such as bank swallow, will benefit from restoring the processes that create and maintain habitat within this unit (CALFED 2000b).

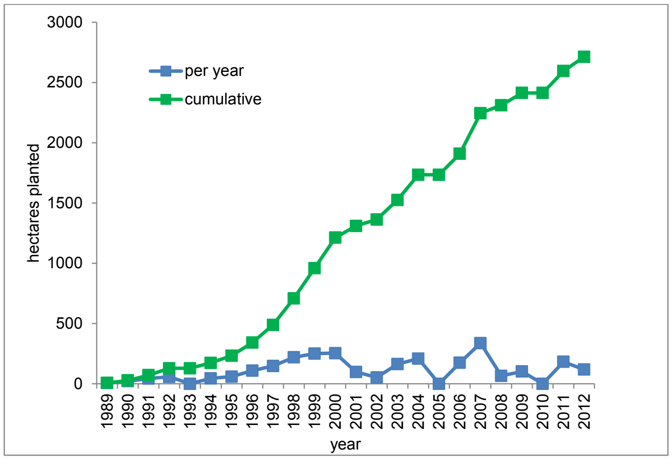

Figure 2 Cumulative and per-year hectares of riparian habitat restored by TNC and River Partners through horticultural restoration on the Sacramento River between Red Bluff and Colusa. A small amount of additional land has been restored by other entities.

lyzed. Included indicators represent the extent and condition of different riparian habitat types, wildlife species abundances, species richness, percent occupancy, community composition, species distribution, fecundity, growth, survival, reproductive success as well as geomorphic and hydrologic attributes. In total, 36 ecological indicators were included in this assessment.

Methods to compute each indicator are provided in individual indicator accounts (Appendix A). These accounts define the indicators and provide the rationale for each being a meaningful indicator of ecosystem health. In addition they summarize and often graphically display the results, and offer interpretations. Readers interested in reviewing details about the individual studies from which this synthesis is drawn should consult this appendix.

Sampling Sites

Field sampling locations for data collection varied by investigation (Appendix A), but all were located within the Middle Sacramento River, between the Red Bluff Diversion Dam and the Colusa Bridge (hereafter the "study reach," see Figure 1). An exception is the investigation of streamflow, which analyzed gauge data collected from a location upstream. This was done strategically, so that inferences could be made about conditions in the downstream study reach. Sampling was not necessarily sufficient in all cases to characterize the state of indicators across the entire study reach; however, all of the data included in our analyses are representative of some portion of the area.

All of the riparian restoration sites were previously in agriculture, most commonly as walnut orchards, before being revegetated with local ecotypes of indigenous trees, shrubs and understory species. For information on revegetation methods and approaches see Griggs and Peterson (1997) and Alpert et al. (1999). Restoration sites are located in low lying floodplain areas embedded in a landscape matrix of natural remnant habitats, fallow land and agriculture (see Figure 1 in Holl and Crone 2004); none are close to urban areas or dense residential settlements. Surrounding agriculture primarily consists of orchards, and row and field crops, although a few areas are managed as irrigated pasture for livestock.

Study Designs

To collect data and analyze the various indicators, we used a variety of sampling methods and study designs (Appendix A). Some indicator studies focused on status and trends at restorations sites (see Figure 1), while others examined larger landscape processes and patterns.

Studies of restoration sites that were designed to characterize trajectories of change took several different approaches. Some compared restoration sites of different ages (see Figure 3 in Golet et al. 2008); others compared restoration sites with remnant riparian forests or agricultural sites. Remnant sites have vegetation that naturally recruited, and were never cleared or used for agriculture. Comparisons among different site types (restoration, remnant, and agriculture) are informative because they enable us to determine if characteristics of restoration sites are more similar to patterns observed at remnant forest sites than at agricultural sites. If so, then this is one measure of restoration success. It is understood, however, that conditions in remnant forests are not ideal.

To varying degrees, they are isolated and invaded by non-native species.

Synthesis of Indicator Data

We synthesized indicator information in two ways. First, we assessed what all relevant indicators convey about the status and trends of six ecosystem components: (1) riparian habitats, (2) native plant species and communities, (3) invasive riparian and marsh plants, (4) birds and other wildlife, (5) streamflows and flood processes, and (6) river planform and geomorphic processes. We ranked trend information for each ecosystem component—as strongly positive, positive, neutral (no difference), negative, or strongly negative—based upon the status and trends of the individual indicators collectively.

Second, we synthesized relevant indicators to characterize progress toward specific CALFED Ecosystem Restoration Program goal statements. These statements were grouped into three main categories: (1) habitats and vegetation, (2) wildlife, and (3) natural river processes. For each stated ERP goal we assigned qualitative progress rankings of "Poor," "Fair," "Good," and "Very Good," based on combined evidence derived from analyses of the associated indicators.

Whereas all of the ecological indicators that were included in our analyses contributed important information, the strength of evidence that individual indicators provided differed considerably. Some were calculated from data that were collected over a long time span and/or at numerous sites (including both restoration and reference habitats), while others were based on shorter term or less intensive investigations. For example, songbird data were first collected in 1993, whereas the first geomorphic data analyzed were from the early 1900s. Thus, for some indicators, only recent patterns can be described; for others, current trends can be set in an historical context.

As well, some indicators have a more direct conceptual linkage than others to the particular ecosystem element or ERP goal that they are meant to represent. As a result, not all of the included indicators are equally robust. To address this issue in our synthesis, we did not apply any formalized weighting scheme. Instead we used our best professional judgment in a collective weight of evidence approach that sought to take into account the different factors that influence the information value that each indicator provided. Thus, even though the data that are used in our assessments are highly quantitative and were derived through objective studies, the summarized rankings we report are subjective. Regardless, for any given ecosystem element or goal statement, most indicators were in agreement. Thus, our judgments of the relative importance of different indicators had little influence on the overall rankings assigned in the assessments.

SPECIFIC ERP VISION STATEMENTS AND ASSOCIATED ECOLOGICAL INDICATORS

Below are specific goal statements that were presented in the ERP Program Plan (CALFED 2000b), followed by relevant indicators. The geographical area of inference for all indicators is the Sacramento River riparian corridor between Red Bluff and Colusa. Brief explanatory text is included below for individual indicators, although the reader is referred to Appendix A for more comprehensive definitions. Appendix A also provides the rationale for why particular indicators are meaningful, the methods for quantifying them, and detailed results. Although we selected these indicators to characterize the status of ecological resources on the Sacramento River, many could be applied to other alluvial rivers, either in their current form, or with slight modification.

Habitats and Vegetation

Riparian and Riverine Aquatic Habitats. The goal is to maintain and restore extensive areas of riparian and riverine aquatic habitats. This entails providing conditions for riparian vegetation growth along channelized portions of the Sacramento River, increasing the ecological value of low-to moderate-quality shaded riverine aquatic (SRA) habitat by changing land use and land management practices, and maintaining existing streamside riparian vegetation.

Associated Ecological Indicators

- *Forest Patch Core Size.* This is a landscape pattern indicator (derived by FRAGSTATS, McGarigal and Marks 1994) defined as the size of the forest patch, minus the edge effect zone.
- *Forest Patch Proximity.* This is a FRAGSTATS landscape pattern indicator defined as the proximity of a forest patch relative to other forest patches. It is the corollary of patch isolation.
- *Forest Edge Contrast.* This is a FRAGSTATS landscape pattern indicator defined as the structural contrast between forest habitat and other adjoining habitat types. For example, a high contrast edge is found between a row crop field and a remnant patch of mature riparian forest, while a low contrast edge is present between mature riparian forest and older restored riparian forest.
- *Percent of Historical Riparian Zone Currently in Conservation Ownership.* The historical riparian zone is defined based upon the Holmes and Nelson (1916) soil map of the Sacramento River Valley (see Figure 1). Conservation ownership includes both agency and non-governmental organization lands that are managed for their habitat values.
- *Percent of Historical Riparian Zone Currently in Natural Habitat.* Natural habitat includes remnant areas and restoration sites.
- *Percent of Riparian Shoreline Bordered by >500 m of Natural Habitat.*
- *Number of In-channel Large Woody Debris Aggregations.* This is based on mapping of in-channel large woody debris aggregations that were observed near or above the surface on aerial photographs.
- *Soil Organic Carbon.* This is the percent of carbon in the soil.

Native Plant Species and Communities. The goal for plant species and communities is to protect and restore these resources in conjunction with efforts to protect and restore wetland and riparian and riverine aquatic habitats.

Associated Ecological Indicators

- *Areal Extent of Native Vegetation.* This is the area mapped as annual and perennial grassland, Fremont cottonwood (*Populus fremontii*) forest, mixed riparian forest, riparian scrub, and valley oak (*Quercus lobata*) woodland from visual interpretation of georectified aerial photographs.
- *Basal Area of Woody Species.* This is the total cross-sectional area of woody species within a plot. It includes all tree species as well as shrubs with woody stems such as willows (*Salix* spp.), blue elderberry (*Sambucus caerulea*), and coyote brush (*Baccharis pilularis*).
- *Frequency of Woody Species in Various Size Classes.* This is the frequency distribution of stem diameters of the major native tree species in this system [i.e., Fremont cottonwood, valley oak, box elder (*Acer negundo*), and Goodding's black willow (*Salix gooddingii*)].
- *Importance Value of Woody Species.* Importance value for a species is defined as the sum of relative density + relative basal area. This parameter was calculated for all native tree species as well as shrubs with woody erect stems such as willows, elderberry, and coyote brush.
- *Native Understory Frequency of Occurrence.* Native understory species frequency of occurrence is the proportion of quadrats in which at least one native species is present.
- *Native Understory Species Richness.* Native understory species richness is the number of native herbs, shrubs, and vines observed. It does not include tree species seedlings which may be found in the understory.
- *Relative Native Understory Cover.* Relative native understory cover is the percent native cover divided by percent total cover.

Invasive Riparian and Marsh Plants. The goal is to reduce the spread or eliminate invasive non-native riparian species such as giant reed (*Arundo donax*) and salt cedar (*Tamarix ramosissima*) that compete with native riparian vegetation.

Associated Ecological Indicators

- *Areal Extent of Giant Reed.* The areal extent of this plant species (and those listed below) was mapped from visual interpretation of geo-rectified aerial photographs.
- *Areal Extent of Himalayan Blackberry (Rubus discolor).*
- *Areal Extent of Water Primrose (Ludwigia peploides).*
- *Importance Value of Black Walnut.* Importance value is defined as the sum of relative density + relative basal area.

Wildlife

Neotropical Migratory Birds. The goal for Neotropical migratory birds is to maintain their diversity, abundance and distribution by protecting and restoring riparian and riverine aquatic habitats upon which they depend. Wide riparian corridors or patches should be created to help reduce brown-headed cowbird (*Molothrus ater*) predation. Specific goals for yellow-billed cuckoo and bank swallow are listed separately.

Western Yellow-billed Cuckoo. The goal for the yellow-billed cuckoo is to contribute to the recovery of this state-listed endangered species. Potential habitat for the cuckoo should be expanded by protecting and restoring riparian and riverine aquatic habitats, restoring ecosystem processes and functions, and reducing or eliminating stressors. Restoration of riparian woodlands along the Sacramento River for cuckoos should focus on natural stream meander, flow, and natural revegetational/successional process.

Bank Swallow. The goal for the bank swallow is to contribute to the recovery of this state-listed threatened species. Potential habitat for bank swallows will be improved by sustaining the river meander belt and increasing the coarse sediment supply to support meander and natural sediment erosion and deposition processes.

Associated Ecological Indicators

- *Nest Survival of Black-headed Grosbeak (Pheucticus melanocephalus), Lazuli Bunting (Passerina amoena), and Spotted Towhee (Pipilo maculatus).*[b] Nest survival for these landbirds is defined as the probability of a nest with egg(s) fledging at least one chick.
- *Adult Survival of Black-headed Grosbeak and Spotted Towhee.* Apparent adult survival for these landbirds is defined as the probability that an adult will survive from one year to the next.
- *Landbird Species Richness.* Landbird species richness is defined as the number of landbird species detected.
- *Abundance of Black-headed Grosbeak, Common Yellowthroat (Geothlypis trichas), Yellow Warbler (Dendroica petechial), and Yellow-breasted Chat (Icteria virens).* Abundance for these landbirds is defined as the number of birds per hectare during the breeding season.
- *Number of Occupied Yellow-billed Cuckoo Territories.*
- *Number of Bank Swallow Nest Burrows.* This is defined as the total number of active nest burrows at bank swallow colonies.
- *Number of Bank Swallow Nesting Colonies.* This is defined as the total number of bank swallow colonies with active nest burrows.

Valley Elderberry Longhorn Beetle. The goal for the valley elderberry longhorn beetle (VELB) is to recover this federally threatened species by increasing its populations and abundance through restoration of riparian systems.

Associated Ecological Indicators

- *Number of VELB Exit Holes per Shrub.* This is defined as is the average number of recent VELB exit holes per elderberry shrub.

Other Wildlife. The ERP Program Plan (CALFED 2000b) is limited in terms of the components of terrestrial biodiversity that it captures in its goal statements.

b Because of the availability of valuable data, this avian species is included even though it is a resident, as opposed to a migrant.

Even so, it is evident from the plan, as well as from supporting documents (e.g., the Multi-Species Conservation Strategy, CALFED 2000a) that the program seeks to advance a whole systems approach to restoration. In recognition of this, we included four additional indicators in our analyses from three otherwise unrepresented taxonomic groups. These indicators provide valuable perspectives on the status and trends of terrestrial riparian biodiversity on the Sacramento River.

Associated Ecological Indicators

- *Bee Species Richness.* This is the total number of different species of bees detected.
- *Bee Abundance.* This is defined as the total number of bees occurring in a standard 1-ha area.
- *Beetle Species Richness.* This is defined as the total number of different morphospecies of ground beetles occurring in the area. Morphospecies are the lowest taxon that can be distinguished based on morphology, and are surrogates for species (Oliver and Beattie 1996).
- *Bat Abundance.* This is an index defined based on the number of bat calls detected in a given time interval.

Natural River Processes

Central Valley Streamflows. The goal for flow patterns is to more closely emulate the seasonal and inter-annual streamflow patterns. This can be attained through supplemental short-term releases from the major storage reservoirs to provide flows that emulate natural peak flow events.

Natural Floodplain and Flood Processes. The goal is to maintain existing areas where the Sacramento River seasonally inundates its floodplain and to reestablish this seasonal inundation in additional areas. This entails increasing and maintaining floodplains in conjunction with stream meander corridor restoration and restored flow releases.

Associated Ecological Indicators

- *Average Number of Years per Decade without Bed Mobilization.* This is defined as the number of years (over the previous decade) in which there were no flows >55,000 cfs.
- *Average Number of Days per Year with Bed Mobilization.* This is defined as the number of days per year, averaged over the previous decade, with flows >55,000 cfs.
- *Average Number of Years per Decade without Floodplain Inundation.* This is defined as the number of years (over the previous decade) in which there were no flows >70,000 cfs.
- *Average Number of Days per Year with Floodplain Inundation.* This is defined as the number of days per year, averaged over the previous decade, with flows >70,000 cfs.
- *Average Number of Days per Year with Side Channel Connection Flows.* Side channels are connected to the main stem at flows between 5,000 and 50,000 cfs. This indicator considers separately the 10-year running averages of the number of days per year with flows >15,000 cfs, >50,000 cfs, and dry-season flows (from July 15 to September 30) >5,000 cfs.

Stream Meander. The goal is to maintain and preserve existing areas of meander and to reactivate meander in other areas that bank protection activities impair. This entails preserving and improving the existing stream meander belt in the Sacramento River between Red Bluff and Colusa by purchase of fee title or through easements.

Levees, Bridges, and Bank Protection. The goal is to modify or remove structures in a manner that greatly lessens adverse effects on ecological processes, habitats and aquatic organisms. This entails constructing setback levees along leveed reaches of the river as part of the stream meander corridor restoration.

Associated Ecological Indicators

- *Area of Floodplain Reworked.* This is defined as the amount of newly created floodplain that formed from lateral migration over a given time-span.
- *Length of Bank with Riprap.* This is defined as the total length of riverbank that is hardened with revetment.
- *Whole River Sinuosity.* This is defined as the sum of the arc lengths for all bends divided by the sum of the half wave lengths. The arc length and half wave length are both measured between successive inflection points of single bends.
- *Total Channel Length.* This is defined as the distance along the channel centerline.
- *Average Bend Entrance Angle.* This is defined as the average bend entrance angle for all segments of the river. Segments are separated by subsequent inflection points. The angle is defined by the line that connects the bend inflection point and a tangent to the channel centerline at the next upstream inflection point.
- *Length of River with Conservation Ownership on Both Banks.* This is defined as the length of the river that has land in conservation ownership on opposing banks.

RESULTS

Below we summarize the results of the indicator investigations in terms of what they reveal about the status and trends of the six riparian ecosystem components (Table 1), and the amount of progress that has been made toward the goals of the CALFED Ecosystem Restoration Program. Although especially noteworthy findings are highlighted, the reader is referred to the Results and Interpretations sections of the individual indicator accounts (Appendix A) for more complete presentations of findings.

Status and Trends of Riparian Ecosystem Components

A. Riparian Habitats

The overall trend in riparian habitats is positive (Table 1A). Especially noteworthy is the >600% increase in forest patch core size that has taken place from 1999 to 2007, and the 43% increase in the percent of the river that has a border of natural habitat >500 m wide. These statistics speak to the success of the horticultural restoration program in building large blocks of connected habitat along the river corridor.

The 48% increase in forest edge contrast from 1999 to 2007 was likely the result of new forest establishment in areas that adjoin agriculture. For core forest-dependent species, an increase in edge contrast is expected to extend adverse edge effects into the forest patch interior; however, in this case, the impact is likely offset by increases in overall patch size.

A substantial (48%) reduction was observed from 1999 to 2007 in the number of large woody debris aggregations in the river. Although such a decline could be caused by a reduction in river meander, we suspect that in this instance the decline was caused by differences in flooding patterns in the years preceding data collection. Large and sustained overbank flows in 1997 may have delivered woody debris that remained in the river through 1999. No similar flood events preceded the 2007 sampling period.

Between 1999 and 2007 the percent of the historical riparian zone in natural habitat increased 11%, and the percent in conservation ownership increased at least 35%. The increase in habitat reflects the implemented restoration, and the more substantial increase in conservation ownership land illustrates that additional properties have been acquired but are yet to be restored.

B. Native Plant Species and Communities

The overall trend in native plant species and communities is positive (Table 1B). Areal cover of native vegetation in the historical riparian zone, between Red Bluff and Colusa, increased by at least 16% from 1999 to 2007 (Table 2). It likely increased by considerably more than this because some of the areas that were categorized as cottonwood forest, valley oak woodland, and black walnut (a non-native species) in 2007 were coded as mixed riparian in 1999. This must be considered when interpreting the apparent decline in mixed riparian forest, as well as the pronounced increases in some of the other vegetation categories between 1999 and 2007.

In total ~25% of the area mapped as riparian habitat was found on restoration sites. These sites contained disproportionately high percentages of the total area mapped as valley oak (41%) and Fremont cottonwood (35%).

At restoration sites, basal area of native woody species increased by an average of 95% in 5 years (Figure 3). At the restoration-site level, there was substantial variability, with forest development at some sites being hindered by poor soils. Nonetheless, this increase suggests that woody species are responding favorably to growing conditions at many of the restoration sites.

Comparisons between restoration sites and remnant habitat revealed that the size distributions of woody shrubs and trees are becoming more similar. The importance of certain species that provide valuable wildlife habitat (e.g., valley oak) increased at restoration sites over time. However, some species such as blue elderberry and western sycamore declined in importance value as other species, such as coyote bush and box elder, increased in prominence in the riparian community.

Native understory cover and frequency did not increase consistently at restoration sites over a 6-year period. Overall native cover increased 12%, but values were highly variable across sites. Where native cover increased, it was largely from increases in bedstraw (*Galium aparine*), a single, widespread spe-

Table 1 Synthesis of ecological indicator data from studies of the Middle Sacramento River (between Red Bluff Diversion Dam and Colusa Bridge) partitioned into six categories. To characterize magnitudes of change over time, the percent increase or decrease in each indicator is reported (along with starting values, in parentheses). The trend column indicates whether or not the observed results suggest a favorable trajectory of change. A "+" indicates positive result, a "–" indicates a negative result, and a "0" indicates no change. Multiple symbols indicate strong or mixed results. For Streamflows and Flood Processes (E), and Planform and Geomorphic Processes (F), data were analyzed over a long time span, and thus results can be presented both for recent decades, and for the long term (in parentheses). Long-term trends are useful for setting the historical context. Detailed information regarding each indicator, including definition, rationale, methods, results and interpretations is provided in Appendix A.

(A) RIPARIAN HABITATS

Ecological indicators	Geographic study area	Temporal horizon	Results	Sources	Trend
Forest patch core size	Riparian zone between Red Bluff and Colusa	1997 and 2007	Increased by 610% (from 12 ha)	Schott and Shilling (unpublished)	++
Forest patch proximity	Riparian zone between Red Bluff and Colusa	1997 and 2007	Increased by 1,215% (from 16)	Schott and Shilling (unpublished)	+
Forest edge contrast	Riparian zone between Red Bluff and Colusa	1997 and 2007	Increased by 48% (from 49)	Schott and Shilling (unpublished)	-
Percent of historical riparian zone currently in conservation ownership	Riparian zone between Red Bluff and Colusa	1999 and 2007	Increased 35% to 43% (from 6,830 ha)	Golet and Paine (unpublished)	++
Percent of historical riparian zone currently in natural habitat	Riparian zone between Red Bluff and Colusa	1999 and 2007	Increased by 11% (from 4,406 ha)	Golet and Paine (unpublished)	+
Percent of riparian shoreline bordered by >500 m of natural habitat	Shoreline between Red Bluff and Colusa	1999 and 2007	Increased by 43% (from 16%)	Golet and Paine (unpublished)	++
Number of in-channel large woody debris aggregations	Mainstem river channel between Red Bluff and Colusa	1999 and 2007	Decreased by 48% (from 738)[a]	Golet and Paine (unpublished)	- -
Soil organic carbon	Restoration and remnant sites of varying ages	All four seasons 2000 – 2001	Increased with age since restoration	Brown and Wood (2002)	+
Overall					**+**

[a] The amount of wood in the river may have been unusually large in 1999 because of large and sustained overbank flows in 1997.

Table 1 Continued

(B) NATIVE PLANT SPECIES AND COMMUNITIES

Ecological indicators	Geographic study area	Temporal horizon	Results	Sources	Trend
Areal extent of native vegetation	Riparian zone between Red Bluff and Colusa	1999 and 2007	Increased by ≥16% (from 6,836 ha)	Nelson et al. 2008	+
Basal area of woody species	Restoration and remnant sites of varying ages	2003 and 2008	Increased by 95% at restoration sites (from 6.5 m^2 ha)	Wood (unpublished)	++
Frequency of woody species in various size classes	Restoration and remnant sites of varying ages	2002, 2003, 2006, and 2008	Distributions among size classes became more similar between restoration sites and remnant habitats	Wood (unpublished)	+
Importance value of woody species	Restoration and remnant sites of varying ages	2003 and 2008	Increases in coyote brush: (198%, from 5), box elder (47%, from 9), valley oak (12%, from 58), and Gooddings black willow (7%, from 7)	Wood (unpublished)	+
			Decreases in arroyo willow: (6%, from 43), blue elderberry (21%, from 50), Fremont cottonwood (4%, from 17) and western sycamore (20%, from 7)		–
Native understory frequency of occurrence	Restoration and remnant sites of varying ages	2001 and 2007	Increased at restoration sites by 16% (from 48.1%)	Holl and Crone 2004; McClain et al. 2011	+
			Values still far below remnant (87%)		0
Native understory species richness	Restoration and remnant sites of varying ages	2001 and 2007	Increased at restoration sites by 43% (from 4.7 species)	Holl and Crone 2004; McClain et al. 2011	+
			Values still far below remnant (10.1 species)		0
Relative native understory cover	Restoration and remnant sites of varying ages	2001 and 2007	Increased at restoration sites by 56% (from 21%)	Holl and Crone 2004; McClain et al. 2011	+
			Values still far below remnant (65%)		0
Overall					**+**

(C) INVASIVE RIPARIAN AND MARSH PLANTS

Ecological indicators	Geographic study area	Temporal horizon	Results	Sources	Trend
Areal extent of giant reed [b]	Riparian zone between Red Bluff and Colusa	1999 and 2007	Increased by 11% (from 49 ha)	Nelson et al. 2008	–
Areal extent of Himalayan blackberry [b]	Riparian zone between Red Bluff and Colusa	1999 and 2007	Increased by 37% (from 91 ha)	Nelson et al. 2008	– –
Areal extent of water primrose [b]	Riparian zone between Red Bluff and Colusa	1999 and 2007	Increased by 14% (from 137 ha)	Nelson et al. 2008	–
Importance value of black walnut [c]	Restoration and remnant sites of varying ages	2003 and 2008	Increased at restoration sites by 50% (from 0.4), but values still very low	Wood (unpublished)	–
Overall					**–**

b This indicator is described under the heading entitled "Areal Extent of Vegetation" in Appendix A.
c This indicator is described under the heading entitled "Importance Value of Woody Species" in Appendix A.

Table 1 Continued

(D) BIRDS AND OTHER WILDLIFE

Ecological indicators	Geographic study area	Temporal horizon	Results	Sources	Trend
Nest survival of black-headed grosbeak, lazuli bunting, and spotted towhee	Restoration and remnant sites of varying ages	1993 – 1999 for lazuli bunting; 1994 – 2003 for other species	Similar for all species at restored and remnant sites, but relatively low overall, especially for lazuli bunting (6%)	Golet et al. 2008	+
Adult survival of black-headed grosbeak and spotted towhee	Restoration and remnant sites of varying ages	1995 – 2000	Somewhat lower for both species at restoration sites than remnant sites	Gardali and Nur 2006	–
Landbird species richness	Restoration and remnant sites of varying ages	1993 – 2003	Increased by ~300% (from ~5 species) on average, as restoration sites matured, approaching levels at remnant sites	Golet et al. 2008	++
Abundance of black-headed grosbeak, common yellowthroat, yellow warbler, and yellow-breasted chat	Restoration and remnant sites of varying ages	1993 – 2003	Increased dramatically (although variably among species) as restoration sites matured, approaching levels at remnant sites	Gardali et al. 2006	++
Number of occupied yellow-billed cuckoo territories	Suitable breeding sites between Red Bluff and Colusa	2000 and 2011	Appeared to decline	Dettling and Howell 2011	–
Number of bank swallow nest burrows	Mainstem river between Red Bluff and Colusa	1999 – 2010, excluding 2006	3-year running average declined by 31% (from 17,963 burrows)	BSTAC 2013	– –
Number of bank swallow nesting colonies	Mainstem river between Red Bluff and Colusa	1999 – 2010, excluding 2006	No real trend is apparent in the data; however, the 3-year running average increased by 10% over the period of record.	BSTAC 2013	0/+
Number of VELB exit holes per shrub	Restoration sites of varying ages	2003	Older restoration sites had higher levels of VELB occupancy than younger sites	River Partners 2004	++
Bee species richness	8-yr old restoration sites and remnant habitats	February – August 2003	Restoration sites had similar (7% lower) richness to remnant sites	Williams 2010	+
Bee abundance	8-yr old restoration sites and remnant habitats	February – August 2003	Restoration sites had similar (26% higher) abundance to remnant sites	Williams 2010	+
Beetle species richness	Young restoration, older restoration and remnant habitats	December 2000 – November 2001	Remnant habitats had the most species and were more similar to older restoration sites than young sites	Hunt 2004; Golet et al. 2008	+
Bat abundance	Orchards, young and older restoration sites, and remnant habitats	September – October 2002	The older restoration site had higher levels of bat activity than the young restoration site	Stillwater Sciences et al. 2003; Golet et al. 2008	+
Overall					**0/+**

Table 1 Continued

(E) STREAMFLOWS AND FLOOD PROCESSES

Ecological indicators	Geographic study area	Temporal horizon	Results	Sources	Trend [g]
Average number of years per decade without bed mobilization [d]	Middle Sacramento River	1892 – 2010	Unchanged in recent decades	Kondolf and Rubin (unpublished)	0
			Increased by 113% (from 22%) relative to pre-dam conditions		(–)
Average number of days per year with bed mobilization [d]	Middle Sacramento River	1892 – 2010	Unchanged in recent decades	Kondolf and Rubin (unpublished)	0
			Decreased by 10% (from 8%) relative to pre-dam conditions, but highly variable from year to year		(0/–)
Average number of years per decade without floodplain inundation [e]	Middle Sacramento River	1892 – 2010	Unchanged in recent decades	Kondolf and Rubin (unpublished)	0
			Increased by 129% (from 2.8 years) relative to pre-dam conditions		(––)
Average number of days per year with floodplain inundation [e]	Middle Sacramento River	1892 – 2010	Unchanged in recent decades	Kondolf and Rubin (unpublished)	0
			Declined by 41% (from 4.4 days per year) relative to pre-dam conditions		(––)
Average number of days per year with side channel connection flows [f]	Middle Sacramento River	1892 – 2010	Unchanged in recent decades	Kondolf and Rubin (unpublished)	0
			Declined relative to pre-dam conditions for high and middle elevation side channels		(–)
			Greatly increased for low elevation channels		(––)
Overall					**0/(––)**

(F) RIVER PLANFORM AND GEOMORPHIC PROCESSES

Ecological indicators	Geographic study area	Temporal horizon	Results	Sources	Trend [g]
Area of floodplain reworked	Riparian zone between Red Bluff and Colusa	1906 – 2007	Decreased in recent decades	Larsen (unpublished)	–
			Highly variable over long term, although trending downward		(–)
Length of bank with riprap	Mainstem river channel between Red Bluff and Colusa	1936 – 2002	Increased in recent decades	Henderson (unpublished)	–
			Dramatic increase over long term, especially since the 1960s		(––)
Whole river sinuosity	Mainstem river channel between Red Bluff and Colusa	1906 – 2007	Increased slightly between 1997 and 2007	Larsen (unpublished)	0
			Decreased significantly (by 6% from 1.31) over the period of record		(–)
Total channel length	Mainstem river channel between Red Bluff and Colusa	1906 – 2007	Decreased in recent decades	Larsen (unpublished)	–
			Decreased significantly (by 4%, from 160,529 m) over the period of record		(–)
Average bend entrance angle	Mainstem river channel between Red Bluff and Colusa	1906 – 2007	Decreased since 1987 (to lowest value ever in 2007)	Larsen (unpublished)	–
			Decreased significantly (by 13%, from 46 degrees) over the period of record		(–)
Length of river with conservation ownership on both banks	Mainstem river channel between Red Bluff and Colusa	1999 and 2007	Increased by at least 71% (from 40,806 m)	Golet and Paine (unpublished)	+
Overall					**–– /(––)**

d This indicator is described under the heading "Frequency and Duration of Bed Mobility" in Appendix A.
e This indicator is described under the heading "Frequency and Duration of Floodplain Inundation" in Appendix A.
f This indicator is described under the heading "Duration of Connectivity of Former Channels" in Appendix A.
g Long-term trends are indicated in parentheses.

cies. Native understory species richness increased, but remained far below what was observed at remnant sites.

C. Invasive Riparian and Marsh Plants

The areal extent of invasive riparian and marsh plants increased from 1999 to 2007 (Tables 1C and 2). Especially noteworthy was the large (37%) increase in the area mapped as Himalayan blackberry. Giant reed and water primrose increased more moderately, by 11 and 14%, respectively. As noted above, differences in analysis methodology likely explain much of the reported increase in the areal extent of black walnut. Even so, analyses of field collected data (see importance value results) suggest that black walnut increased at least modestly at forest study plots.

D. Birds

The overall trend in birds is variable, although generally positive (Table 1D). Abundance and species richness of landbirds observed during the breeding season increased dramatically as restoration sites matured, approaching levels observed at remnant sites; however, not all species showed positive trends. Pronounced declines were observed in the number of bank swallow burrows on the river's cut banks (Figure 4), and the number of occupied yellow-billed cuckoo breeding territories declined during the past decade.

Restoration sites appeared to provide similar quality nesting habitat to remnant areas. Lazuli bunting, spotted towhee and black-headed grosbeak all had similar nest survival rates at restoration and remnant sites. However, adult survival for the latter two species was slightly lower at restored sites compared to remnant sites.

E. Other Wildlife

Other terrestrial wildlife showed more uniformly positive responses (Table 1D). Older restoration sites had higher levels of Valley elderberry longhorn beetle occupancy than younger sites. Bee abundance and species richness was similar at restored and remnant sites, and ground beetles at older restored sites had communities more similar to those at remnant sites than those at more recently planted sites. Finally, among bats, older restored sites had higher levels of

Table 2 Comparisons of area mapped as various vegetation classes in two time-periods from aerial imagery. Because mapping methodologies changed, not all values are strictly comparable (see text for details).

	Area mapped (ha)		
Vegetation class	**1999**	**2007**	**% Change**
Natives			
Annual and perennial grasses and forbs	1,386	1,779	28
Fremont cottonwood (*Populus fremontii*) forest	1,678	3,113	85
Mixed riparian forest	2,216	456	-79
Valley oak (*Quercus lobata*) woodland	663	1,594	140
Riparian scrub	893	972	9
Total	**6,836**	**7,913**	**16**
Non-native invasives			
Giant reed (*Arundo donax*)	49	55	11
Black walnut (*Juglans hindsii*)	91	1,027	1023
Water primrose (*Ludwigia peploides*)	137	157	14
Himalayan blackberry (*Rubus discolor*)	91	125	37
Total	**369**	**1,364**	**270**

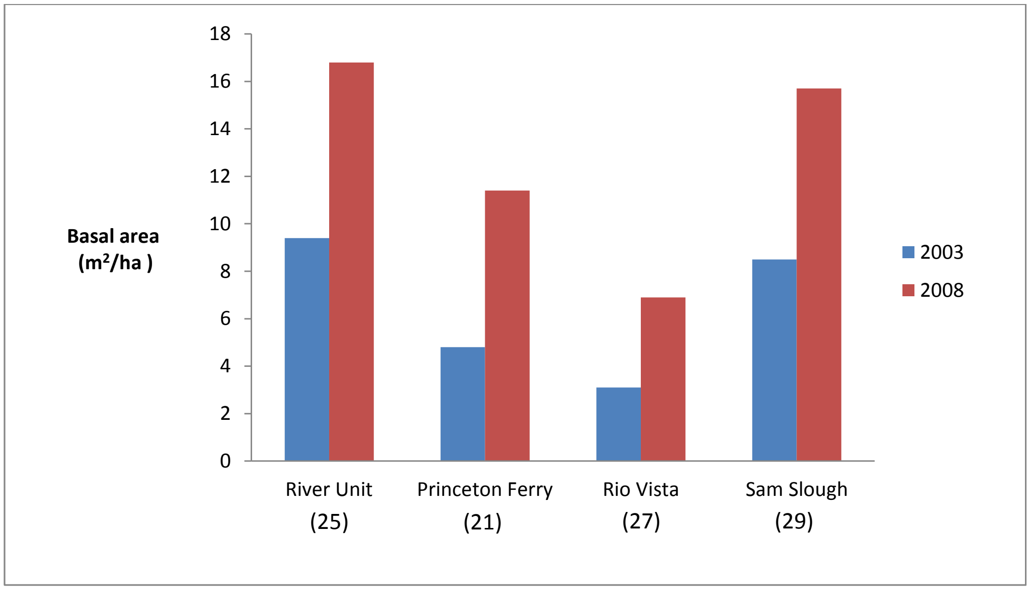

Figure 3 Basal area of woody species at Sacramento River restoration sites over two time periods.

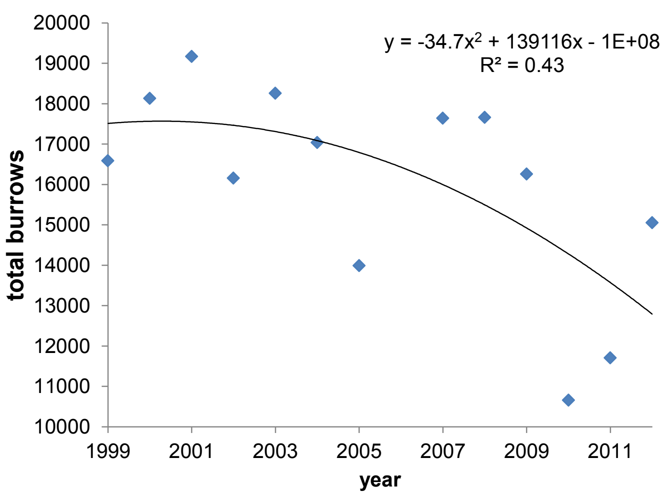

Figure 4 Bank swallow (*Riparia riparia*) burrow counts on the Sacramento River, Red Bluff to Colusa

activity than younger sites, suggesting that as the sites mature they provide better habitat for these species.

F. Streamflows and Flood Processes

There has been no discernible positive change in recent decades in streamflows and flood processes on the Middle Sacramento River (Table 1E). The degraded post-Shasta Dam (after 1944) conditions have remained. The number of years without bed mobilizing flows increased from 22% of pre-dam years to 47% of post-dam years. Also, since the construction of the dam, reductions have been seen in the number of days per year when the floodplain is inundated, and in the number of days when higher elevation side channels are connected to flows in the main channel (Figure 5).

G. River Planform and Geomorphic Processes

The overall trend in river planform and geomorphic processes is negative over the long term (1906 to 2007), although some of the indicators (e.g., total river length, whole river sinuosity, number of higher sinuosity bends) show a positive or stable pattern in recent years (Table 1F). The recent trend included a reprieve in riprap installation through the 1990s, but this was followed by several large projects. Over the longer term (past 50 years), the length of river bank locked in place with riprap increased dramatically (Figure 6). With less area available to erode, there has been a concomitant decrease in the area of floodplain reworked. Overall the channel has simplified, being less sinuous and having reduced channel length (Figure 7) relative to historical conditions. On a posi-

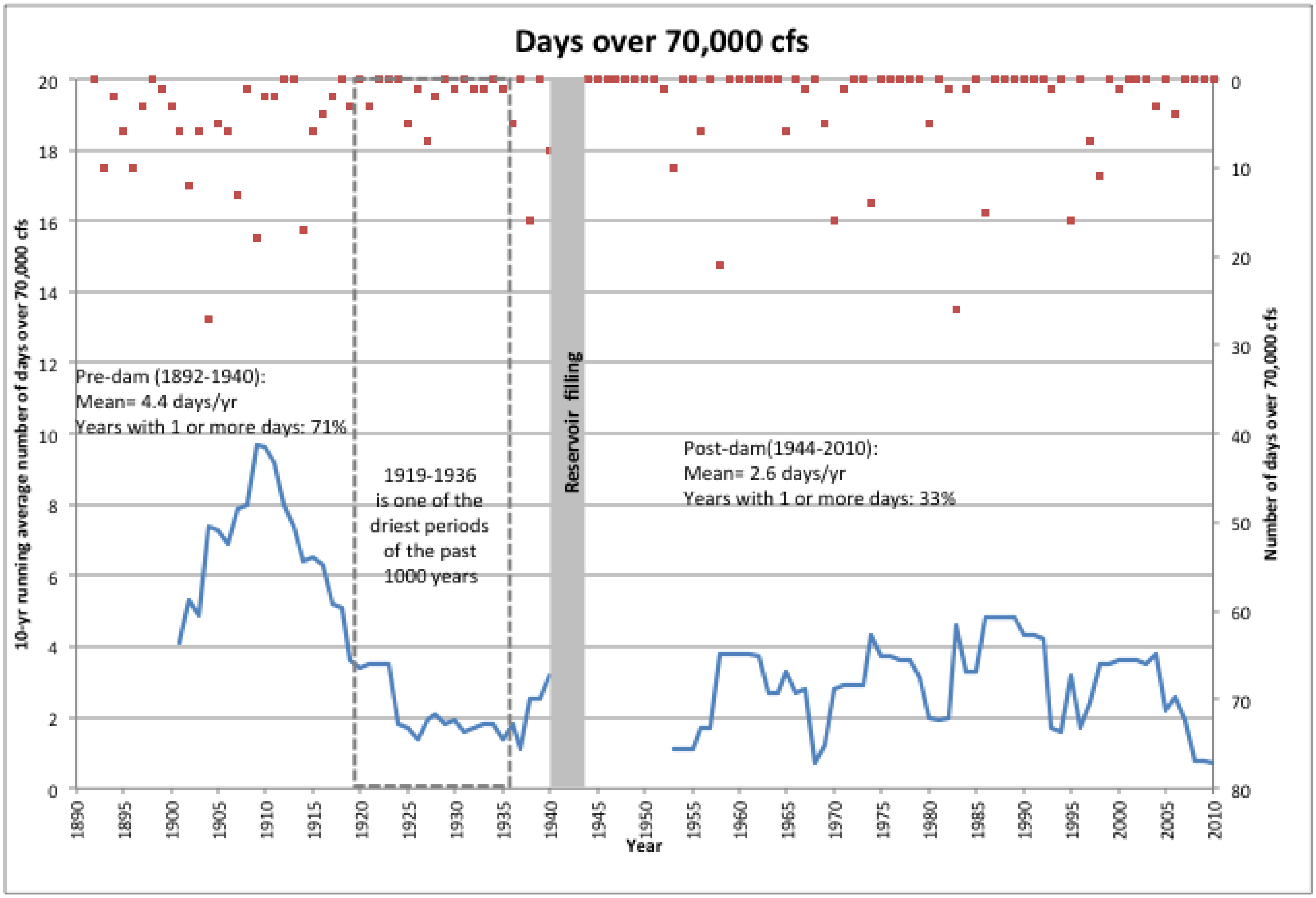

Figure 5 Number of days each year (red data points, right y-axis labels), and 10-year running average of number of days each year (blue line, left y-axis labels), with flows sufficient (over 70,000 cfs) to inundate the floodplain. Flows recorded at the USGS gauge on the Sacramento River at Red Bluff.

tive note, there has been a large increase in the length of the main river channel with conservation ownership on both banks. This reduces the likelihood that riprap will be installed and increases the potential for its removal.

Progress Toward ERP Goals

Overall, progress toward achieving ERP goals for riparian and riverine aquatic habitats was rated "fair." Small increases were observed over the past 20 years in the percent of historical riparian zone currently in conservation ownership, and the percent of historical riparian zone currently in natural habitat. Landscape metrics such as forest patch proximity, and forest patch core size showed positive changes with restoration. Additional indicators such as length of river with conservation ownership on both banks and percent of the riparian shoreline bordered by >500 m of natural habitat also increased. Indicators that prevented progress toward this goal being rated "good" include total channel length and whole river sinuosity. Both declined since the early

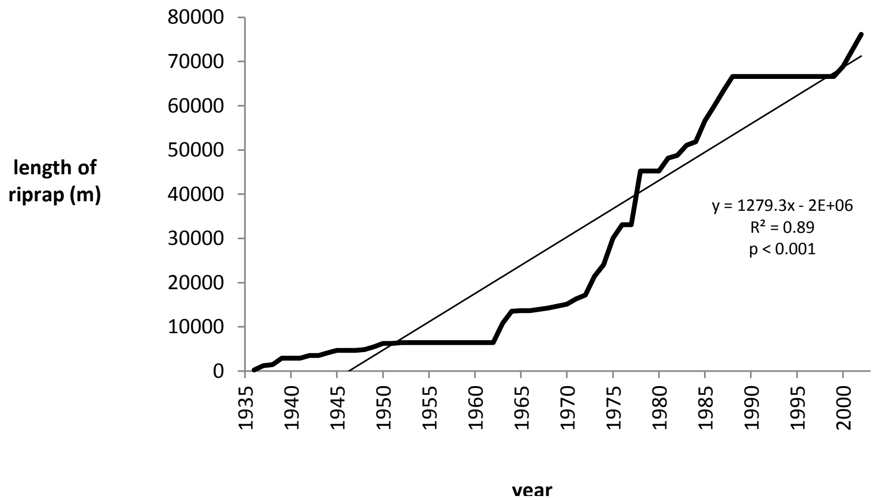

Figure 6 Length of riprapped banks on the Sacramento River between Red Bluff and Colusa from 1937 to 2002

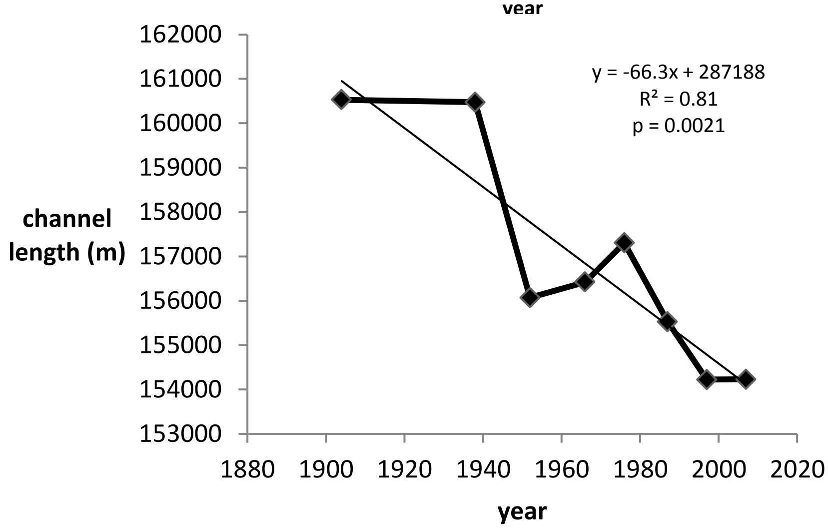

Figure 7 Total channel length of the Sacramento between River Red Bluff and Colusa from 1906 to 2007

1900s, and have not changed substantially in recent decades.

Overall, progress toward achieving ERP goals for plant species and communities was rated "good." The acreage of native vegetation increased significantly, largely as a result of all the planting that has been done at restoration sites. At restoration sites there were positive responses in terms of habitat development. Basal area of woody species increased, as did diameter at breast height. Changes in importance values of different species suggest that the sites are proceeding along a successional pathway that generally supports native species. Coyote brush, box elder, and valley oak increased, although elderberry and sycamore decreased.

Less encouraging is the status of understory vegetation. At restoration sites native understory species were slow to colonize, and frequency of occurrence of native species was low. These findings have led to the implementation of an understory component to more recent (post-1999) restoration plantings. Survival of understory plantings has generally been good and resulted in modest increases in some native understory species (McClain et al. 2011), although long-term monitoring is needed.

Overall, progress toward achieving ERP goals for Neotropical migratory birds has been "fair." Nest survival remained low for lazuli bunting, black-headed grosbeak, and spotted towhee. Apparent adult survival was variable, with black-headed grosbeaks faring better than spotted towhees; however more data are needed to accurately report trends in these parameters. In contrast, bird species richness increased quite dramatically at restoration sites as has abundance for certain species (e.g., black-headed grosbeak, common yellowthroat), but not others (e.g., yellow warbler and yellow-breasted chat). Numbers of occupied yellow-billed cuckoo territories were very low, and the number of bank swallow burrows has declined strikingly.

Progress toward achieving the goal for valley elderberry longhorn beetle has been "good." At restoration sites there was a dramatic increase in the percent of elderberry shrubs occupied by the VELB. However, the importance value of the VELB's host plant declined as sites matured, raising the question of what the long-term VELB habitat availability will be at these sites.

Progress toward restoring healthy populations of other native terrestrial fauna (not specifically called out in the ERP Program Plan, CALFED 2000a) has been "good." Similar to what was found with landbirds, species richness of beetles was higher at older restoration sites than at younger sites. Bees had similar species richness at restoration sites and remnant habitats, although there were considerable differences in the species assemblages. More bats were detected at older restoration sites than at younger sites, suggesting increased abundances.

Progress toward achieving the goal for Central Valley streamflows and natural floodplain and flood processes has been "poor." While there have been some small scale-efforts to set back levees to permit floodplain inundation, there have been no efforts to increase deliberate high flows to mobilize the bed and inundate floodplains, both of which were reduced as a result of flow regulation. The frequency and duration of floodplain inundation was lower after dam construction than in all pre-dam years except the extended drought of the 1930s. Floodplain disconnection from the channel was made worse along much of the reach by levees, which extend up to Ord Bend, and limit overbank flow. Since regulation by Shasta Dam (and since interbasin water transfers from the Trinity River), the average number of days with flows sufficient to connect the highest elevation side channels decreased slightly. A larger decrease in hydraulic connectivity was observed for middle-elevation side channels, while a substantial increase was seen for the lowest elevation group. These changes are reflective of river management which, since reservoir construction, has emphasized winter storage and summer conveyance.

Overall, progress toward achieving the goal for stream meander was "poor." Channel dynamics and channel complexity indicators varied considerably over time (in part from flow variations), but declined over the period of record (1906 to 2007), with no improvement in recent years. Despite goals being set to achieve the opposite, some of the most important indicators of stream meander (e.g., meters of bank with riprap) have continued to decline.

Overall, progress toward achieving the goal for levees, bridges and bank protection also has been "poor." New riprap has been installed, and although the length of river with conservation ownership on both banks has increased, little on-the-ground work has been done to remove or modify infrastructure that currently limits natural river processes.

Progress toward achieving the goal for invasive riparian and marsh plants has been "poor." Reductions were not observed in the areal extent of non-native riparian and marsh plants—quite the contrary—giant reed, black walnut, Himalayan blackberry, and water primrose all increased from 1999 to 2007. Thus competition that native flora face from non-native species does not appear to be diminishing.

DISCUSSION

Our analysis provides clear evidence of both successes and failures in the restoration of the Sacramento River riparian ecosystem. It demonstrates where progress has been made, where conditions have remained unchanged, and where there has been continued degradation—information that is vitally important for guiding future restoration efforts. Our study has wide application. It shows that through simple association of indicators with ecosystem elements and programmatic goal statements, the effectiveness of large-scale restoration projects can be assessed, despite this seldom being done (Bernhardt et al. 2005; Roni et al.

2008). In fact, many of the indicators that we developed and applied may be suitable for characterizing other lowland river systems.

Our synthesis of ecological indicator data suggests that the status of vegetative floodplain habitats and the terrestrial species that inhabit them on the middle Sacramento River is fairly good and that conditions are generally improving. This is mostly the result of successful reestablishment of relatively large swaths of native vegetation across the floodplain over the past two and a half decades. Many positive outcomes have been observed as a result of these efforts, as revealed by landscape analyses, comparisons over time at restoration sites, and comparisons between restoration sites and remnant habitats. An exception is the continued proliferation of invasive riparian and marsh plants in remnant areas, and the limited success that has been made in restoring understory plant communities at restoration sites.

In contrast, the status of natural riverine habitats appears to be generally poor and declining. This is the direct result of the river's hydrologic and geomorphic processes being constrained by continuing anthropogenic alterations. For the most part, the impacts to these parameters occurred before the restoration initiatives that we are evaluating took place. Even so, our characterizations over the longer time frame are important. They provide a meaningful baseline of current conditions that can be used to evaluate the effects of any future restoration actions, while also characterizing pre-impact conditions which may be useful for refining restoration objectives.

Major factors responsible for continued degradation of riverine habitats include riprap, which has been steadily increasing since the 1930s, and alteration of the natural flow regime, which has taken place since the mid-1900s. As more and more riprap has been installed, and the hydrology has been increasingly altered, the river has lost much of its natural dynamism, and with that a reduction in its ability to create and maintain the habitats essential to native species and communities. Planting of native riparian vegetation in recent decades has been an important stopgap measure; however, without the restoration of natural riverine processes, these planted areas will likely follow an altered successional pathway, and not provide the long-term habitat value that they otherwise would (Stromberg et al. 2007; Shafroth et al. 2010).

Ecological research demonstrates that past notions which consider 'stability' to be desirable in ecosystems are outdated, and that disturbance is not only inevitable in many systems, but is essential to their regeneration (Naiman et al. 2005). The greatest riparian and aquatic habitat complexity and biodiversity result from dynamic river processes. These include erosion, deposition, and overbank flooding which lead to the recruitment of large wood, and the creation of vertical cutbanks, fresh bar surfaces, and diverse floodplain habitats (Gurnell et al. 2002; Stanford et al. 2005; Florsheim et al. 2008). When these processes are inhibited through human alterations such as riprap installation, or a reduction in flood flows and sediment supply by upstream dams, a net reduction in habitat complexity results (Ward and Stanford 1995).

The desired endpoint in ecological restoration is to have a mosaic of habitat types of appropriate size and connectivity to support native species and communities, and to restore the important natural processes required to maintain these habitats (SER 2004). Research from this project and others demonstrates that the future of Sacramento River riparian resources depends on the degree to which natural riverine processes of erosion, sediment deposition, and flooding can be restored (Florsheim et al. 2008). Native species have evolved with these processes intact, and many attributes of their life history are uniquely suited to conditions that result from their interplay across the landscape. Examples include cottonwoods, which are specifically adapted to colonize gravel point bars on the receding limb of the spring hydrograph (Mahoney and Rood 1998), and bank swallows, which require recently eroded cutbanks for their breeding colonies (Garrison 1999).

One of the most effective ways to advance restoration in alluvial river systems, such as the Sacramento, is to restore river meander. This can only be done, however, where it does not cause adverse effects on important human infrastructure (e.g., roads, bridges). Meander migration is beneficial to the ecosystem because it initiates a process of floodplain regeneration that can advance fairly quickly, especially when coupled with high flow events. On the Sacramento River, the rate of meander migration has been shown to increase in direct proportion to cumulative effective stream power (Larsen et al. 2006). In fact, on rivers with sufficient stream power to actively erode and deposit sediment, the most efficient and cost-effective approach to habitat restoration may be to allow the river a zone in which to erode and deposit freely (Kondolf 2011, 2012). This basic restoration concept has been promoted by agency and stakeholder groups for the Sacramento River (CALFED 2000a; SRCAF 2003).

Why then, has restoring hydrogeomorphic processes on the Sacramento River been so difficult? Have other river projects been successful in this, and what, if anything, can be done to facilitate greater success in this system? Below we consider these questions separately for restoration of river meander and restoration of the flow regime.

Restoration of River Meander

Meander migration has not been restored on the Sacramento River because riprap has not been removed and continues to be installed. From a permitting standpoint, it is much simpler to install new riprap than it is to remove it. There is a longstanding and well established process for its installation, yet no process exists for its removal. When riprap is installed in response to "emergency" repair needs—as is done on the Sacramento River by the U.S. Army Corps of Engineers (USACE) and the California Department of Water Resources—permitting is streamlined and environmental review is waived (CDWR 2006). Also, private landowners commonly dump riprap on the riverbanks, and despite this being illegal, there is little enforcement.

Removal of riprap at sites where it is no longer needed may be the most appropriate mitigation for installation of new riprap; however, to date, this has not occurred. Removing USACE riprap, or even allowing it to degrade naturally through the erosive forces of the river, requires de-authorization and quantitative analysis of the likely consequences, which the USACE has yet to do anywhere. Instead "onsite" mitigation is done at the repair sites. This entails incorporating wildlife habitat elements (e.g., woody debris) into the construction of the project. A fundamental flaw in this approach is that the onsite habitat features that are typically constructed as mitigation do not serve the same ecological functions that were lost. At other times the protection of existing habitat is counted as mitigation; however, this still leads to in a net loss of habitat.

Both internationally and in California riprap has been removed and levees have been set back to promote meander migration and floodplain reconnection. In Western Europe, levees were set back on lengthy channelized sections of the Rhine to retain floodwaters and retard river discharge, imitating the historical situation to the extent possible (Grift et al. 2001; Nienhuis and Leuven 2001). On the Cosumnes River in California's Central Valley, revetted levees were intentionally breached for ecosystem benefits (Florshiem and Mount 2002; Swenson et al. 2012). Progress made on these other rivers suggests that it may be possible to take these important restorative actions on the Sacramento River, although some different stakeholders would need to be involved in the process.

To promote meander restoration, we recommend that mitigation requirements for riprap installation projects be made more stringent. Mitigation should entail replacing the same ecological functions that are lost. This necessitates the removal of riprap, which would have to follow an as-yet-unestablished process and include analyses of likely consequences. In addition, mitigation should be implemented for all previously implemented rocking projects that have unmet mitigation requirements. Finally, responsible agencies should enforce existing laws prohibiting unauthorized placement of riprap by private individuals.

Restoration of the Flow Regime

Inadequate consideration of ecosystem flow needs in reservoir operations could contribute to the lack of progress in restoring the flow regime on the

Sacramento River. The river is managed primarily for flood control, water storage and conveyance. Environmental parameters considered are limited to requirements of the federal Endangered Species Act (e.g., providing sufficient flows for outmigration of endangered juvenile winter-run Chinook salmon). The challenge is to expand these considerations to include the life-history needs of broader ranges of species without diminishing important services that the river provides to society.

Yet developing an understanding of how alternative flow patterns affect river ecosystems is challenging. The task is made more difficult because relationships between environmental flow alterations and biotic response may not be readily transferrable from one river system to another (Arthington et al. 2006; Poff et al. 2010), and thus there is a need to develop river-specific empirical relationships. Although many uncertainties exist, progress has recently been made along these lines for the Sacramento River through the development of the Ecological Flows Tool (EFT, *http://www.essa.com/tools/EFT/download.html*). This decision analysis tool models how a suite of focal species (including bank swallow, Fremont cottonwood, Chinook salmon, and steelhead) are affected by flow management actions, and thus may be used to expand consideration of ecosystem effects in Sacramento River flow management decisions.

Working collaboratively to establish a more naturalized flow regime may seem a daunting task; however, there are examples to draw from in the United States, Australia, and South Africa (Postel and Richter 2003). For example, on the Green River in Kentucky, conservation groups worked with the USACE to make relatively minor adjustments to flow patterns for the benefit of the ecosystem (especially native fishes and mussels), without adversely affecting water supply for people (Richter et al. 2003). Similarly, on the San Pedro River in Arizona, a diverse partnership of stakeholders developed a consensus-based flow prescription to reduce human impacts while simultaneously setting realistic limits on ecosystem allocations. On Australia's Brisbane River, a stair-stepping approach was used to develop scenarios relating flow thresholds to biodiversity functions. These scenarios were then incorporated into a model used to manage the dam-and-reservoir system to define the feasibility of providing environmental flows while ensuring water supply reliability (Postel and Richter 2003). A common ingredient in these successful collaborations is the understanding that water management that supports a healthy ecosystem while simultaneously meeting human needs is highly desirable. It provides society with a suite of valuable ecosystem services (e.g., water quality, flood control, groundwater recharge, fisheries, recreation) that are diminished when the river is in a degraded state (Wilson and Carpenter 1999; Baron et al. 2002; Golet et al. 2006, 2009).

CONCLUSIONS

By characterizing the current status of the Middle Sacramento River ecosystem, and showing where restoration has been successful and where it has not, our indicator assessment provides vital information that can be used to inform strategic decision-making. Our analyses confirm that horticultural restoration has been effective in creating terrestrial floodplain habitats that are utilized by a broad suite of native and special-status species. Yet, at the same time, they reveal that there has been little progress in the restoration of the natural river processes that are required to create and maintain the dynamic landforms and habitat conditions of larger riverine landscape. Addressing this deficiency will require management entities to develop creative new solutions to old problems. It will require novel partnerships to be formed, and the development of new business models that support experimentation and adaptive management. Examples from elsewhere demonstrate that this is possible, but the challenge remains to identify and set into action the most productive approach for our particular situation; however before any of this can happen, public support for restoration must increase. Whether or not such support will come remains to be seen, but it is encouraging that increasingly people are recognizing that healthy and productive ecosystems benefit not just nature, but also human society at large.

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