Using Science to Evaluate Restoration Efforts and Ecosystem Health on the Sacramento River Project, California

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ABSTRACT. The Nature Conservancy (TNC) and its partners are attempting to restore the riparian ecosystem of the Sacramento River over ~100 river miles, from Red Bluff to Colusa. To evaluate baseline ecosystem conditions, determine how the system is responding to current management practices (including restoration efforts) and better define current threats, TNC is collaborating with scientists from academic institutions, state and federal agencies, and other non-profit organizations. Our scientific investigations combine broad-based monitoring and focused research. Monitoring a wide range of biological, physical and chemical parameters helps us track system dynamics, and conducting focused research allows us to resolve key uncertainties concerning ecosystem function. In this paper we introduce important studies that are currently underway and identify future research needs. Only through comprehensive scientific investigation and coordinated effort will we achieve our goal of restoring ecosystem health to this complex system.

INTRODUCTION

In 1988 The Nature Conservancy (TNC) and its partners (including the U.S. Fish and Wildlife Service, the CA Department of Water Resources, the CA Department of Fish and Game, and the CA Department of Parks and Recreation) launched the Sacramento River Project. Broadly stated, the goal of the Sacramento River Project (hereafter "the Project") is to restore the riparian ecosystem of the Sacramento River over ~100 river miles, from Red Bluff to Colusa. To achieve this goal the Project is pursuing the following strategies: 1) acquiring flood-prone lands (giving priority to those that contain and/or border remnant riparian habitats), 2) revegetating land with native trees, shrubs and understory, and 3) restoring natural river processes. The goals and strategies of the Project are consistent with those described in the Sacramento River Conservation Area Handbook (CA Resources Agency 2000). To maximize the success of the Project we are developing a multifaceted science program (Figure 1). The purpose of the program is to provide scientific understanding of ecosystem dynamics so that conservation actions can be critically evaluated and new restoration strategies can be developed. In this paper we provide an overview of some of the important projects that are currently underway and present

the direction in which the program is heading. In addition to communicating some important initial findings, this paper illustrates the process whereby current scientific investigations are being used to inform future research and monitoring initiatives.

BACKGROUND

The Sacramento River is the largest river in California. Its watershed comprises approximately 67,728 square kilometers, 17% of the state's total land area, but supplies approximately 35% of the state's total water supply (Buer et al. 1989). Even in its present degraded condition the Sacramento River is the most diverse and extensive river ecosystem in California, composed of a rich mosaic of aquatic habitats, oxbow lakes, sloughs, seasonal wetlands, riparian forests, valley oak woodlands, and grasslands. Riparian habitats in general are rich in biological diversity (Naiman et al. 1993). In the arid and semi-arid portions of the western United States these habitats harbor the highest number of bird species (Knopf et al. 1988), and although several species have been extirpated from the region (e.g., Least Bell's Vireo [*Vireo*

FIGURE 1. Conceptual model of the Sacramento River Project's research and monitoring program. The overall objective of this program is to improve our understanding of ecosystem dynamics so we may better characterize baseline conditions, define current threats, evaluate ecosystem response to management practices and prioritize restoration strategies.

bellii pusillus]) the Sacramento River continues to provide important nesting habitat for many species including the CA endangered Yellow-billed Cuckoo (*Coccyzus americanus*), and the CA threatened Bank Swallow (*Riparia riparia*) and Swainson's Hawk (*Buteo swainsoni*). The breeding distributions of many neotropical migratory bird species are restricted relative to what they were historically, however, suggesting that current land and water management practices threaten the long-term viability of the avifauna in this region. Once common species that are now only patchily distributed as breeders in the northern Sacramento Valley include the Yellow Warbler (*Dendroica petechia*), Song Sparrow (*Melospiza melodia*), Yellow-breasted Chat (*Icteria virens*) and Blue Grosbeak (*Guiraca caerulea*) (Nur et al. 1997a).

The Sacramento River watershed also provides habitat for 125 species of fish (Wang 1986), and is the state's most important resource for salmonids. Although four distinct runs of chinook salmon (*Oncorhynchus tshawytscha*) still ply these waters to reach their spawning grounds, their overall abundance has declined precipitously (by more 75% since the 1950's, Yoshiyama et al. 1998), and both the winter and spring runs have special status (federally endangered, and federally threatened respectively). Other special-status fishes include the federally threatened Central Valley steelhead trout (*Oncorhynchus mykiss*) and Sacramento spittail (*Pogonichthys macrolepidotus*). Thus although the diversity of fishes in this region is still great relative to other areas, the future of many species that inhabit this watershed is uncertain, and extirpations of some species (e.g., the thick-tailed chub, *Gila craisicauda*) have already been observed.

The current condition of the Sacramento River can best be understood by considering the anthropogenic alterations of the landscape that have taken place over the past 150 years. Human activities that have reshaped the ecosystem include dam, weir and levee construction, bank revetment, installation of floodplain drainage systems, gravel mining, hydraulic mining, urban and agricultural encroachment, pollution, vegetation removal (including logging), and the introduction of non-indigenous invasive species. Scott and Marquiss (1984) discuss how human alteration of the Sacramento Valley has affected the river, and Patten (1998) provides a general review of the risk that such alterations pose to riparian ecosystem health in semi-arid regions. A detailed examination of the effects of an altered flow regime on ecosystem processes within the Project area is provided by Kondolf et al. (2000).
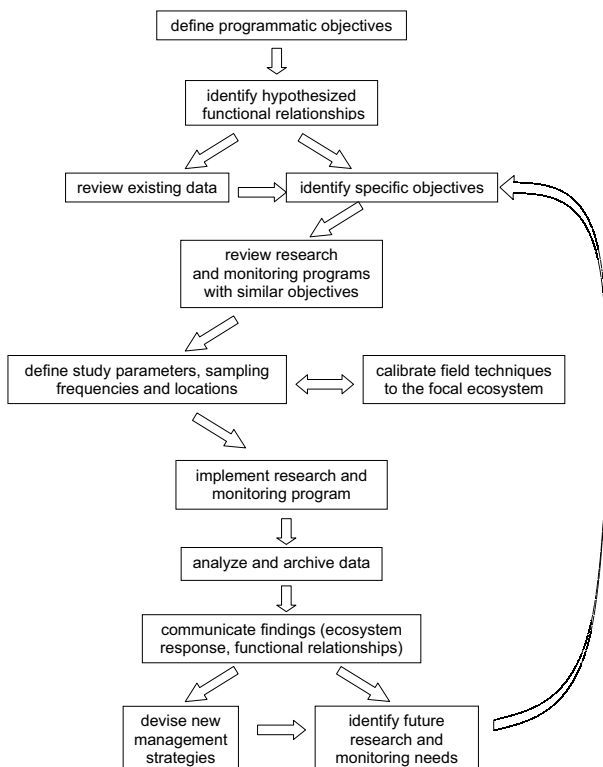
The Sacramento River Project is focusing conservation efforts on the Red Bluff to Colusa stretch of the river because it is here that the potential for ecosystem restoration is greatest. Prior to European settlement, this area harbored a vast amount of riparian habitat (Figure 2), and although degraded, this river stretch still retains some connection with its floodplain, and thus some semblance of ecosystem function (Gore and Shields 1995). South of the Project area natural riverine ecosystem processes are much more compromised as the river is confined to its banks by levees. In general from Red Bluff to Colusa the river is sinuous and anabranching, although the northerly stretch tends to be of a slightly steeper gradient than the southerly stretch. Above Chico Landing there are short stable reaches that are relatively narrow and straight with low sinuosity and minor bank erosion. Interspersed between these reaches are sinuous unstable sections. Below Chico Landing there are fewer islands, overall sinuosity is greater, and natural levees bordering the river are more well developed (Buer et al. 1989).

Prior to European settlement, the Project area had an estimated pre-settlement riparian zone of approximately 88,376 ha. We determined this by clipping Greco's (1999) historical riparian zone coverage (derived from the Holmes et al. [1913] soil map) by the area outlined in Figure 2. Included in this coverage were both mixed riparian forests and valley oak woodlands. Today, only 10% of the historical riparian zone

FIGURE 2. Maps of the A) northern and B) southern areas of The Sacramento River Project. The historical riparian zone was mapped by Greco (1999), based on interpretations of the Holmes et al. (1913) soil map. Coverage of remnant riparian habitat is from the Geographical Information Center at California State University, Chico and coverage of lands in conservation ownership is from the U. S. Fish and Wildlife Service, the CA Department of Parks and Recreation, the CA Department of Water Resources, the CA Department of Fish and Game and The Nature Conservancy.
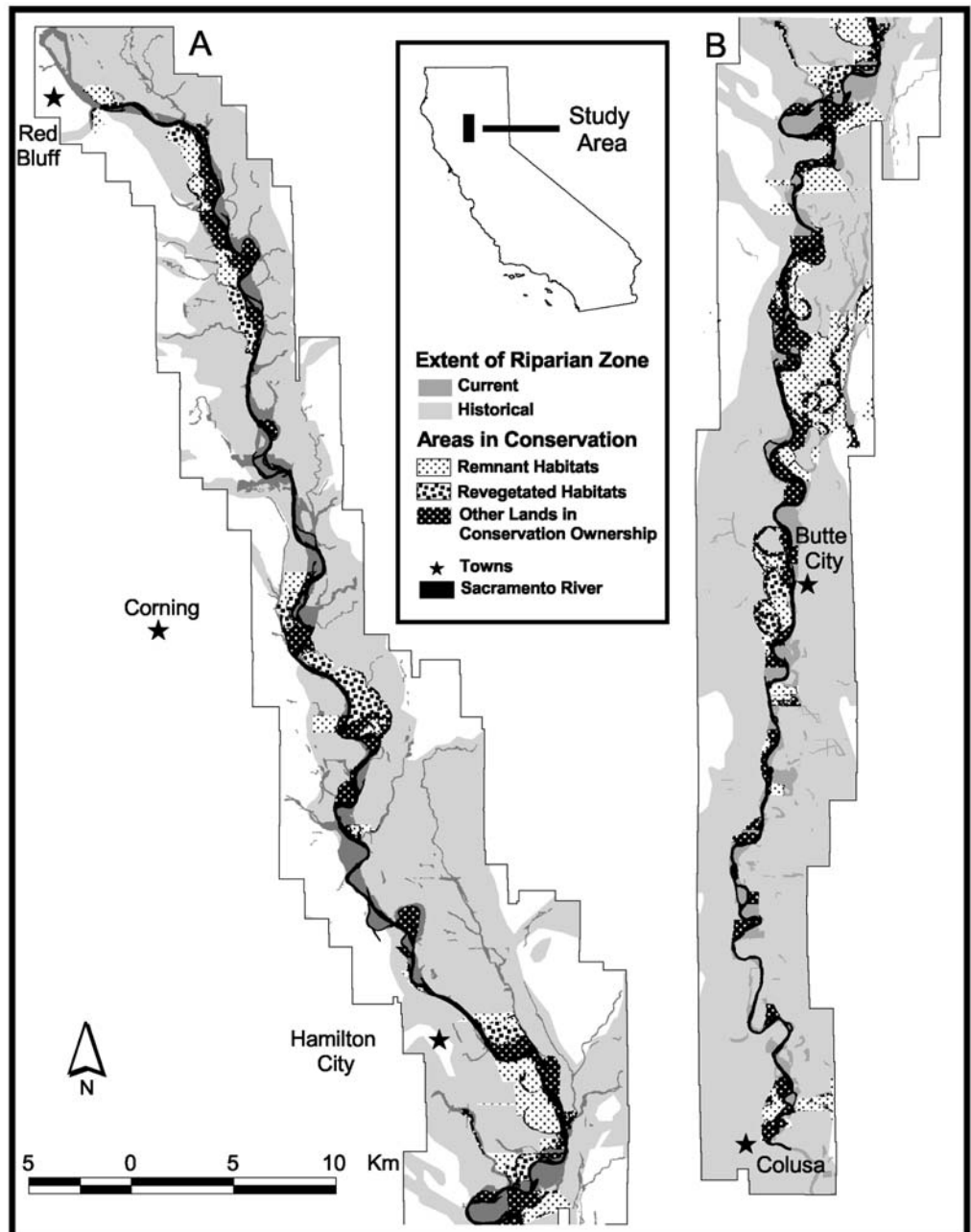
TABLE 1. Amount of a) remnant habitat, and b) land in conservation ownership within the 2.5-year FEMA flood zone, and the area depicted in Fig. 1. Habitat type mapping was done by the Geographic Information Center at California State University, Chico through inspection of high-resolution (1:7,200) aerial photographs taken in 1999. Areas given in hectares, and percents indicated in parentheses.

	category	within 2.5-year flood zone	within the area depicted in Fig. 1
a)	Remnant Habitat Type		
	blackberry scrub	24 (<1)	54 (1)
	cottonwood forest	1,449 (21)	1,683 (19)
	disturbed	171 (3)	200 (2)
	highly disturbed riparian	2 (<1)	43 (1)
	gravel bar	1,232 (18)	1,355 (15)
	giant reed (*Arundo donax*)	30 (<1)	48 (1)
	herbland cover	861 (13)	951 (10)
	marsh	104 (2)	233 (3)
	mixed riparian forest	2,124 (31)	3,382 (37)
	riparian scrub	760 (11)	997 (11)
	valley oak	28 (<1)	170 (2)
	Total	6785	9114
b)	Land in Conservation Ownership		
	remnant habitat	2,796 (45)	3,377 (39)
	revegetated habitat	621 (10)	1,168 (13)
	other (farmland and roads, etc.)	2,767 (45)	4,247 (48)
	Total	6184	8792

remains. Furthermore only 43% of the remnant habitat (approximately half of which is forested, Table 1) in this region is protected.

In 1987 the U.S. Congress passed legislation mandating the establishment of the of a 7,284 hectare National Wildlife Refuge on the Sacramento River, and as of June 2003, the Refuge consisted of 3,667 flood-prone hectares distributed in 22 units. In addition to the U.S. Fish and Wildlife Service, entities that acquire and/or manage conservation lands in this area include: two other federal agencies (U.S. Bureau of Land Management, U.S. Forest Service), three California state agencies (CA Wildlife Conservation Board, CA Department of Fish and Game, CA Department of Parks and Recreation), and several non-profits (e.g., The Nature Conservancy, River Partners). The Project area encompasses seven counties with local jurisdiction for lands and activities along the river.

Significant conservation milestones that have helped propel conservation efforts of this Project forward include the passage the Central Valley Improvement Act, CA Senate Bill 1086, CA State Propositions 12, 13 and 40 Senate

Concurrent Resolution No. 62, and the CALFED Bay Delta Program (see http://www.calfedewp.org/).

CURRENT RESEARCH AND MONITORING

Current research and monitoring efforts are focusing on gathering baseline data, refining ecosystem function models (e.g., the U. S. Army Corps of Engineer's Ecosystem Function Model [Jones and Stokes 2000]) and adapting and implementing draft monitoring plans (including CALFED's Terrestrial and Amphibious Monitoring Plan [A. J. Atkinson, *personal communication*]), CALFED's Aquatic Monitoring Plan [R.L. Brown, *personal communication*], and TNC's guide to watershed monitoring [D. Braun, the Freshwater Initiative, *personal communication*]). Appropriate metrics for tracking ecosystem dynamics are being identified from these studies and used to populate our recently developed monitoring framework (TNC 2003). We are developing and calibrating field techniques specifically for the Project area. Coordination with ongoing efforts, TNC-funded or otherwise, is playing a major role in the process. A sampling of the current research and monitoring studies that are

underway is provided below. We selected a few of these studies (the first three) for detailed discussion because they present some interesting initial findings with respect to ecosystem health, and also because they provide valuable lessons with regard to how research and monitoring programs are structured.

TURTLES (PRINCIPLE INVESTIGATOR [PI]: D. WILSON)

Introduction and Methods

The western pond turtle (*Clemmys marmorata*) is a long-lived vertebrate that is dependent upon backwater habitats and adjacent terrestrial uplands (Gibbons et al. 1990). Female freshwater turtles may travel on land over considerable distances (up to 500 m in some species) to find appropriate nesting sites (Wilson 1998, Goodman et al. 2000). Juvenile turtles need shallow, vegetated backwaters to avoid large predators. Studies of this species thus present a unique window on the riparian systems it inhabits. Here we report initial findings of a study of the western pond turtle that was designed to gather and compare basic demographic data between turtles inhabiting a stretch of the Sacramento River and those inhabiting a relatively pristine tributary in Big Chico Creek Ecological Reserve. Prior to this study little to no data had been collected on this CA species of special concern in this region. This study demonstrates that multiple benefits can come from collecting basic monitoring data. Not only do the turtles provide us with a characterization of ecosystem functionality, but they also identify existing knowledge gaps, thereby identifying future research needs.

FIGURE 3. Frequency histogram of western pond turtle carapace length at Big Chico Creek Ecological Reserve (BCCER) and the Sacramento River (SR). Field work was conducted from April - September, 2000.

Field work was conducted from April to September, 2000. Study sites included an ~ 1 km stretch of creek within the Big Chico Creek Ecological Reserve (BCCER) (39°50'47" N, 121°42'40" W) and three backwaters (Sam Slough, Jenny Lind Bend, Kaiser Slough) within a few km of one another along the west side of the Sacramento River (collectively referred to as the SR site, 39°41'58" N, 121°57'38" W). The SR and BCCER sites are ~ 27 km apart. Turtles were captured at both sites using wire funnel traps baited with dead fish. At BCCER turtles were also captured by hand while snorkeling. All captured turtles were individually marked by filing triangular notches in the marginal scutes of their carapace. Several morphological measurements, mass, and sex were recorded for each turtle. We tested for a difference in the sex ratio between the two sites with a log liklihood ratio test (*G-test*) (Fienberg 1970), and used a 2-way *ANOVA* with sex and site entered as independent variables to test for differences in turtle size. We report means ± standard deviation.

Results and Discussion

The sex ratios of the captured turtles differed significantly between sites, with fewer female turtles being captured at the Sacramento River site than at BCCER, (SR: 26 ± 6 % female, n = 43 turtles; BCCER: 60 ± 7 % female, n = 58 turtles, G = 12.4, p < 0.001). Furthermore, turtles captured at SR were significantly larger (as assessed by carapace length) than turtles captured at BCCER (SR: 178 ± 20 mm, n = 43 turtles; BCCER: 149 ± 19 mm, n = 58 turtles, $F_{[1,97]}$ = 41.3, p < 0.001, Figure 3). The capture method did not appear to affect either the size ($F_{[1,54]}$ = 0.25, p = 0.62) or the sex (p = 0.20, Fisher exact test) of the turtles captured.
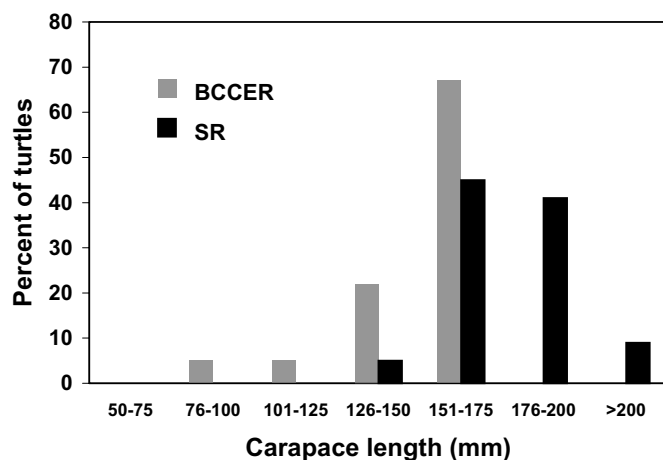
These results suggest a potential problem for western pond turtles at the SR, as the sex ratio was highly skewed toward males and there was no evidence of juveniles recruiting into the population. There are several plausible explanations for the observed patterns, the most likely perhaps being that female turtles are facing high levels of mortality when they leave the aquatic habitat and venture into the uplands for nesting. The upland areas of the Sacramento River have been heavily altered by agricultural development, and contrast greatly with the pristine uplands that surround BCCER. Another factor that may be affecting the SR population is the presence of a non-indigenous turtle species, the red-eared slider (*Trachemys scripta*), which is not found at BCCER. Although it is not known to what extent these species may compete for resources, the introduced turtle grows to a larger

body size and produces twice as many eggs as the native turtle (Ernst et al. 1994).

This study demonstrates some of the benefits that can come from basic monitoring investigations, particularly when they are matched by data collection at appropriate reference sites. This research has identified important knowledge gaps and identified critical research needs. Future work will determine how western pond turtles use floodplain habitats on both a daily and seasonal basis and attempt to identify causes of mortality. This information will help us better evaluate how current management practices are affecting this special-status species.

SONGBIRDS (PIs: S. SMALL, G. GEUPEL, AND N. NUR)

Introduction and Methods

Because birds have high levels of energy expenditure and are at the top of the food chain they can tell us much about ecosystem function. Birds typically have fairly specific habitat requirements; thus avian research and monitoring programs often yield valuable information about the condition of different habitat types within an ecosystem. The Project area is used by many species of birds during all seasons of the year, as it provides important habitat for breeding, dispersal, migration, and overwintering (Gaines 1977). Indeed, riparian areas are considered to be the most critical habitats for landbirds in all of California (Manley and Davidson 1993, DeSante and George 1994).

Systematic studies of landbirds in the Project area were initiated by the Point Reyes Bird Observatory (PRBO) in 1993. These studies have yielded a wealth of biological information regarding the ecological condition of both restoration sites and remnant habitats. Furthermore, these studies provide a striking example of the increased understanding of ecosystem dynamics that can come from gathering data on parameters additional to species distribution and abundance.

We used multiple monitoring methods to assess the status of bird populations along the Sacramento River. This is one of the longest running bird population studies in California's Central Valley, complementing other avian monitoring projects on the Cosumnes and San Joaquin Rivers (also being conducted by PRBO scientists). Because these studies use nationally standardized monitoring methods (BBIRD, Ralph et al. 1995) results can readily be compared across study sites and bioregions.

To determine whether bird use of sites along the river varied among habitat types, and to assess whether bird diversity increased as revegetation sites matured, point count surveys were conducted three times at each site during the breeding season, following the protocol of Ralph et al. (1995). Species diversity was calculated for each point count station based on a set of 56 known riparian breeders from the Sacramento River region (see Appendix 3 in Small et al. 2000). Species diversity provides a measure of the number of species detected weighted by the number of individuals of each species observed (Krebs 1994).

Although studies that only measure numbers of birds (abundance, diversity, density, etc.) are valuable, they may be misleading (Van Horne 1983). Long-term demographic data are necessary to evaluate whether populations are self-sustaining over time. To gain a better understanding of the viability of breeding bird populations along the Sacramento River, we estimated nest success of three common opencup nesting species, the Black-headed Grosbeak (*Pheucticus melanocephalus*), the Lazuli Bunting (*Passerina amoena*), and the Spotted Towhee (*Pipilo maculatus*). These species were selected for study because they are numerous, and because they breed in both remnant forest habitats and in areas that have been revegetated with native plantings. These species differ somewhat in the habitats they select for nesting. Black-headed Grosbeaks place their nests in the mid-canopy shrub layer, Lazuli Buntings nest low in herbaceous and shrubby vegetation, and Spotted Towhees nest on or very near the ground, typically concealing their nests within ground litter or herbaceous and shrubby vegetation.

We conducted analyses of nest survivorship using nest data collected from1993 -1999. Nest success was estimated using the Mayfield method (Mayfield 1975), a technique that calculates the probability of nest failure ("nest mortality") on a daily basis by dividing the number of failed nests by the total number of days nests were observed active. Daily nest survival equals one minus daily nest mortality. Standard errors associated with this value were calculated following Johnson (1979). We calculate "total nest survivorship", the probability of a nest surviving the entire nesting cycle (laying, incubation, and nestling periods), by raising the daily nest survivorship value to the power of the total number of days in the nest cycle.

Results and Discussion

Riparian bird diversity increased significantly over time as revegetation sites matured (*p <*

FIGURE 4. Overall riparian bird diversity (Shannon-Wiener index) and age (in years) on four TNC Sacramento River restoration sites: Phelan Island, Rio Vista, Flynn, and Ryan. Species diversity was measured using a transformation of the standard Shannon-Wiener function (H, defined on p.704 in Krebs 1994). We used the transformed index (N1), equal to 2 H, because it yields a value that can readily be compared to species richness. Data points represent mean annual diversity of individual point count stations. Data are jittered to allow individual points to be seen. Least squares line of best fit is shown. Data have been standardized to eliminate year effect. This was done by fitting a model which simultaneously accounted for calendar year effects and restoration age, and then subtracting the estimated year effect for each year of observation. Based on point count data from 1994-1999.
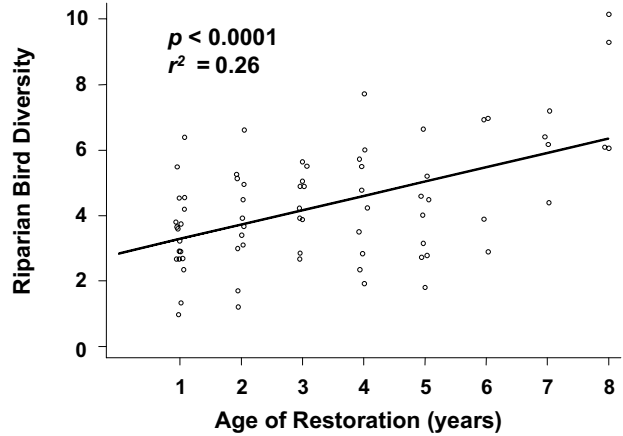
0.0001, $r^2 = 0.26$; Figure 4). Furthermore, at revegetation sites with native plantings greater than five years old, bird diversity approached what was observed in remnant riparian areas along the river (Small et al. 2000). These findings suggest that planting restoration sites with native trees and shrubs is beneficial to riparian songbirds and that basic monitoring of the distribution and abundance of species can be informative in assessing ecosystem response to management actions.

However, additional data from the bird studies do not paint as optimistic a picture for the songbird community along the Sacramento River. In riparian forests and revegetation sites combined (no difference was detected between these habitat types), total estimated nest survivorship was extremely poor for both understory nesting Lazuli Buntings (6%), and Spotted Towhees (11%, Figure 5). With source/sink population modeling techniques Nur et al. (1997b) demonstrated that bunting reproductive success would have to at least triple over observed levels for the Sacramento River population to be self-sustaining. Although similar detailed analyses have not yet been done for the spotted towhee it is likely that present

levels of nests survivorship are also well below what is needed for the population to be self-sustaining. On the San Joaquin River, another understory-nesting species, the Song Sparrow, has also experienced extremely low nest survivorship (Ballard et al. 1999), suggesting that there may be widespread problems for ground nesting species in the Great Valley.

The primary cause of nest failure was predation for the Spotted Towhee and the Black-headed Grosbeak. The Lazuli Bunting also suffered high predation rates, although nest parasitism by Brown-headed Cowbirds (*Molothrus ater*) was equally responsible for nest failure (Small et al. 2000). While none of these species are classified as threatened or endangered, it is likely that these populations are only being sustained by emigration from other "source" populations. Efforts to model population dynamics of songbirds breeding on the Sacramento River, using local productivity and annual survival data, are now underway (see Small et al., in review).

Aside from the intrinsic value of the information that these avian studies provide, they are useful in what they reveal about how we prioritize our data gathering efforts when monitoring

FIGURE 5. Mayfield estimates of total nest survivorship, by habitat type, of three open-cup nesting species on the Sacramento River, 1993-1999.
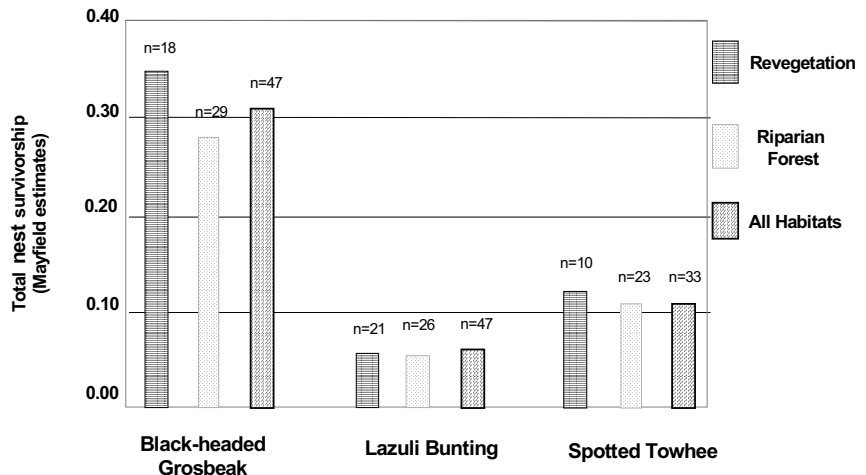
populations. The bird studies clearly demonstrate the importance of assessing reproductive performance of populations where possible, and further they show that simple characterizations of distribution and abundance, when considered by themselves, may provide misleading information regarding the health of local populations. Like the turtle studies, these investigations also demonstrate that monitoring can be an effective way to identify knowledge gaps and prioritize future research. Future avian studies will investigate causes of nest predation, and attempt to identify factors (e.g. flow regime, landscape effects) that affect reproductive success and predation rates.

DIRECTING FLOWS (PIS: E. LARSEN AND S. GRECO)

Introduction and Methods

Empirical modeling of hydraulic factors that control meander migration can improve our ability to evaluate long-term effects of floodplain management on ecosystem dynamics. Here we demonstrate how the mechanics of flow and sediment transport in a curved river channel can be used to simulate channel migration patterns predicted to result from alternative management scenarios. The results of these simulations have implications for riparian forest regeneration, as meander migration is a fundamental driving force in riparian vegetation succession (Scott et al. 1997, Shafroth et al. 1998, Greco 1999). In addition to predicting channel movement, the model generates estimates of the amount of floodplain bottomland that is reworked, which is indicative of the amount of substrate area that is suitable for riparian vegetation colonization. Regeneration of early successional vegetation communities is an important process in maintaining the habitat heterogeneity required for healthy riparian systems (Naiman, et al. 1993).

California's Department of Water Resources devised a number of alternative bank stabilization scenarios for river miles 216 - 226 of the Sacramento River, near Woodson Bridge

FIGURE 6. Simulations of channel meander following different management scenarios: A) simulates river behavior if free from anthropogenic constraints (riprap removed); B) simulates river behavior if existing riprap is maintained; C) simulates river behavior if current riprap is maintained and additional riprap is added near the bridge; D) simulates river behavior if the channel is redirected from its present location to Kopta Slough (this has been proposed as a method of reducing erosion in the vicinity of the bridge and the state recreation area).
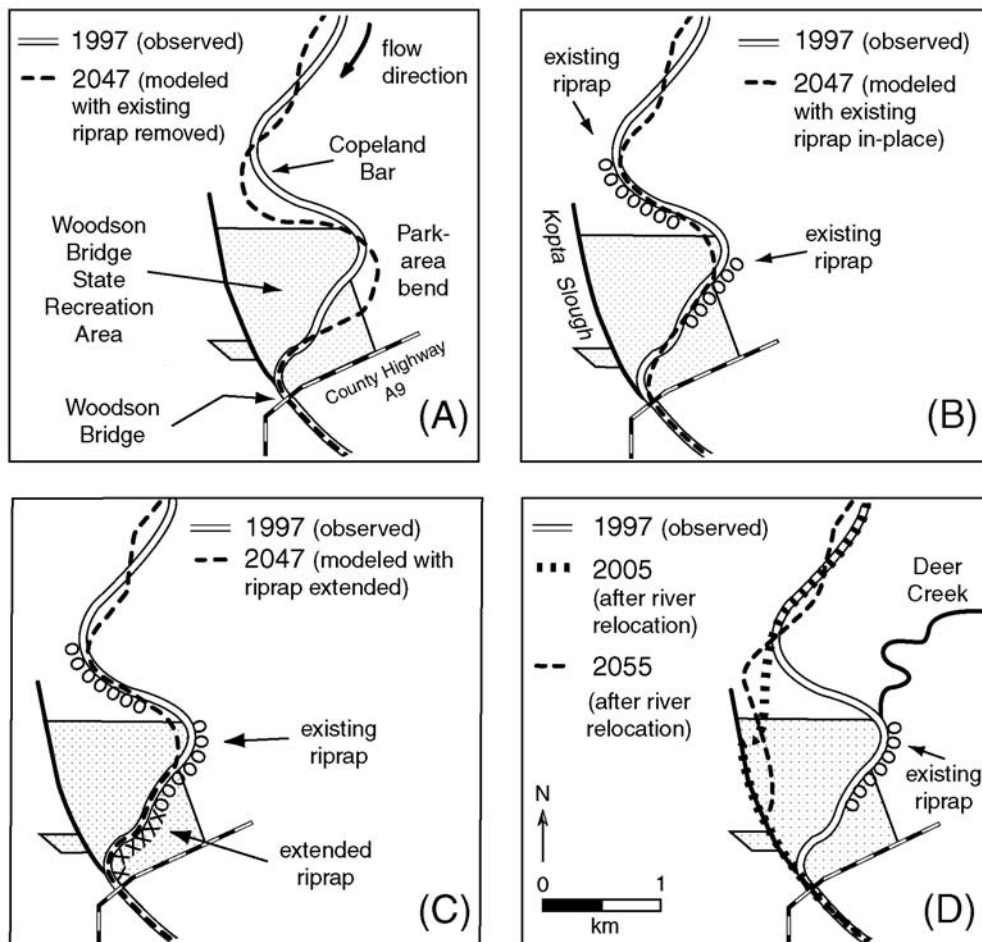
State Recreation Area. These scenarios were defined in part by the extent of channel migration projected to take place over the next half-century (CA Department of Water Resources 1998). Planning scenarios are detailed in the legend of Figure 6, but include allowing unrestrained meandering to occur by removing existing rock revetment (riprap), adding additional riprap, and redirecting the flow of the river through an abandoned river channel (backwater slough).

To evaluate the effects of channel constraints on channel migration, we applied a meander migration model developed by Johannesson and Parker (1989). This model assumes that the local bank erosion rate is proportional to a local velocity factor times a bank erosion coefficient. These two components of the model simulate the erosive force of flowing water (represented by the velocity component) and the resisting force of the banks (represented by the erosion coefficient). The model requires an estimation of a characteristic discharge that mimics the integrated effect of the variable flow regime. The rationale is the same as that used in traditional geomorphic analyses where channel form and processes are scaled by the "bankfull" or "dominant" discharge (Wolman and Miller 1960). Accordingly, the model does not try to simulate the effects of particular flow events, but produces estimates of long-term rates of erosion or channel migration. The velocity field is calculated analytically and the bank erodability is represented by an empirically estimated coefficient (Larsen 1995).

Results and Discussion

The 16-km reach of river channel was found to rework between 8.5 and 48.5 hectares of land in 50 years (Table 2), depending on the management scenario selected. Clear differences in channel meander patterns are predicted to result under varying channel stabilization scenarios. The channel sinuosity decreases with time in the cases where the channel is constrained (Table 2). Decreasing sinuosity means that the channel straightens and therefore increases in longitudinal slope. Importantly, the simulations suggest that the riprap currently in place upstream from the Woodson Bridge State Recreation Area causes more erosion of the recreation area than if no riprap were present upstream. The model suggests that relocating the channel to the west, and allowing subsequent unconstrained migration, could relieve the erosion pressure in the recreation area. This unconstrained migration also appears to rework a substantial area of land (26.5 hectares) during 50 years of projected migration, thus conferring significant ecosystem benefits. This case study demonstrates how sophisticated modeling tools are being applied to evaluate the effects of alternative river management options. Additional details of this study are provided in Larsen and Greco (2002).

ADDITIONAL PROJECTS UNDERWAY

Groundwater, Nutrient Cycling, and Soil Development

PIs: D. Brown and D. Wood. Rivers interact with surrounding terrestrial systems through a complex array of physical, chemical, and biological processes. The types and magnitudes of these interactions vary both spatially and temporally, often spanning several orders of magnitude (e.g., millimeters to kilometers, and minutes to centuries). Selected interactions between the Sacramento River and its floodplain are being investigated at the Rio Vista (formerly "River Vista") restoration unit, located on the east bank of the river south of Woodson Bridge. For example, we are studying the evolution of soil nutrient (carbon and nitrogen) cycles, nitrogen mineralization rates, and plant litter and soil organic carbon dynamics. To monitor these

TABLE 2. Amount of land projected as being reworked and channel sinuosity according to four different management scenarios. Values were predicted from simulations of a meander migration model.

simulation	management action	area reworked (ha)	Sinuosity pre/postmigration
A	No riprap in the study reach	48.5	1.4/1.6
B	Current riprap maintained	12.1	1.4/1.3
C	Riprap extended from park bend to bridge	8.5	1.4/1.3
D	River redirected through Kopta Slough	26.5	1.1/1.1

parameters we placed sample grids in three riparian vegetation sites: Rio Vista revegetation site VII (planted in 1999); revegetation site II (planted in 1994); and an adjacent riparian forest remnant (to provide a reference condition).

We are also investigating the role local riparian systems play in mediating floodplain solute transport to the Sacramento River. Fully functioning riparian ecosystems have repeatedly been shown to improve groundwater and stream quality by removing undesirable constituents such as nutrients and pesticides (Lowrance et al. 1985). To study these processes at revegetation sites and in a remnant riparian forest nine groundwater-monitoring wells were installed along three transects spanning the sites described above. The wells extend from nearby agricultural fields to the edge of the Sacramento River. Quarterly groundwater samples are being analyzed for nitrates, and water levels are being monitored on a weekly to monthly basis, depending on the season. Reconnaissance monitoring for organophosphate pesticides is also planned. Preliminary results of these studies are detailed in Brown and Wood (2002).

Hydraulic/Geomorphic Evolution of Oxbow Lakes

PIs: M. Kondolf, and I. Morken (student). Oxbow lakes and other floodplain water bodies contribute enormous biodiversity to lowland river ecosystems (Bornette et al. 1998, Ward and Stanford 1995). Their unusual ecological value stems in part from their evolution over time from fully aquatic to terrestrial ecosystems as they fill in with nutrient-rich silt and sand during floods. Along the Sacramento River, most of these features have been filled, dyked, or otherwise disconnected from the riverine ecosystem. However, on the reach between Red Bluff and Colusa, a number of oxbow lakes remain. We are collaborating with colleagues from the University of Lyon, France to document the physical and ecological evolution of a set of six oxbow lakes that cut off from the mainstem of the Sacramento River in the twentieth century. We are mapping historical planform from sequential maps and aerial photographs; measuring sedimentation rates from cores; and developing stage-discharge relations from longterm gauging records and observations of stage over a range of flows. Data derived from these initiatives will be used to reconstruct inundation histories to test oxbow evolution models developed in France. Preliminary results from this study are dtailed in Morken and Kondolf (2003).

Identifying a "Naturalized" Flow Regime

PI: M. Roberts. Riparian vegetation provides critical terrestrial and aquatic habitat for wildlife,

improves water quality, and yields aesthetic and recreational values (Patten 1998). Cottonwoods (*Populus* spp.) are a keystone pioneer species of riparian habitats, but land-use practices and river regulation have caused widespread reduction in their distribution and regeneration (Rood and Mahoney 1990, Braatne et al. 1996). Within the Project area some of the point bars have fewer young cottonwood trees than would be expected on an unregulated river (S. Rood, *personal observation*).

To understand how the flow regime may be better managed to support the Sacramento River riparian ecosystem, we are studying the geomorphic and hydrologic factors that govern Fremont cottonwood (*Populus fremontii*) recruitment. By identifying the conditions that cottonwoods need to successfully recruit, we hope to provide information that land and water management agencies can use to revitalize the riparian forests of this important ecosystem.

More specifically, our study aims to calibrate scientifically rigorous cottonwood recruitment models that have been developed in other watersheds (e.g., Mahoney and Rood 1998). Toward this end we have collected dendrochronological, hydrologic and topographic survey data, and have conducted a field reconnaissance of recent cottonwood recruitment sites in the Project area. We used the Indicators of Hydrologic Alteration (IHA) software (Richter et al. 1996) to contrast current and historical hydrographs and to identify factors that may limit recruitment. Our preliminary results (detailed in Roberts et al. 2002) indicate that cottonwoods recruit at higher elevations on the point bars of the Sacramento River than has been observed at other rivers where similar studies have been conducted. This information can inform flow regulation decisions that attempt to maximize both human and ecosystem benefits. Similar definitions of flow requirements are needed for other species.

Riparian Landscape Change Analysis and Geospatial Modeling

PI: S. Greco. We are developing a spatial modeling tool for assessing the impacts of river management actions (e.g., modifications of flow regime, bank stabilization, levee configuration, etc.) on wildlife habitats over time spans of decades to centuries. The empirically-based model seeks to link wildlife habitats to landscape features predicted to arise under different river-management scenarios (see Greco et al. 2002). Wildlife habitats are being defined for a set of riparian-obligate indicator species based upon habitat suitability indices (HSI). To build and calibrate the model we are mapping vegetation from aerial photographs, analyzing historical

flow records, and developing spatially-explicit HSI models.

As a first step in this process, baseline land cover conditions are being mapped from 1997 aerial color photographs (1:12,000) using a stereoscope. Estimates are made of vegetation height and canopy cover according a modified version of the CA Wildlife Habitat Relationship System (Mayer and Laudenslayer 1988). We are combining vegetation data with 1997 topographic and bathymetric data (collected by the U.S. Army Corps of Engineers) to define initial conditions for landscape state-and-transition modeling being conducted with a geographic information system (GIS) following techniques outlined by Plant et al. (1999). Historical photographs are similarly be analyzed to define how the vegetation communities respond to patterns of channel meander and floodplain inundation (see Greco 1999).

We are also developing a multi-media visualization tool to communicate and disseminate to a wide audience the inherently dynamic nature the riparian landscape of the Sacramento River. This tool will effectively demonstrate the dependence of riparian ecosystem function on landscape change. Animations of both historical and forecasted landscape change will be produced.

Pattern and Process in Riparian Vegetation Succession

PI: D. Wood. Riparian vegetation along the Sacramento River has been classified into community types but the transition rates between community types during vegetation succession have received little attention. Understanding the rate and frequency of transition from one community type to another is key to understanding the biotic complexity and management of riparian ecosystems. For example, the rate at which a mixed riparian community becomes a valley oak community is not known, yet valley oak woodland is a valued community type in this ecosystem. Managers need to know how often, or even whether new communities are being created as a result of natural succession.

We are focusing on three transitions: (1) between gravel or point bars and cottonwood-willow; (2) between mature cottonwood-willow forest and mixed riparian forest, and (3) between mixed riparian forest and valley oak woodland. To study cottonwood-willow establishment, a series of permanently marked belt transects have been established running perpendicular from the water to mature forest on active gravel bars. Vegetation, substrate, and elevation are being

recorded in a continuous series of quadrats. Together with hydrological data, this study will establish links between substrate type, hydrology, and survival rates of cottonwoods and willows. To study the latter two transition rates, a series of plots have been established in different-aged stands of all three community types (cottonwood-willow, mixed riparian, and valley oak woodland). Stand age is being determined using a combination of aerial photos and tree ages. In each plot we are determining the density and dominance of all woody species, and estimating the percent cover of herbaceous species. Succession trajectories of different-aged stands (the chronosequence) will be analyzed graphically using standard ordination techniques. Preliminary results from these studies are detailed in Wood (2003a, 2003b).

Understory Vegetation Communities

PIs: K. Holl and E. Crone. Most riparian habitat restoration efforts in the Project area thus far have focused on planting and monitoring woody species. We are surveying the understory vegetation communities in sites planted with woody riparian species at least five years previously and in remnant riparian forests to determine success in restoring understory plant communities. We are combining field data with GIS analyses of surrounding habitat types to test whether understory community composition is more strongly influenced by site-specific factors (e.g., depth to water table, soil texture, previous land use) or landscape-level factors (e.g., distance to river channel, distance to remnant riparian forest). Identifying factors influencing the distribution and abundance of plant species within riparian understory areas will help us better understand (and model) the dynamics of species that depend upon these habitats (e.g., songbirds, see the Biocomplexity Project below). Preliminary results from this study are detailed in Holl and Crone (in review).

Factors Affecting Planted Species

PIs: D. Wood, R. Luster. We are monitoring short- and long-term plant community dynamics at horticultural restoration sites. To date TNC has planted over 1,168 hectares with native trees, shrubs and more recently, herbacecous species. Alpert et al. (1999) reported on factors affecting planted species at a subset of these sites during the maintenance phase (the first three years following planting, when irrigation and weed control are practiced), and more recently Griggs and Golet (2002) provided an assessment of the survival and growth of valley oaks (*Quercus lobata*) following the cessation of maintenance activities. We are furthering these efforts by

collecting data at long-term plots ($n = 106$) that were established during the first year of planting. Data collected at these sites will be analyzed to determine the relative importance of physical and biological factors in dictating 1) the survival and growth of planted species; 2) the structural complexity of the vegetation; 3) what species colonize the sites (in collaboration with K. Holl and E. Crone, see above); and 4) the successional trajectories of the different community types. Also, we have recently initiated a project with H. Cushman and J. Coleman (student) at Sonoma State University to identify appropriate restoration techniques and post-restoration monitoring protocols for riparian-associated grasslands.

Bank Swallow Population and Ecology Studies

PIs: E. Crone and K. Moffatt (student). In California, bank swallow (*Riparia riparia*) populations have been extirpated from approximately half of their historic range, and currently over 70% of the remaining population is found in the Sacramento Valley (Schlorff 1997). Bank Swallows nest colonially in river cut banks, and require active channel meandering to create habitat suitable for nesting. Along the Sacramento River bank swallows have been adversely affected by widespread bank stabilization projects. In addition, because they forage for insects over lands adjacent to the river, their population dynamics may be affected by land use practices (e.g., pesticide use) which vary widely on the floodplain. To better understand the relative importance of hydrological and land-use patterns for bank swallow population viability, we are collaborating with R. Schlorff and B. Garrison to analyze a long-running dataset of colony size and location.

Salmonid Use of the Floodplain

PIs: M. Marchetti and M. Limm (student). Sacramento River floodplains provide beneficial rearing habitat for multiple species of native fish (e.g., chinook salmon Sacramento splittail) (Sommer et al. 2001). Physical factors influencing the quality of habitat for these fishes include water depth, flow rate, area, duration of inundation, temperature, and the amount of vegetation/cover. Riparian restoration efforts in the floodplain along the Sacramento River have been successful in replacing agricultural fields with native vegetation. Yet during flood events, the aquatic ecosystem in the heavily vegetated restoration areas likely experiences lower amounts of solar energy input and therefore lower primary productivity. With a decrease in primary production, one would expect decreased energy transfer to higher trophic-level organisms (including fishes). To determine whether

floodplain habitat type affects juvenile salmon growth rates we are comparing macroinvertebrate drift density, juvenile chinook salmon diet and growth rates (through otolith microstructure examination techniques) at vegetated restoration areas, agricultural fields, backwater habitats, and the main river channel. This work may help us better understand to how floodplain management decisions affect salmon and their prey. Preliminary results of this study are presented in Limm and Marchetti (2003).

Sacramento River National Wildlife Refuge Wildlife Surveys

PI: J. Silveira. Table 3 presents a partial list of species that are surveyed in conjunction with the USFWS in the Project area. Several of these surveys are cooperative, with Refuge personnel assisting PIs from other organizations. Data collected in these surveys provide important baseline data and help us assess how wildlife occurrence patterns change through time and in response to management actions. For example, Bank Swallow survey data suggest a favorable response to a levee removal project implemented at river mile 233 in late fall 1999. Following the removal of the levee the river further eroded and enlarged an existing cutbank. The subsequent spring, a nearby swallow colony expanded into this newly eroded area, forming the largest colony on the river that year (2,770 burrows). The year previous (1999) there were only 930 burrows at this site. These results support the notion that bank swallow population declines in this region are at least in part attributable to decades of habitat loss that began in 1960 when the Sacramento Bank Protection Project was authorized by the U.S. Congress (Schlorff 1997).

A LOOK TO THE FUTURE: LONG-TERM RESEARCH AND MONITORING

A long-term research and monitoring program is being instituted to evaluate baseline ecosystem conditions, determine how the system is responding to current management practices (including restoration efforts), better define current threats, and prioritize restoration strategies (for details see TNC [2003]). Results of the current research and monitoring projects are guiding the program's development. However, prioritizing future efforts remains challenging. Because funding is limited it is imperative that our perceptions of relative importance of scientific investigations are accurate, as these are what dictate the extent to which individual elements of the program are developed. Fortunately, a number of projects currently underway are focusing on this very difficult question of how to prioritize future

TABLE 3. Taxa surveyed at the Sacramento River National Wildlife Refuge.

taxa	special-status designation
Plants	
California hibiscus (*Hibiscus lasiocarpus*)	CNPS[1] List 2
Ferris' milk-vetch (*Astragalus tener var. ferrisiae*)	CNPS List 1B
fox sedge (*Carex vulpinoidea*)	CNPS List 2
square-stemmed spike-rush (*Eleocharis quadrangulata*)	CNPS List 2
Birds	
Bank Swallow (*Riparia riparia*)	CA Threatened
Black-crowned Night Heron (*Nycticorax nycticorax*)	None
Double-creasted Cormorant (*Phalacrocorax auritus*)	CA Species of Special Concern
Great Blue Heron (*Ardea herodias*)	None
Great Egret (*Ardea alba*)	None
Greater Sandhill Crane (*Grus canadensis*)	CA Threatened Species
Osprey (*Pandion haliaetus*)	CA Species of Special Concern
Snowy Egret (*Egretta thula*)	None
Tricolored Blackbird (*Agelaius tricolor*)	Federal Species of Special Concern
White-faced Ibis (*Plegadis chihi*)	Federal Species of Special Concern
Yellow-billed Cuckoo (*Coccyzus americanus*)	CA Threatened
Reptiles	
giant garter snake (*Thamnophis couchi gigas*)	Federally Threatened
Vernal pool crustaceans	
vernal pool fairy shrimp (*Branchinecta lynchi*)	Federally Threatened
vernal pool tadpole shrimp (*Lepidurus parckardi*)	Federally Endangered
California linderiella (*Linderiella occidentalis*)	CA Special Animal[2]

[1]California Native Plant Society

[2]World Conservation Union Red List threatened species

research and monitoring efforts in the Project area. These include the Biocomplexity and Biological Indicators Projects, each of which is introduced below.

BIOCOMPLEXITY PROJECT

PIs: E. Crone, K. Holl, M. Kondolf, and N. Nur. The vast majority of restoration efforts, including those for Sacramento River riparian forests, are based on the assumption that, if appropriate physical conditions are created and woody plants are successfully established at a site, that site will be colonized by native herbaceous plants and animals. Alternatively, establishment of native plant and animal species may be limited by biological processes that operate at larger spatial scales than individual sites, such as dispersal limitation of desired native species and movement of undesirable species (such as weeds, pathogens, and predators) across the landscape. To design efficient restoration strategies, we must understand the relative importance of physical and biological processes in determining longterm community dynamics. This requires working across traditional disciplinary boundaries to link physical and biological processes at site and landscape scales.

In the initial phase of our research, we are combining data from ongoing mapping and monitoring programs (described earlier) to formulate simple empirical models linking hydrology, vegetation, and bird communities in Sacramento River riparian habitats. Current monitoring efforts are not sufficient to parameterize predictive mechanistic models, but may allow us to quantify how certain we are about the relative importance of possible management actions. Using empirical models and traditional sensitivity analysis, we will test which suites of processes (restoring flood regimes, restoring channel meandering, establishing appropriate woody plant species, establishment of connectedness among riparian

sites, or human uses of floodplain habitats) most affect plants and songbirds, based on our current knowledge of ecosystem dynamics. We will also use an uncertainty analysis (that takes into account both sensitivity and estimation error, Schultz and Crone 1998) to ask which areas of future research would most increase our ability to identify correct management actions for restoration.

Data compilation to date has identified broad areas that are not well monitored under existing programs, but are key steps linking restoration of hydrological processes, plant communities, and songbird communities. These include: (1) stage-discharge relationships at restored (planted with woody species) sites, (2) dynamics of herbaceous plants at restored sites, and (3) effects of human land use on insect and mammal communities. We have also identified a set of empirical relationships that link what is known about hydrology, geomorphology, plant communities, and songbird population dynamics. Ongoing modeling will identify which of these, or other areas, are most important to study to direct future restoration efforts. In the future, we hope to develop an increasingly mechanistic, predictive understanding of riparian forest ecosystem dynamics using an iterative process of modeling, manipulative experiments, monitoring, and adaptive management. Preliminary results from the Biocomplexity Project are detailed in Crone and Holl (2002).

BIOLOGICAL INDICATORS PROJECT

PIs: F. Ligon, B. Orr, M. Power, W. Rainey and J. Vick. Operational definitions and measurable indicators of ecosystem health are needed to prioritize restoration efforts, and steer systems toward desired endpoints. The restoration goal for an ecosystem is not a single state, but a range of ecosystem states and processes that occur over time in an ecosystem that supports native species and responds to dynamic environmental regimes representative of natural conditions that applied before systems were massively altered by humans. Increasing our understanding of the linkages between physical structure and processes and biotic responses in Central Valley river systems is critical to improving our ability to predict the effects of various restoration or rehabilitation actions on biological populations of interest (as discussed above for the Biocomplexity Project) and in developing effective indicators to monitor and test the results of implementing such actions (the focus of this study).

Our underlying conceptual model is shown in Figure 7. In this model, natural watershed inputs (e.g., water, sediment, nutrients) and anthropogenic alterations to these inputs

influence important physical processes (e.g., sediment transport, channel migration, stream heating). These processes determine the physical and chemical attributes (e.g., hydroperiod, bed substrate composition, nutrient availability) that affect habitat structure and connectivity in river-riparian-floodplain systems. Species abundance and distribution and trophic structure are directly affected by these habitat attributes. For instance, the species composition and age-class-structure of riparian vegetation are affected by inundation regimes and sediment deposition patterns. Attempts to restore these systems will generate processes and feedback loops that will have short-term (days to months) and long-term (years to decades) effects on aquatic, riparian, and upland terrestrial ecosystems. For example, in the short-term, breaching levees would alter spatial patterns of sediment deposition and texture and the depth, timing, and duration of inundation. These changes would affect survival, recruitment, and hence spatial and taxonomic structure of riparian vegetation and aquatic macrophytes, and the microbial films associated with their submerged surfaces. Changes in larger, rooted vegetation would also generate longer-term feedback in spatial patterns of sediment deposition and texture, both of which would reconfigure habitat structure and alter the food production base for invertebrates, fish, amphibians, reptiles, mammals, and birds.

FIGURE 7. A simplified conceptual model of the physical and ecological linkages used in developing biotic response indices of river ecosystem health.
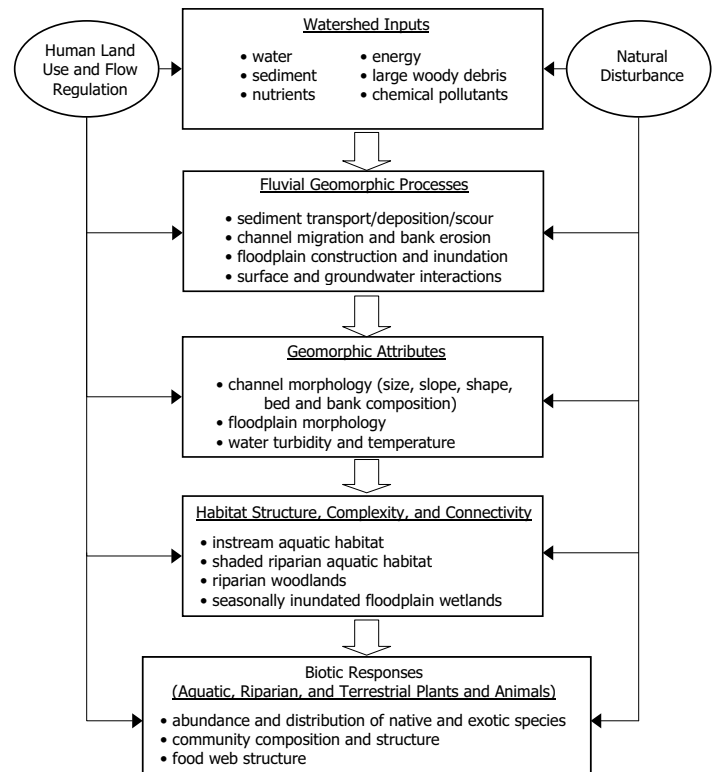
Determining whether management is moving systems toward more desirable, healthier states is a research question, as emphasized above for the Biocomplexity Project. In particular, there is a need to develop indicators of ecosystem processes, such as nutrient cycling and food web interactions, that can complement more commonly used indicators based on ecological patterns (e.g., patterns of distribution and abundance of individual species or assemblages of species) (Bunn et al. 1999, TNC 2003). To meet this need, we are conducting a pilot study to examine, at a range of sites along the Sacramento River, several potential indicators that integrate over various spatial and temporal scales.

A small-scale indicator, but one that might be meaningful for understanding energy flow through food webs, is the accrual of organisms at various trophic levels on substrate particles in river channels. Different disturbance, sedimentation, light, nutrient, temperature and other physical and chemical regimes have been shown to favor different taxa of primary producers and decomposers at the base of the food web. These basal species will have differential vulnerabilities and nutritional values for primary consumers (grazers and detritus-feeding organisms), which in turn will support different levels of production of predators higher in the food web. By monitoring the succession of lower trophic levels on experimental substrates over periods of weeks and months we hope to provide some indication of how well conditions in different reaches of the river are supporting the food base of desirable fishes and other predators.

As a group, bats may also be useful as ecological indicators for river-riparian systems because their response to habitat alteration is integrated over a broader spatial scale than many other species currently being studied. Bats account for a substantial fraction of the native mammal diversity on the Sacramento Valley floor, and all are insectivorous with the foraging of many species being concentrated near rivers, streams and riparian vegetation. Foraging styles and movements differ among species, but range from a fraction of a kilometer to several tens of kilometers per night. On the alluvial Sacramento Valley floor most natural cavity roosts are in large defective trees in mature riparian forest remnants, and thus the persistence (or restoration) of local bat populations is intimately tied to riparian forest dynamics. Existing research and historic site records indicate that the western red bat (*Lasiurus blossevillii*) relies heavily upon cottonwood and sycamore riparian forests, and recent findings suggest that naturalistic flood regimes may benefit this species (Pierson, Rainey, and Corben, unpublished data).

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In recognition of this, the Western Bat Working Group recently passed a resolution supporting further research, inventory, conservation, and maintenance of existing stands, and restoration and reestablishment of historic cottonwood and sycamore ecosystems across western North America (Pierson, pers. comm., 2002). To further our knowledge of how bats interface with the Sacramento River ecosystem we are conducting reconnaissance-level acoustic surveys during summer and fall. With the aid of passive acoustic detectors we are collecting baseline information on bat diversity and foraging activity at a broad range of habitats including: main channel, tributary channel, oxbow lake, mature cottonwood riparian forest, horticultural restoration sites, orchards, row crops and grasslands. We also intend to do follow-up surveys at selected sites in winter and spring to test for seasonal differences in bat activity.

Over larger (watershed) scales, stable nitrogen and carbon isotope analyses of aquatic organisms and terrestrial insectivores, such as bats, swallows, and spiders show promise as potential indicators of river-to-watershed fluxes of nutrients and contaminants (e.g., nutrients and contaminants exported from watersheds to rivers can be incorporated back into terrestrial food webs via aquatic insect emergence) (Cabana and Rasmussen 1996, Cabana et al. 2000). Emerging insects from contaminated aquatic areas can deliver contaminants to terrestrial insectivores, which may be concentrated in riparian habitats. Stable isotopic signatures of nutrients or contaminants of aquatic versus terrestrial origin can then be followed through the food web because the uptake of stable isotopes across trophic levels occurs at a known rate of fractionation (Vander Zanden and Rasmussen 1999). We are surveying $^{15}N{:}^{14}N$ and $^{13}C{:}^{12}C$ ratios in widely distributed organisms at different trophic levels to construct a picture of isotope enrichment at selected sites within the Project area that can be correlated with present and historical land use. These data will form an invaluable baseline reference for future studies of environmental change, and permit comparisons of watershed impacts to be drawn between the Sacramento River and other watersheds where similar data are being collected (e.g., the South Fork Eel and Cosumnes Rivers). Initial results from the Biological Indicators Project are detailed in Stillwater Sciences et al. (2003).

CONCLUSION

In this paper we have introduced an incomplete sampling of the research and monitoring studies that are currently being conducted to evaluate

how the Sacramento River ecosystem is responding to management actions (full reports from many of these studies are posted electronically at http://www.sacramentoriverportal.org). Initial results suggest that current horticultural approaches to restoration are advancing our conservation goals, but that much additional benefit may be gained from implementing complementary naturalprocess restoration strategies. Although there are many important studies underway, there is a clear need to increase scientific scrutiny upon this important riverine ecosystem. We are at a pivotal time in the Great Valley's history as a great deal of resources are being directed at salvaging the degraded Sacramento River ecosystem. It is our goal to build a science program that can effectively contribute to this revitalization.

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