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PATCH CHANGE AND THE SHIFTING MOSAIC OF AN ENDANGERED BIRD'S HABITAT ON A LARGE MEANDERING RIVER

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ABSTRACT

The yellow-billed cuckoo is a state-listed endangered bird in California. The largest population of cuckoos in California is on the meandering portion of the middle Sacramento River. I studied two time periods (1952 and 1987) of a 127-km study reach of the Sacramento River to document regeneration and spatial shifts in yellow-billed cuckoo habitat patches due to fluvial geomorphic processes, vegetation recruitment and succession over a 35-year period. The spatial co-occurrence of natural riparian vegetation and floodplain age <65 years were used to identify sub-patches of cottonwood forest, a preferred habitat element, within larger patches of contiguous riparian forest. Only 247 ha (15%) of the 1664 ha of habitat sub-patches identified in 1952 were coincident with those in 1987. Seventeen (27%) of the 62 sub-patches delineated for 1987 emerged anew and independently of the 1952 patches; the remaining 83% formed by shifting adjacent to the patches from 1952. Comparing observation data (1987–1990) with modelled patches (1987) indicates that 79% of the modelled sub-patches correctly predicted cuckoo presence or absence. The commission and omission errors were 7% and 14%, respectively. The goal of sustaining the yellow-billed cuckoo population will require that river channel management encourage channel meander dynamics and channel cut-off to maintain natural regeneration of cottonwood and willow pioneer plant communities. The active management of hydrodynamic (flow) and geomorphic processes, including the use of prescription flows and the removal of bank revetment (riprap), will be important tools towards achieving this goal.

KEY WORDS: floodplain age; patch dynamics; Sacramento River; yellow-billed cuckoo

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INTRODUCTION

Conservation of natural processes that create and maintain habitats of endangered species is critically important. It is well established that patch dynamics can have a key role in sustaining populations over long time periods (Pickett and Thompson, 1978; Kozakiewicz, 1995; Wu and Loucks, 1995). There is a need to quantify the physical dynamics and the shifting mosaic of a species' habitat (Pickett and Rogers, 1997), and relatively few studies have investigated the temporal dimension of habitat models (Morrison, 2002), although interest is increasing (Bissonette and Storch, 2007). The Sacramento River population of yellow-billed cuckoos (*Coccyzus americanus*) in northern California is ideal for studying habitat change because it uses trees and shrubs that colonize some of the most dynamic parts of a meandering river system: point bars on river bends that form from lateral erosion of banks and floodplain (oxbow) lakes that form from channel cut-offs. Pioneer riparian forests in those areas of the floodplain have high growth rates and recruit through primary successional processes and are subject to frequent flooding, erosion and depositional processes (Vahgti and Greco, 2007). Riparian forest patches on the Sacramento River can change rapidly (Greco and Plant, 2003), and a high rate of change in landscape pattern is known to be a significant factor in population survival (Harrison and Fahrig, 1995).

The yellow-billed cuckoo is a medium-sized bird and neotropical migrant that breeds in summer in North America and winters in South America (Hughes, 1999). Population declines have been observed throughout its summer range since 1980, but none more dramatic than in the western United States (Wiggins, 2005). The cuckoo was listed by the state of California as threatened in 1971 and as endangered in 1988 (CDFG, 1998) under the state's Endangered Species Act. It is currently a candidate for listing under the federal Endangered Species Act as a distinct population segment. The status of the western subspecies (*Coccyzus americanus occidentalis*) has a long and complex history. The western subspecies, also known as the California cuckoo, was first described by Ridgway (1887), and the American Ornithologists' Union recognized the subspecies from 1895 to 1957 (AOU, 1895, 1910, 1931, 1957). Presently, the western subspecies is not recognized by the US Fish and Wildlife Service; however, there is active debate from both morphological and phylogenetic viewpoints (Bent, 1940; Banks, 1988; Franzreb and Laymon, 1993; Pruett *et al.*, 2001; Fleischer, 2001).

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Historically, the California statewide population was estimated at approximately 15 000 pairs (Hughes, 1999), and Belding (1890) noted that the cuckoo was a relatively common bird in the Central Valley. Precipitous declines were noted by naturalists in the 1940s (Grinnell and Miller, 1944), and in 1977, the statewide population was estimated at 122–163 pairs (Gaines and Laymon 1984), and in 2000, only 100 pairs remained extant (Halterman *et al*., 2001). The Sacramento River cuckoo population (the largest in the California) declined from 96 pairs in 1973 (Gaines, 1974) to approximately 60 pairs in 1977 (Gaines and Laymon, 1984), and a 4-year survey by Halterman (1991) found the total number of pairs from 1987 to 1990 to vary between 23 and 35 pairs. In 2000, Halterman *et al*. (2001) found 40 pairs on the Sacramento River, and the most recent census in 2010 detected 18 individuals from which an occupancy analysis estimated the population to be between 38 and 76 individuals (Dettinger and Howell, 2011). Clearly, this population is in poor condition, and stochastic effects from disease (e.g. West Nile virus), genetic, or environmental impacts, could result in extirpation. In addition to dramatic summer range habitat loss over the last two centuries in North America (e.g. 5% remains in California's Central Valley), the impacts to the yellow-billed cuckoo population also must consider the contributing effects from the wintering grounds (Wiggins, 2005). It is unknown precisely where the western population segment of cuckoos over winters in South America, and thus, it is unknown what the threats and stressors are in that aspect of their life history. Pesticides have been identified as another potential stressor for cuckoos (Gaines and Laymon, 1984).

Yellow-billed cuckoos typically arrive in North America in late June and depart to South America with their young in mid-August to early September. Their preferred food items are green caterpillars, hornworms, katydids, tent caterpillars, tree frogs, grasshoppers and cicadas. The average clutch is two to four eggs, and the young are fledged at an age of one week. In years of high food abundance, successful double and triple brooding has been observed (Halterman, 1991; Laymon *et al*., 1997; Halterman, 2009). Field studies of the yellow-billed cuckoo's nesting and foraging habitat requirements indicate that it is a riparian-obligate species that has an average home range of 20–51 ha (Laymon, 1980; Halterman, 2009); the preferred habitat is large (>5 ha), thick (>100 m) patches of gallery riparian forest consisting of Fremont cottonwood (*Populus fremontii*) and various willow (*Salix*) species in combination with open water habitats, such as an oxbow lake or backwater sloughs (Gaines, 1970; Gaines, 1974; Laymon and Halterman, 1989; Laymon and Halterman 1989; Halterman 1991; Laymon *et al*., 1997; Halterman *et al*., 2001). In wildlife habitat relationship modelling, a specific plant association, such as cottonwood–willow, within a larger patch of a more general vegetation community type, such as riparian forest is called a 'special habitat element' (Mayer and Laudenslayer, 1988).

Previous work and context for this study

I have been involved in several studies to geographically analyze cuckoo habitat on the Sacramento River. A series of multivariate analyses of the vegetation composition of cuckoo habitat patches on the Sacramento River revealed that area of cottonwood forest was the single most important habitat variable to predict occupancy by yellow-billed cuckoos (Girvetz and Greco, 2009). That same study utilized a novel method of delineating habitat patches using a geographic information system (GIS) algorithm called PatchMorph (Girvetz and Greco, 2007). To study the temporal dynamics of cuckoo habitat, a geographic wildlife habitat relationship model was developed and implemented by Greco *et al*. (2002) for the yellow-billed cuckoo on the Sacramento River along a limited extent of the river (35 km; representing only 27% of the current study). That model was applied to a geographic time series (i.e. land cover maps) of six time periods between 1937 and 1997 (see Greco and Plant, 2003), and the modelling results showed the dynamic nature of the cuckoo's habitat in that limited section of the river. That model utilized 'floodplain age' as a surrogate variable for presence of the cottonwood–willow plant association. 'Floodplain age' is the time elapsed since a low-flow (e.g. during the dry season) channel has changed state from water to land as a result of channel migration from fluvial geomorphic deposition and erosion processes (Greco *et al*., 2007). The concept is illustrated in Figure 1(a). From a floodplain age surface model that tracked 127 years (1870–1997) of channel movement, cottonwood was found to dominate in the floodplain on 10–58 year old land (Greco *et al*., 2007).

The study presented in this paper is an extensive retrospective habitat analysis examining the portions of riparian forest patches most important to yellow-billed cuckoos, those that contain a dominance of cottonwood forests (as predicted by floodplain age) and how they change over time. This 'sub-patch' approach is illustrated in Figure 1(b). Cottonwood trees colonize new land either deposited on river bends through channel meander dynamics driven by lateral bank erosion (Mahoney and Rood, 1998) or by land exposed by sedimentation and dewatering processes of abandoned channels (e.g. oxbow or floodplain lakes; Greco and Plant, 2003; Michalková *et al*., 2011; Stella *et al*., 2011). I used two riparian vegetation geospatial datasets (1952 and 1987), two floodplain age geospatial datasets (1870–1952 and 1870–1987) and observation data of yellow-billed cuckoos (1987–1990) from Halterman's (1991) study.

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I had four main research questions: (i) How much riparian vegetation and yellow-billed cuckoo habitat was lost between 1952 and 1987?; (ii) How does yellow-billed cuckoo sub-patch habitat structure (i.e. area and width) change over time?; (iii) How does the habitat sub-patch mosaic shift in space with respect to time?; and (iv) How accurate is the sub-patch habitat model (using patch size, width and land age as a surrogate variable for cottonwood) at predicting presence or absence of yellow-billed cuckoos?

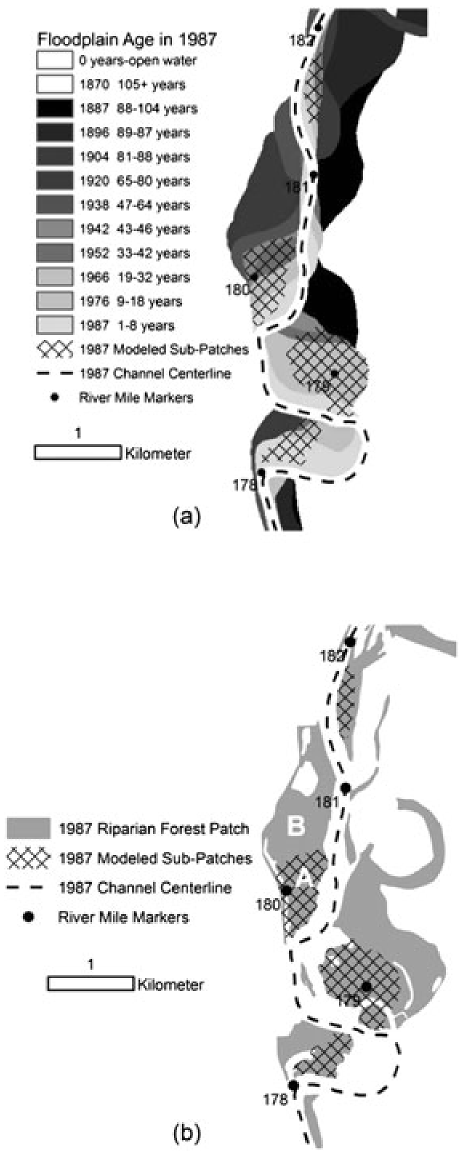

Figure 1. Concept diagrams. (a) The floodplain age concept; the lighter shades of gray are lands aged less than 65 years that support a dominance of cottonwood trees and willow species; (b) the concept of a habitat 'sub-patch', A, within a larger riparian forest patch, B. Each of the patches depicted were occupied by yellow-billed cuckoos in the surveys conducted from 1987 to 1990

STUDY AREA

The Sacramento River is the largest river in California, and its riparian forests are a valuable and biologically rich natural resource with a long history (Thompson, 1961). Although 95% of the riparian forests have been lost in California's Central Valley (Bay Institute, 1998) due to agricultural, urban and flood control purposes, a field survey of birds by Hehnke and Stone (1978) found that the riparian zone of the Sacramento River supports 90 avian species. The Sacramento River flows from north to south from the southern tip of the Cascade Range through the alluvial soils of the Sacramento Valley and drains into the San Francisco Bay (Figure 2(a)). The mediterranean climate in the Sacramento Valley has hot

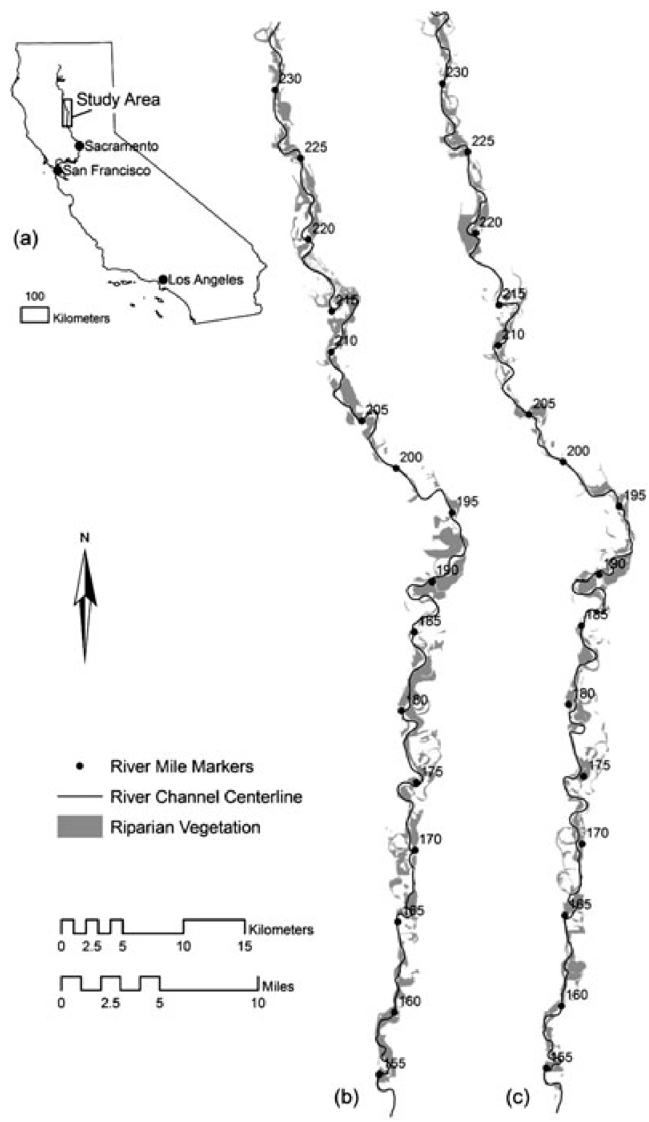

Figure 2. (a) The Sacramento River and location of the study area; (b) 1952 vegetation data set (whole patches); and (c) 1987 vegetation data set (whole patches)

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dry summers and cool wet winters with precipitation averaging 455 mm year^{-1}. The Sacramento River has the largest dam in the state (Shasta Dam), and in the post-dam era (after 1945), the 1.5-year recurrence interval discharge ($Q_{1.5}$) is 1727 m^3 s^{-1}, and instantaneous peak flows exceed 4000 m^3 s^{-1} (measured at the Bend gauge, USGS #11377100; CALFED, 2000).

A river mile (RM) marker system was established on the Sacramento River in the 1960s by the US Army Corps of Engineers. The RM markers no longer accurately represent the length of the centerline because of the meandering channel, but the markers are used as a *de facto* geographic area location system.

The study area (river reach) used in the analysis is 127 km in length, from the RM 155 near Colusa to RM, 234 near Red Bluff and about 2–4 km in width (Figure 2(b and c). This section of the river contains the highest quality riparian forests in the river system because levees are set back from the river channel and natural meander dynamics still function to recruit riparian forests.

METHODS

Vegetation/land cover data

Two GIS land cover datasets (1952 and 1987) were obtained from the California Department of Water Resources, Northern District Office, as ArcInfo coverages (ESRI, 2010, Redlands, CA, USA). Both datasets were created with the same methods and classification systems (CDWR, 1978) under the direction of R. R. McGill Jr, a land use analyst who studied changes in the riparian zone of the Sacramento River for several decades. The land cover mapping was completed from sets of aerial photography spanning the length of the river channel. McGill (1987), as part of his 1987 land use change assessment, had the mapping of the river digitized and georeferenced along with mapping from 1952 aerial photographs (R. R. McGill, Jr, unpublished data).

Both datasets were digitized from RM 155 to 235; however, the 1952 dataset had a gap in mapping from RM 214 to 220. This gap was filled between RM 214 and 218 with mapping from a 1952 data set in a previous study (Greco and Plant, 2003) and supplemental mapping from one aerial photograph between RM 218 and 220. I scanned the aerial photograph (dated 26 June 1952; scale 1:20 000; source US Department of Agriculture) and georeferenced it using four control points in ArcGIS (version 9; ESRI, 2010) and obtained a root mean square error of 3.7 m. I digitized those areas covered by woody riparian vegetation and the river channel within that small section of the river (between the two other datasets). All three data sets from 1952 were merged into a single shapefile.

All natural woody vegetation polygons from the 1952 and 1987 data sets were selected and exported to separate shapefiles for analysis. The vegetation categories selected were: V1L, V2H, V2L, V3H, V3L, V4H, V4L, P and P2 (definitions in CDWR 1978). These vegetation data sets are shown in Figure 2(b and c). A summary table was created in ArcGIS to sum the total amount (area) of riparian vegetation from each time period.

Deriving sub-patches from floodplain age surface data

I first converted the vector vegetation datasets (from the previous step) to rasters with a 20-m cell size using the Spatial Analyst extension for ArcGIS to create the sub-patches of riparian vegetation from the larger (full) patches. Two raster floodplain age surfaces with 20-m cell size from Greco *et al.* (2007), 1870–1952 and 1870–1987, were, respectively, paired with the 1952 and 1987 vegetation data sets and used to extract those portions of the larger patches that contained floodplain land <65 years of age. The co-occurrence of young (<65 year of age) floodplain with woody riparian vegetation was accomplished using a conditional statement in the raster calculator of the Spatial Analyst extension.

The resultant rasters, those containing vegetation on young floodplains, were used as input to the PatchMorph algorithm (Girvetz and Greco, 2007) to delineate sub-patches >5 ha in size (Halterman *et al.*, 2001). The other parameters for the PatchMorph algorithm were: a patch gap threshold (patch contiguity) of 100 m, a spur threshold (minimum patch width) of 100 m and a hard barrier using the main channel of the river to prevent patches from being delineated across the river channel (Girvetz and Greco, 2009). The resultant sub-patches were converted to vector shapefiles and attributed with two patch metrics for each time period: area (m^2) and width (m).

Sub-patch shifting mosaic

I conducted a vector-based map overlay union analysis in ArcGIS between the 1952 sub-patches and the 1987 sub-patches from the shapefile generated in PatchMorph to characterize the shifting mosaic of sub-patches (Mitchell, 1999). This analysis can distinguish which sub-patches spatially coincide with one another (i.e. are shared) between time periods, which are adjacent and which are independent (i.e. the sub-patches that ‘blinked off’ from 1952 to 1987 or those that ‘arose anew’). I visually recorded these respective patterns from the resultant union analysis map.

Sub-patch habitat model accuracy

I used the observations of yellow-billed cuckoos collected by Halterman (1991) from 1987 to 1990 in the study area to assess the accuracy of the sub-patch habitat model. The

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4 years of observations for each site were pooled (summed) for each survey site (Table I). Yellow-billed cuckoos observed at least once at a survey site over the 4 years of observation were considered being in an occupied patch. These patch occupancy data were related to the modelled 1987 vegetation sub-patches (Table I) using RM descriptors and maps. A contingency analysis was performed to assess the habitat model's ability to predict yellow-billed cuckoo presence and absence. A contingency table, a Chi-square likelihood ratio (G^2) test and a Kappa statistic (measure of agreement) were computed using JMP software (Version 9; SAS Institute 2010, Cary, NC, USA).

RESULTS

Vegetation and floodplain age data

The sum total area of all riparian vegetation in 1952 was found to be 7057 ha and 5931 ha in 1987, a reduction of 16% over the 35-year time period. This loss of riparian forest is most likely attributable to agricultural land development adjacent to the river (most of this land is privately owned). The sum total area of the sub-patches for 1952 was 1664 ha and for 1987 was 1479 ha, representing an 11% reduction over the 35-year interval.

Sub-patch habitat model and patch change

Sub-patch characteristics were measured in terms of size (area) and width (Figures 3, 4). The total number of modelled sub-patches that contained at least 5 ha of floodplain with land age <65 years was 63 and 62 for 1952 and 1987, respectively. The range of values for the sizes of the modelled sub-patches for 1952 was 6–99 ha with a mean of 26 ha [standard error (SE) = 2.8, standard deviation (SD) = 22.5], and for 1987, it was 5–93 ha with a mean of 24 ha (SE = 2.5, SD = 19.9; Figure 3). The range of values for sub-patch width for 1952 was 127–714 m and the mean was 310 m (SE = 19, SD = 152), and for 1987, it was 139–806 m and the mean was 316 m (SE = 20, SD = 155; Figure 4).

Sub-patch shifting mosaic

The spatial coincidence analysis of sub-patches between 1952 and 1987 (Figure 5) revealed that only 247 ha (of the 1664 ha in 1952) were coincident; only 15% of the sub-patches in 1952 was shared in common with the 1987 sub-patches. Thus, 85% of the sub-patches in 1952 changed to an age >65 years by 1987. Fifteen (24%) of the 63 sub-patches identified in 1952 were lost, and 48 (76%) shifted adjacent to the sub-patch in 1987. Seventeen (27%) of the 62 patches in 1987 arose anew independently of the sub-patches in 1952; and thus, the remaining 83% formed from shifting adjacent to the existing sub-patches from 1952.

Sub-patch habitat model accuracy

The contingency analysis (Table II) indicates that overall accuracy of the sub-patch habitat model was 79% for correctly predicting cuckoo presence and absence (59% and 20%, respectively). The commission error was 7%, and the omission error was 14%. A commission error is predicting the presence of a cuckoo at a survey site where none was observed. An omission error is not predicting the presence of a cuckoo at a survey site and one (or more) was observed. The likelihood ratio Chi-square test was significant [$G^2 = 13.8$, degree of freedom (df) = 1, $p < 0.001$], and the Kappa (K) statistic indicated moderate agreement ($K = 0.496$, SE = 0.12). These model results conform to those from previous cuckoo habitat modelling efforts by Greco *et al*. (2002) and Girvetz and Greco (2009).

DISCUSSION

The habitat occupied by the yellow-billed cuckoo population on the Sacramento River is a highly dynamic mosaic of patches that arise anew, disappear and shift in response to geomorphic channel processes and vegetation succession over decadal timescales. There is a great need for management of ecosystems on the basis of patch dynamics (Pickett and Rogers, 1997), especially in riparian landscapes (Malanson, 1993; Rood *et al*., 2003), to sustain populations dependent on specific attributes of patches and successional states. Thus, natural river channel processes, such as flow regimes, erosion and lateral channel movements that promote pioneer riparian forest development, should be viewed as 'desirable' (Florsheim *et al*., 2008) and essential to a management and restoration strategy focused on patch dynamics (Poff *et al*., 1997; Richter and Richter, 2000). The critically important ecosystem processes that create and maintain patches of pioneer riparian forests are: lateral channel migration through bank erosion and point bar deposition that create new floodplains and channel bend cut-offs that create new floodplain lakes.

Channel dynamics are largely driven by inter-annual flows and the composition of near-bank channel materials—either natural (e.g. geological, soil, vegetation) or artificial (e.g. engineered bank revetment) (Larsen and Greco, 2002). Water impoundment and flow regulation by major dams, such as Shasta and Keswick on the Sacramento River, can decrease stream power that decreases the ability of the river channel to migrate laterally (Larsen *et al*., 2006) and reduces the quantity of new land production which subsequently decreases the amount of new pioneer riparian forests (Greco *et al*., 2007). The 1.5-year recurrence interval (RI; $Q_{1.5}$) flow

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Table I. Yellow-billed cuckoo survey sites and observed presence (compiled from Halterman, 1991) in relation to the 1987 modelled sub-patch size (area) on a floodplain land <65 years old

Study site patch number	Halterman (1991) site number	River mile	Bank side[a]	Sub-patch area (ha)	Cuckoo presence[b]
1	10	234.5	R	0.0	0
2	11	232.5	L	17.7	+
3	12	232.0	R	0.0	+
4	13	231.0	L	0.0	0
5	14	228.5	L	13.0	+
6	15	228.0	R	10.9	0
7	16	225.5	R	0.0	0
8	17	223.0	L	11.3	+
9	18	220.0	L	36.4	+
10	19	219.0	R	27.4	0
11	20	213.5	L	0.0	0
12	21	210.5	R	0.0	0
13	22	207.0	R	0.0	0
14	23	205.5	R	13.7	0
15	24	204.5	L	0.0	+
16	25	203.0	L	87.8	+
17	26	197.0	L	93.3	+
18	27	195.5	L	17.5	+
19	28	194.0	R	9.3	+
20	29	193.5	L	0.0	0
21	30	192.0	R	39.9	+
22	31	192.0	L	0.0	0
23	32	191.5	L	41.3	+
24	33	190.5	L	0.0	+
25	34	190.5	R	21.9	+
26	35	189.0	R	35.6	+
27	36	188.0	L	51.9	+
28	37	187.0	R	15.3	+
29	38	186.5	R	6.0	0
30	39	184.5	R	25.2	+
31	40	184.0	L	9.4	+
32	41	183.0	R	42.6	+
33	42	182.5	L	0.0	+
34	43	181.5	L	13.3	+
35	44	180.0	R	39.8	+
36	45	179.0	L	62.8	+
37	46	178.0	R	20.4	+
38	47	177.0	L	0.0	+
39	48	175.0	L	53.2	+
40	49	174.0	L	6.4	+
41	50	173.0	L	0.0	+
42	51	172.0	R	37.2	+
43	53	170.5	R	12.6	+
44	52	170.0	L	26.7	+
45	54	169.5	R	20.7	+
46	55	167.0	R	7.3	+
47	56	166.0	L	80.2	+
48	57	165.5	L	0.0	+
49	58	164.0	R	0.0	+
50	59	163.0	L	0.0	0
51	60	162.5	R	9.9	+
52	61	161.5	L	0.0	+
53	62	159.0	R	14.3	+
54	63	158.5	L	0.0	0
55	64	157.0	R	24.4	0
56	65	155.5	L	9.2	+

[a]R = right bank (facing downstream); L = LEFT bank.
[b]+ = presence; 0 = absence.

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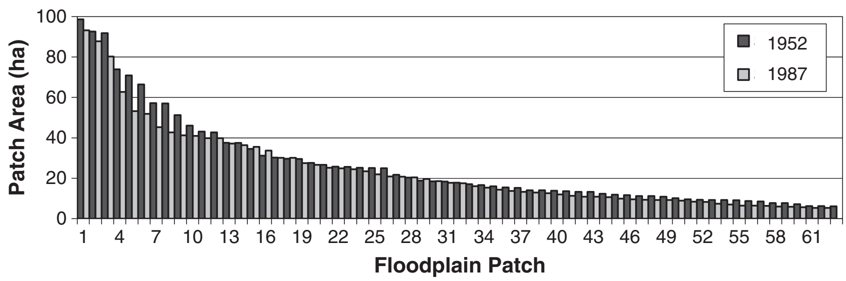

Figure 3. Modelled sub-patch area (ha) frequency distribution for 1952 and 1987.

is a typical indicator of a channel-forming flow. The pre-Shasta Dam 1.5-year RI discharge ($Q_{1.5} = 2435\,m^3\,s^{-1}$) was reduced 30% (post-Shasta Dam $Q_{1.5} = 1727\,m^3\,s^{-1}$), and the pre-Shasta dam 10-year RI discharge ($Q_{10} = 6173\,m^3\,s^{-1}$) was reduced 61% (post-Shasta Dam $Q_{10} = 3794\,m^3\,s^{-1}$) (CALFED 2000). The mean annual peak discharges before (1879–1944) and after (1944–1993) the dam were $3426\,m^3\,s^{-1}$ and $2{,}237\,m^3\,s^{-1}$, respectively (CALFED, 2000), a 65% reduction. Hence, stream power on the Sacramento River has dramatically decreased since 1945, and channel migration potential has decreased 38% as a result of the changed flows (Fremier, 2007). Compounding the flow regulation stream power problem are numerous in-channel water diversions and pumping plants for agricultural uses from major structures (e.g. Red Bluff diversion dam near RM 246 and the Glen-Colusa Irrigation District diversion facility near RM 205, capable of diverting $>85\,m^3\,s^{-1}$). In Table II, from Greco *et al*. (2007), the total land area with an age <65 years in 1952 was 7818 ha and 4026 ha in 1987, a 52% reduction. However, in this study, I found the rate of colonization of cottonwood (sub-patches) on those young (<65 years of age) floodplains moderately increased from 21.3% in 1952 to 36.7% in 1987, thus partially offsetting the severe reduction in new land produced. A likely cause for this increase is the reduction of scour from regulated flows and floodwaters held behind Shasta Dam that acted to preserve cottonwood stands rather than erode them.

Greatly exacerbating the ecological cascade effect is the construction of bank revetment, such as piled rock or concrete riprap, engineered to prevent the channel from migrating laterally. About 50% of the channel in the study area has bank revetment installed mainly by the US Army Corps of Engineers (CALFED, 2000). The channel migration potential on the Sacramento River has decreased 79% from pre-dam conditions when channel revetment is considered in addition to the stream power reductions (Fremier, 2007). Hehnke and Stone (1978) found 93% less bird density and 73% less species diversity on banks with revetment than in riparian forest plots along the Sacramento River. These findings highlight the severe negative ecosystem consequences of bank revetment. Some bank revetment is necessary to protect valuable human-engineered infrastructure on the river, such as bridges, but much of the bank revetment is preventing channel migration from eroding agricultural fields. Given the expense to install and maintain the revetment, justifying the protection of field crops is questionable as to its beneficial use, given the ecological consequences.

Given the magnitude of the reduction in hydro-geomorphic processes on the Sacramento River, one might reasonably expect to see larger reductions in cottonwood forest production than the 11% found in this study. One likely explanation is the increased colonization rate from the reduction of scour potential as discussed earlier. Moreover, there was remarkable sub-patch mosaic stability over the 35-year time interval, with nearly the same number of patches, mean size, mean width and variability, yet only 15% of those patches were in the same spatial location. The patches of cottonwood that shifted adjacent (from 1952 to 1987) were generally those colonizing migrating river bends (point bars), whereas the patches that arose anew and independently were mostly formed by oxbow or floodplain lake

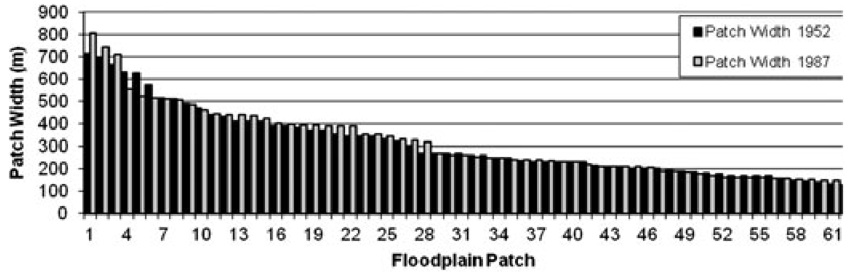

Figure 4. Modelled sub-patch width (m) frequency distribution for 1952 and 1987.

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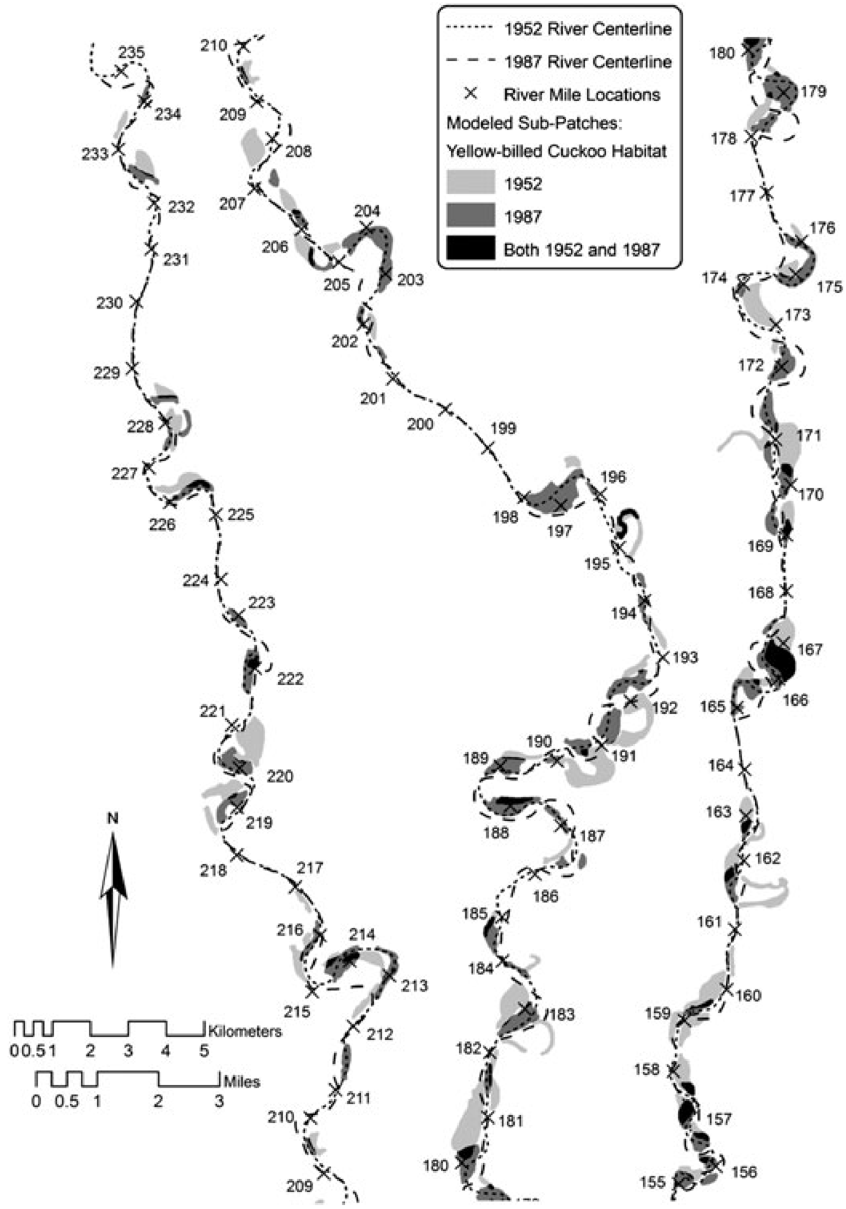

Figure 5. Results from the geographic information system temporal analysis show the location of 1952 and 1987 vegetation sub-patches and their co-occurrence (overlap) in time on a floodplain <65 years in age. This diagram illustrates the shifting mosaic of habitat sub-patches for the yellow-billed cuckoo

processes (from bend cut-off). These results point to the crucial need for maintaining these ecosystem processes and augmenting them to increase the amount of suitable habitat for yellow-billed cuckoos.

Long-term sustainability and viability of the yellow-billed cuckoo population on the Sacramento River will thus require process-based restoration (Greco, 2008). Specifically, management actions directed at sustaining and recovering the population will require river management that encourages channel meander dynamics and channel cut-offs, wherever feasible, to permit continual creation of new floodplain and natural regeneration (recruitment) of large patches of Fremont cottonwood and willow pioneer plant communities. Maintaining a stable mosaic of these patches should be the minimum near-term goal. The active management of hydrodynamic (flow) and geomorphic processes, including occasional prescription flows ($Q > 2{,}800\,\mathrm{m^3\,s^{-1}}$) (CALFED, 2000) in the spring with drawdown (recession) rates (*sensu* Mahoney and Rood 1998) timed to coincide with cottonwood seeding and targeted removal of bank revetment (i.e. riprap), will be important tools towards achieving the ultimate goal of creating more

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Table II. Contingency analysis of the number of sample sites ($n = 56$) where yellow-billed cuckoos were detected or not detected in a field survey in relation to modelled sub-patches

Count (*n*) Percent %		Cuckoo field observation		
		Present	Absent	Total
Modeled sub-patches with land age <65 years	Present	33 58.9	4 7.1	37 66.1
	Absent	8 14.3	11 19.5	19 33.9
Total (*n*) Total (%)		41 73.2	15 26.8	56 100

pioneer plant community patches (CALFED, 2000). There are two projects on the Sacramento River that are currently in the planning stages to intentionally remove or fail to maintain bank revetment to allow river channel bend cut-offs to create floodplain lake habitats. One is at Woodson Bridge State Recreation Area (RM 219; Larsen and Greco, 2002), and the other is at the Llano Seco Unit of the Sacramento River National Wildlife Refuge complex (RM 178; MBK Engineers, 2005). Other important ecosystem benefits of eroding banks on the Sacramento River include creation of bank swallow (*Riparia riparia*) nesting habitat and recruitment of gravel and wood for fish habitat (Buer *et al*., 1989).

The yellow-billed cuckoo population on the Sacramento River is the largest in California. The most recent census in 2010 indicated there are <100 individuals extant, and this is small in relation to a population ecologist's recommendations for long-term viability. There is no magic number of individuals to determine a minimum viable population for species of conservation interest according to Flather *et al*. (2011). However, the authors conclude that: 'We suspect... that multiple populations of thousands (not hundreds) of individuals will be needed to ensure long term persistence' (Flather *et al*., 2011:314). It will be challenging to recover the western population segment of the yellow-billed cuckoo to those levels.

The results from this study suggest that floodplain age is an important ecosystem attribute that could be monitored as a variable to assess riparian ecosystem functionality for yellow-billed cuckoos. As development pressures from agricultural, urban and industrial sectors of society intensify around the river corridor over time, the river will be subjected to greater constraints on natural processes. This is already the case for the lower 232 km of the Sacramento River system, in which the main channel is lined with large levees (dikes) and riprap almost continuously from RM 0–144 with virtually no meander dynamics, and, as a result, has no yellow-billed cuckoo habitat in this portion of the river. The 150-km portion of the river (from RM 144–245—largely the focus of this study) upstream of the industrialized section has the greatest potential to maintain large patches of naturally regenerated stands of cottonwood forest because the levees are setback from the river channel and about half of the eroding banks and point bars are still active to some degree. As stands of cottonwood age beyond 65 years, other tree species increase in frequency and relative cover changing the forest to a 'mixed riparian' community type (Greco *et al*., 2007) which is less suitable (i.e. less functional) to yellow-billed cuckoos. In this study, I found that 85% of the sub-patches from 1952 had aged beyond 65 years by 1987. The floodplain environment of a large, low gradient meandering river system should have a variety of land ages associated with the movement of the active channel such that a diverse array of plant communities is continually present and in flux. Documenting floodplain age on a basis of 5–10-year intervals would be a highly efficient method to monitor this diversity and the habitat conditions for yellow-billed cuckoos on the Sacramento River.

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