CALFED BAY-DELTA PROGRAM

CALFED SCIENCE FELLOWS PROGRAM

Sea Grant California

In cooperation with the

California Sea Grant College Program

FELLOWSHIP APPLICATION COVER PAGE

APPLICANT TYPE [x] Postdoctoral Researcher [ ] Ph.D. Graduate Student

PROJECT NUMBER ______

PROJECT TITLE Modeling Physical Drivers and Age Structure of Cottonwood Forest Habitat: An Integrated Systems Approach

FINANCIAL SUMMARY

First Year CALFED Funds Requested: $76,250

Total CALFED Funds Requested: $228,750

Duration: 3 years

Proposed Start/Completion Dates: March 1, 2008 - February 28, 2011

APPROVAL SIGNATURES

FELLOW: [signature]

Name: Alex Fremier

Position/Tit Postdoc Fellow

Departmen Department of Forest and Natural Resource Mgmt

Institution: SUNY College of Environmental Science and Forestry

Address: 1 Forestry Drive, 206 Marshall Hall

City, State Syracuse, New York 13210

Telephone: 315-470-4902

Fax: 315-470-6535

E-mail: fremier@gmail.com

MENTOR/PRINCIPAL INVESTIGATOR: [signature]

Name: John C. Stella

Position/Title: Assistant Professor

Department: Department of Forest and Natural Resource Mgr

Institution: SUNY College of Environmental Science and Forestry

Address: 1 Forestry Drive, 206 Marshall Hall

City, State & Z Syracuse, New York 13210

Telephone: 315-470-4902

Fax: 315-470-6535

E-mail: stella@esf.edu

AUTHORIZED INSTITUTIONAL REPRESENTATIVE: [signature]

Name: Neil H. Ringler

Position/Title: Dean of Research

Department: Research

Institution: SUNY College of Environmental Science and Forestry

Address: 1 Forestry Drive, 200 Bray Hall

City, State & Z Syracuse, New York 13210

Telephone: 315-470-6606

Fax: 315-470-6779

E-mail: neilringler@esf.edu

Will animal subjects be used? [ ] Yes [x] No

APPROVAL DATE: ______ PROTOCOL #: ______ PENDING: ______

Does this application involve any recombinant DNA technology or reseai [ ] Yes [X] No

MODELING PHYSICAL DRIVERS AND AGE STRUCTURE OF COTTONWOOD FOREST HABITAT: AN INTEGRATED SYSTEMS APPROACH

INTRODUCTION AND PROJECT OBJECTIVE

Problem Statement

In the Central Valley of California, Fremont cottonwood (*Populus fremontii*) dominates the near-channel ecosystems of the Valley rivers. The ecological and hydrological functions of these riparian zones are directly tied to the population dynamics of Fremont cottonwood. It is the largest, fastest-growing, and most abundant primary producer to colonize the young floodplain surfaces of the near-channel zone. It builds the ecological foundation of these ecosystems by stabilizing the substrate, fixing carbon, generating large woody debris, and creating vertical stratification for wildlife habitat (Patten 1998). Declines in the cottonwood population will have a direct impact on the health of the adjacent river system (Gregory et al. 1991). Improving our knowledge of the ecology and population dynamics of Fremont cottonwood is a necessary foundation for managing the more complex dynamics of all the biota associated with it in riparian communities.

Cottonwood trees, which are classic disturbance-dependent organisms, have a suite of life history traits that allow them to establish and thrive under a highly variable flow regime and a spatially complex geomorphic setting (Braatne et al. 1996; Mahoney and Rood 1998). Over the last century, the near-channel riparian zone on rivers throughout the Central Valley has been greatly altered by land conversion and flow alteration, resulting in severely constrained habitat with an artificially stable physical regime (Katibah et al. 1984; Ligon et al. 1995; Poff and Hart 2002). Climate change threatens to further shift the physical patterns that drive the ecosystem (Cayan et al. 2001). Though physiological traits and germination requirements for cottonwood and related species are well-known (Braatne et al. 1996; Karrenberg et al. 2002), very little is known about its population dynamics in whole river corridors; this includes rivers in the Central Valley. Restoring the non-equilibrium riparian cottonwood communities poses the daunting challenge of understanding both the physical and ecological processes that operate on inter-annual and decadal time scales to structure riparian-floodplain ecosystems. CALFED and other agencies have allocated millions of dollars to map and restore cottonwood-dominated woodlands. Acquiring and applying this ecological knowledge has important practical consequences.

The focus of our research is to formalize existing knowledge and model the current state and future dynamics of remnant riparian forest stands dominated by Fremont cottonwood along a 100-mile reach of the Sacramento River (Red Bluff to Colusa; Figure 1) using a spatially-explicit landscape population model. We chose this reach because of its ecological complexity and relatively intact physical processes, the wealth of existing data available and the intense interest in conservation by The Nature Conservancy, resource agencies and other stakeholders (e.g., Stillwater Sciences 2007). In order to understand the current state of the cottonwood population on the Sacramento River it is necessary to quantify the distribution of the remnant stands, their size and age structure and their establishment processes.

There is a large and growing body of field data addressing these needs, as well as models of physical processes that drive channel migration and creation of new riparian forest habitat (See *Background* section for details). In this project, we will integrate existing, field-based information on cottonwood establishment to parameterize a dynamic population model and integrate it with a modified meander migration model that predict zones of habitat. We will use this linked model to understand the current status of the cottonwood population and project trends under current physical regimes (climate, flow and floodplain sedimentation rates), as well as under regimes of altered climate and flow regulation. The results of this study will be important for prioritizing high-value habitat, understanding population-sensitive processes and planning corridor-wide conservation efforts (e.g., Stillwater Sciences 2007). Finally, the methods and analyses developed will have added benefit to other river ecosystems where similar natural processes and development pressures are at work (e.g., Ain River, France; Piégay et al. 2000).

Background

Following an early interest in California riparian systems in the 1980s (Sands 1980; Warner and Hendrix 1984; Abell 1989; Fenner et al. 1985), a new initiative is underway focusing research on the restoration of floodplain processes (e.g., Faber 2003; CALFED 2000). Thus far, research has been conducted at various scales, including calibration of cottonwood seedling establishment processes in relation to flow regime (Roberts et al. 2003; Wood 2003a; Stella 2005; Morgan 2005) and landscape-scale modeling of geomorphic and vegetation change (Fremier et al. 2006; Greco et al. 2007; Larsen et al. 2006). The research plan described here aims to build on this research by integrating existing concepts and datasets into an overall, predictive modeling framework for cottonwood-dominated forest areas in the Central Valley.

The proposed study stems from work completed by two loosely defined research teams. One team of researchers has begun a project to understand historical and current establishment pathways for Fremont cottonwood. This is a joint effort between University of California, Berkeley (Dr. John Battles), State University of New York (Dr. John Stella), the French National Center for Scientific Research (CNRS, Drs. Hérve Piégay and Simon Dufour), in collaboration with The Nature Conservancy (Chico, CA). In spring 2006, a joint team conducted a coordinated field effort to document topography, fine sediment depth, riparian plant community composition and cottonwood stand age along the Sacramento River. These data are being used to develop and calibrate a conceptual model for cottonwood stand establishment on abandoned channel sites, a process that is believed to be fundamentally different from forest development on active channel point bars. Work will continue throughout 2007-08 on both former channel and active channel sites to document cottonwood stand size and age structure and relationship to geomorphic surface evolution.

The other team of researchers aims at understanding the landscape-scale patterns of vegetation and the physical processes that maintain them through fluvially driven changes to the floodplain (channel migration and overland scour). This team consists of researchers at University of California, Davis (Drs. S. Greco and E. Larsen) in collaboration with the California Department of Water Resources (Red Bluff, CA) and The Nature Conservancy (Chico CA). I completed my dissertation at UC Davis working with this group. This research links information on quantitative fluvial geomorphology and historical channel migration patterns with ecological data to explore how flow regime initiates changes in river channel dynamics that ultimately affect vegetation patterns. Spatial data in a geographic information system (GIS) of historic channel movement and land cover is coupled with a mechanistic model of river channel migration to describe vegetation response to historical events and predict potential future outcomes under various scenarios. Currently, this team is working with the CALFED Ecosystem Restoration Program; the work will commence in 2007 and will continue to collect and interpret aerial photography in the 100-mile reach and analyze historic vegetation patterns. The research described in this present proposal will use these data and formalize the results in a computer model of cottonwood recruitment.

Our proposed study represents a convergence of ideas and research aimed at understanding riparian plant communities, in particular Fremont cottonwood, at multiple spatial scales. The project leverages existing remotely-sensed and field data to advise the formation and calibration of computer-aided modeling procedures (See list below). In addition, it fills in the gaps of knowledge regarding cottonwood recruitment on off-channel habitats. The research applies an interdisciplinary approach, combining tools and concepts from ecology, geomorphology and geographic information science. Moreover, the approach is tractable, considering that much the foundational work and data already exist. The progress to date sets the conditions for a new integrative model to be coded, tested and applied to real-world management and climate change scenarios. The scenarios proposed here stem directly from community members at The Nature Conservancy in Chico and the California Department of Water Resources in Red Bluff. Community mentors are closely allied with the project goals and have been working on solving these complex issues for several years along with both research teams (Golet et al. 2003; Stillwater Sciences 2007).

Development of conceptual and analytical models provides multiple necessary functions for the scientific and stakeholder community. The model proposed here will (1) consolidate existing data and information concerning cottonwood population dynamics into a formalized and testable structure, (2) investigate the predictive power of such a model to simulate real-world patterns and (3) provide value insight to prescribed flow alteration and floodplain restoration over time scales pertinent to projected climate change and human population growth.

Existing data sources include:

- digital photo series by UC Davis (S. Greco), California Department of Water Resources, Red Bluff (A. Henderson), and orthorectified series by the French CNRS (Hérve Piégay)
- multiple channel traces and GIS layers of vegetation by UC Davis (UC Davis E. Larsen and S. Greco)
- LIDAR and remotely-sensed surface (1997) of elevation relative to low flow water surface (UC Davis)
- 1999 vegetation layer by CSU Chico Geographical Information Center (C. Nelson)
- cottonwood population and field measured data by The Nature Conservancy (Chico), CSU Chico (D. Wood), SUNY (J. Stella), UC Berkeley (J. Battles), and UC Davis (S. Greco)

APPROACH AND STUDY PLAN

Conceptual Model

Our approach is guided by a general conceptual model, modified from Strange et al. (1999) of riparian community composition and function determined largely from physical ecosystem drivers (Figure 2). In this model regional physical factors of climate (precipitation and temperature) and basin characteristics (e.g., latitude, area, elevation, topography, and parent material) are the ecosystem drivers, similar to state factors in other ecosystem models (Jenny 1941; Groffman et al. 2004). These factors determine the fluvial geomorphic regime (flow and sediment), which in turn structure the potential distribution of cottonwood throughout the Central Valley, including geographic range, patch location, and population age structure. Actual distributions are narrowed further by human modification of the landscape and flow regime. Biotic interactions such as competition and herbivory are generally considered less important in structuring this disturbance-driven ecosystem than physical factors and dispersal (Johnson 2000; Menge and Sutherland 1976). Major human impacts to the ecosystem occur at all levels of the model by modifying drivers, processes, community structure and landscape patterns. The most important alterations are to the climate (via global warming and subsequent changes in precipitation and temperature regimes), flow regulation (with changes in river hydrology and sediment regime) and landscape modification, particularly agricultural conversion and streambank hardening.

With this conceptual model of linked physical-biological processes as the template, we will model the reach-wide cottonwood population as an aggregate of patches distributed throughout the river corridor. Each patch in this system will have its own age structure corresponding to the time of patch recruitment and the particular establishment pathway. These pathways include recruitment on point bars, former channels in the floodplain and on mid-channel islands (Figure 3; see text below). We will model the patch creation process using a spatial, physically-based meander migration model applied to the entire reach (Larsen et al 2006a-c). The meander model will determine the rate and location of eroded banks, which will change the size and distribution of existing forest patches. On top of this spatial and temporal template, we will 'grow trees', using field-based data from a current study on cottonwood growth rates and age structure (J. Stella, J. Battles and M. Hayden, unpublished data). The integration of the physical habitat template, germination site availability and stand growth patterns will determine the composition of the entire population throughout the reach at all time steps. Key physical parameters that will drive the meander model include annual cumulative effective stream power (which determine near-bank shear stresses and therefore erosion rates), channel and planform geometry (which influence cutoff rates) and floodplain sedimentation rates. Model rates of meander and cutoff will be calibrated against empirical rates determined in the aerial photo record. Mean floodplain sedimentation rates will be determined using dendro-geomorphololgical methods (described below in Task 1).

Cottonwood Establishment Pathways

An innovative component to our approach is to consider the different pathways by which cottonwood forest establishes on floodplains (Figure 3). The current conceptual model of cottonwood establishment emphasizes recruitment on point bars and channel edges under favorable hydro-geomorphic conditions (i.e., timing of seed dispersal with spring flood waters draw down – Mahoney and Rood 1998). A good deal of field-based research has been done on this process along the Sacramento River (Roberts et al. 2003, Morgan 2005) and more studies are currently underway (D. Wood, personal communication). However, less is understood about cottonwood recruitment in off-channel locations. These include recruitment on the terrestrial portions of abandoned channels (e.g., cutoffs avulsions and side channels) and mid-channel islands (Abbe and Montgomery 1996, Sako 1997, Piégay et al. 2000).

Abandoned channels may constitute an important alternative establishment pathway to point bars, because they incorporate both open substrate conditions necessary for recruitment and protection from scour that removes seedlings along active channels (Figure 3). These areas of the floodplain may be considered ‘safe sites’, or habitats that both provide germination requirements and protection from disturbance (Enright and Lamont 1989; Weltzin and McPherson 1999; Polzin and Rood 2006). On riparian floodplains, patterns of survival related to off-channel sites protected from scour and deposition have been documented for *Populus trichocarpa* seedlings on the Elk River, Canada (Polzin and Rood 2006) and for *Fraxinus platypoda* along an abandoned channel in the Chichibu Mountains, Japan (Sakio 1997). Some studies (e.g., Sakio 1997; Piégay et al. 2000, Kondolf et al. 2006) and preliminary field work on the Sacramento River (J. Stella et al. unpublished data) suggest that these off-channel sites support single, pulsed recruitment events that results in cottonwood stands with fairly unimodal age structures, in contrast to the multi-aged linear bands of trees that typically establish on point bars.

On meandering and braided rivers, vegetation development is patchy and frequently occurs as mid-channel islands (Gurnell and Petts 2002). Island formation is typically initiated by large woody debris deposited within the channel (Abbe and Montgomery 1996); this event traps sediment, providing substrate for live plants to establish. This process initiates a positive-feedback loop in which established vegetation provides even more hydraulic resistance to flow, trapping more sediment and creating additional substrate that can be colonized by riparian plants.

Systems Modeling and Integration

To date, these three establishment pathways (point bars, former channels, and islands), which have been documented independently, have not been integrated into a single population-level model. We are proposing to do that by combining the dynamic, spatially-explicit meander model with an age-structured population model that will simulate the total population structure over time. Because the population drivers are primarily physical (i.e., flow magnitude and geomorphic change), the population will be sensitive to modifications to the physical regime, such as climate shifts and human flow regulation. This approach leverages a great deal of work done to date in the Central Valley on understanding river meandering processes (Larsen et al 2006a-c) cottonwood recruitment dynamics (Roberts et al. 2003, Stella 2005, Morgan 2005), riparian community patterns (Fremier 2003, Fremier et al. in prep_a; Greco 1999), as well as extensive digital datasets of available GIS imagery and information (e.g., Greco 2003).

Our approach is innovative in that it considers several different forest stand establishment pathways (point bars versus safe sites) and integrates a spatially explicit model with population dynamics. Conceptually, our approach addresses calls for integrating population dynamics in highly variable aquatic environments proposed by John Wiens (2000) and others. Practically, our study builds off recent work by Lytle and Merritt (2004) who developed a structured population model for *Populus deltoides*, a closely-related species to Fremont cottonwood along the Yampa River in Colorado. Their cohort-based, spatially-implicit model was driven by a fluvial disturbance regime and successfully captured some aspects of real cottonwood population dynamics in which the seedling stage is characterized by frequent boom and bust cycles while adult cohort sizes fluctuate modestly over time. Together with the field work currently underway on cottonwood establishment in off-channel sites (J. Stella et al. unpublished data), our work expands the dominant conceptual model of recruitment limitations for riparian trees (Mahoney and Rood 1998) and explores the implications of these developments for forest habitat and corridor planning.

This information is critical for understanding the limiting factors leading to riparian forest decline and in identifying restoration priorities. For example, it is well known that under flow regulation, conditions for cottonwood seedling recruitment on point bars along the Sacramento River are less favorable than historically (Roberts et al. 2003). However, recruitment along former channels, which have continued to form and evolve in the post-Shasta Dam era (Kondolf et al. 2006), may mitigate to some degree the loss of active channel habitat and trees available for population seed sources. Former channel recruitment may effectively provide ephemeral population source areas, with the frequency determined by rates of channel cut-off. The set of data analyses and process-based spatial model that we propose will help resolve the degree to which each process (on- versus off-channel establishment) are important contributors to forest dynamics within the reach.

Proposed Study

As a CALFED postdoctoral fellow, I propose to adapt existing models of floodplain dynamics to simulate creation and evolution of riparian forest habitat and predict future trends. Specifically, I plan to model linked geomorphic and ecological processes for the 100-mile middle reach of the Sacramento River (Red Bluff to Colusa). Building upon existing data and previous research, I propose to complete the follow new tasks:

1. *Adapt the physical meander migration model to predict the spatial habitat template for cottonwood forests on alluvial rivers.*

   This task includes two subtasks to fill in key knowledge gaps:
   - *1a. Simulate cross-sectional evolution and near-channel floodplain topography.*
   - *1b. Measure floodplain sedimentation rates using dendro-geomorphology in different floodplain habitats (active vs. off-channel).*
2. *Analyze cottonwood establishment pathways and population structure using current and historical aerial photographs and field verification.*
3. *Develop a joint physical/biological model that simulates reach-wide cottonwood population structure over time.*
4. *Evaluate model scenarios for current conditions, for projected climate changes and modified flow regimes.*

Results from these studies will be used to formulate and parameterize a GIS-based model of Fremont cottonwood and to refine our understanding of establishment pathways for a wider range of conditions than currently available (e.g., Fremier et al. in prep_a; Stella et al. in prep_b; Roberts et al. 2002). This project pulls on a wide range of available data and ideas. Moreover, coupling data captured at the landscape and plot scale, these analyses integrate geomorphic and ecological understanding to formalize, test and apply predictive models of cottonwood establishment.

The formalized landscape model of cottonwood will employ five types of data to estimate historic conditions and simulate future environments: (1) historical data of channel migration and a relative elevation surface; (2) historic river channel cross-sections; (3) corridor-wide distributions of cottonwood woodland patches and available habitat from aerial photos and GIS databases; (4) a long-term dataset of re-surveyed vegetation transects over multiple active point bars; and (5) site-based data on density of adult trees in remnant stands and seedling densities on all types of floodplain surfaces.

The modeling design emphasizes a systems approach, adapting previously formulated models of landscape evolution, eco-physiology and population dynamics. Previous landscape models examined large-scale interactions among key ecosystem components such as flow regime and floodplain development. Future research will focus attention to understanding the functional links between landscape scale components and local biotic dynamics (i.e., Fremont cottonwood life history). The final integrated model will present system complexity at an appropriate coarse scale.

Together with the riparian studies conducted to date, this project will develop a powerful suite of tools for understanding the current aerial extent and population size and trends, targeting the most influential life stage(s) and land forming process and evaluating potential restoration strategies (e.g. flow releases versus horticultural restoration, progressive migration versus chute cutoff). In addition, the expanded model including abandoned channels with population models will provide insights into how the species may respond to directional climate change.

Project Tasks

The proposed study has four primary tasks and will be completed in three years. Table 1 lists the tasks, proposed investigation and completion timeframe.

Task 1. Adapt the meander migration model to predict the spatial habitat template for cottonwood forest.

The first step is to develop a predictive physical model of cottonwood habitat based on known relationships between cottonwood recruitment success and river channel geometry. This will require several adaptations of the existing meander migration model as well as a limited field study to calibrate floodplain sedimentation rates. These would be achieved in two subtasks, to be completed within the first 1½ years of the project:

Task 1a. Simulate cross-sectional evolution and near-channel floodplain topography.

The meander migration model predicts channel movement and estimates in-stream bed topography based on the physics of flow and sediment transport (Larsen et al. 2006a-c; Johanesson and Parker 1989). As yet, the model has not been used to predict bar height of the near-channel floodplain. This advancement would greatly improve the predictability of cottonwood recruitment sites on point bars. For example, point bars tend to be steeper at the entrance of a bend than at their inflection points; estimating this slope would allow us to create a temporal set of topographic surfaces. These will then be used as templates to run the cottonwood population model. This work would be completed under the supervision of Dr. Eric Larsen at UC Davis.

Task 1b. Measure floodplain sedimentation rates using dendro-geomorphology in different floodplain habitats (active vs. off-channel).

Fine sediment accumulation on floodplain surfaces is highly variable and an important control on cottonwood recruitment (Mahoney and Rood 1992). In this task we will derive empirical sedimentation rates in both point bar and former channel habitats in order to simulate landform change in the meander model. These data will provide the necessary link between the landscape and cottonwood recruitment habitat. The data collection and analysis procedure compares tree core age (core extracted at buried base of stem) and adjacent sediment core depth to calculate annual sedimentation rate (core depth divided by tree age). Sites will be selected by stratifying the landscape by floodplain type. Multiple cores will be taken at each site to estimate local variation in sedimentation rate. This technique has been successfully piloted recently on the Sacramento River at former channel sites (H. Piégay and J. Stella, unpublished data). In addition, the sedimentation rate data will be used to validate current models of relative elevation (elevation relative to summer low flow water surface, Greco et al. personal communication). Integrating these datasets with modeling procedures described in Task 1a will elucidate patterns of floodplain development and critical conditions of riparian vegetation development.

Task 2. Analyze cottonwood establishment pathways and population structure using current and historical aerial photographs and field verification.

Currently models of cottonwood establishment emphasize cottonwood recruitment on active near-channel floodplains (i.e. the recruitment box, Mahoney and Rood 1990). There has been relative little scientific attention given to alternative paths of cottonwood and mixed riparian forest development on other floodplain surfaces such as mid-channel islands and land created by channel abandonment. Further analysis will use both field and GIS data to extract historic patterns of cottonwood recruitment. Figure 4 shows an example of existing data available for this task, including a 1999 coverage of riparian forest communities (CSU Chico), aerial photography and pre-existing vegetation datasets (Greco and Alford 2003, Greco 1999, H. Piégay unpublished data). These will be used to follow patch recruitment over time and subsequent development of existing floodplain surfaces. Specifically, multiple time steps of GIS layers of vegetation and floodplain development (channel migration and chute-cutoffs) will be overlaid and patch development quantified. In addition to the extensive GIS data available, this task will draw on data currently being collected on forest stand composition and age structure by J. Battles, J. Stella and others to identify cottonwood stand structure and growth rates. To augment these existing data, a limited number of sites will be surveyed to document species composition and stand structure, focusing attention on conditions of cottonwood establishment. There will be some overlap with Task 1b in site selection, field visits and GIS analysis to reduce redundancy.

Task 3. Develop a joint physical/biological model that simulates reach-wide cottonwood population structure over time.

In this task we will combine the physical template information (Task 1) and with the reach-wide establishment patterns (Task 2) into an integrated, dynamic model that simulates the reach-wide population over time. The overall model will consist of two parts, a patch model of cottonwood recruitment and a structured population model. The habitat patch model will simulate the physical environment using a modified model of meander migration including the cross section evolution algorithm to simulate floodplain deposition/erosion. Floodplain age, relative elevation and floodplain type will be the main physical parameters in predicting regeneration niche space including a flow component based on existing cottonwood recruitment work (Mahoney and Rood 1998; Roberts et al. 2003; Stella 2005). Model parameters will be based on field data both from previous studies as well as research proposed in this study (see Figure 5 for an example). The modeled vegetation surface will be the spatially explicit data matrix input into the structured population model at each yearly time step. The initial surface will be generated from existing current condition data on the Sacramento River.

The population model will be a density-dependent structured population model with a stochastic term to simulate natural variation (see Lytle and Merritt 2004). Model parameters will be estimated using existing data on cottonwood growth and mortality rates, fecundity and seed set timing (Stella et al 2006; J. Battles and J. Stella, unpublished data). Cottonwood is assumed not to be dispersal limited and therefore propagule sources from individual cottonwood trees will not be explicit tracked. However, the spatial structure is implicit in the patch model and the resource competition over time (i.e. succession). The integrated model will be used to simulate observed data and test scenarios of decreased fecundity due to altered flow and climate patterns (runoff and temperature) and patch creation/destruction due to human action (land conversion and/or restoration).

Task 4. Evaluate model scenarios for current conditions, for projected climate changes, and under modified flow regimes.

In this task we will run the model under different scenarios of climate change and flow regulation. Currently, the conditions under which cottonwood-dominated forest stands develop are not in equilibrium. Riparian communities along the Sacramento River are still adjusting to the regulated flow conditions imposed after construction of Shasta Dam (Fremier et al in prep_a). Future restoration efforts are considering altering flow schedules for multiple ecosystem benefits (e.g., Stillwater Sciences 2007). Furthermore, regional climate models predict that several factors will affect runoff and temperature regimes (including regional warming) a reduced Sierra snowpack, an increased incidence of drought and an earlier peak runoff period due to early snowmelt and increased winter storms (Cayan et al. 2006). These shifting conditions will likely affect cottonwood forest development and evolution.

Scenario selection and the creating realistic simulation procedures is an important step in the river corridor planning process. Generating realistic and testable scenarios will be an interactive process between our research team, CALFED and our community mentors. The model will be capable of simulating the effects on cottonwood population dynamics caused by altered flow patterns and floodplain management actions. Climate change may alter cottonwood fecundity by shifting runoff patterns and seed set timing (e.g. Dettinger and Cayan. 1995; Stella et al. 2006). The overall model will be capable of integrating data from existing climate change (e.g., regionally downgraded general circulation models such as the Hadley and Canadian GCM's) or water accounting models (e.g., simulated environmental flow releases) to predict potential impacts to the floodplain and conservation of cottonwood populations. In addition, considering future uncertainty the modeling approach will be iterative to allow for a variety of scenarios with a range of estimated parameters.

Project Feasibility

Our ongoing riparian research experience focuses on developing scientifically sound and practical methods for monitoring riparian ecosystem patterns, processes and functions, both within the Central Valley and in similar ecosystems elsewhere. I have focused on the linked ecological and physical processes of Central Valley riparian zones for the last six years as both a graduate student and consultant.

As a graduate student at UC Davis, I helped to incorporate two data-driven components into a mechanistic model of river channel migration: a variable flow and variable bank erodibility component. We linked the meander model to a GIS to model geomorphic change under altered flow and floodplain (levee configuration) scenarios (Fremier et al. in prep_a; Larsen et al. 2006a-c). My dissertation research focused on the landscape ecology of riparian vegetation of Sacramento River (Fremier and Talley in review, Fremier et al. in prep_a, Fremier and Greco, in prep_b). In addition, I am familiar with CALFED's mission and the complexity of issues in the Valley through my consulting work with CALFED's Delta Regional Restoration Implementation Plan and being a technical advisory member for various CDWR and River Partner, Inc. projects on the river and Delta ecosystems.

The team I will join consists of Drs. Stella and Battles. They are quantitative field ecologists who are currently applying a wealth of experience and methodologies from work in forest ecosystems to key issues of Central Valley riparian ecology and ecosystem sustainability. In particular they are experienced with field-based research approaches and methodologies integrated within this project, including forest population dynamics and disturbance impacts (Battles et al. 2002; Battles and Fahey 2000), dendrochronological analyses (e.g., Battles et al. 2002), isotopic techniques for determining physiological water use efficiency (Stella et al., in prep_a), and seed release phenology (Stella et al. 2006).

In conducting this research, we will coordinate efforts with other researchers and agency representatives working in the project area. We are coordinating our study with the most active researchers on the Sacramento River, many of whom have made extensive datasets available. These relationships and data sources are summarized in the Community Mentor Work Plan. We will consult with these individuals and others as appropriate for assistance in identifying mutually beneficial research goals, selecting study sites, standardizing sampling methods wherever possible and peer review of study plans and project deliverables.

ANTICIPATED PRODUCTS AND PROJECT BENEFITS

We will integrate the analyses from Tasks 1-4 into a series of peer-reviewed journal papers, conference presentations, and publicly available data sets. The goal is to have the results of each component contribute to improving one or more conceptual or quantitative models that have direct application to CALFED and other restoration and resource management issues in the Central Valley. Deliverables will include 3-5 manuscripts summarizing individual study component and management implications of the overall project findings; these are listed below:

Task	Manuscript Description	Example of Target Peer-Review Journals
1a	Modeling and predicting geomorphic channel change for floodplain topography	Geomorphology, Environmental Management
1b	Dendro-geomorphology of cottonwood establishment and sedimentations rates in abandoned channel segments	Dendrochronologia, Geomorphology, Wetlands
2	Multi-scale analysis of historic floodplain development to develop relative rates for cottonwood establishment pathways	Wetlands, Ecology, Plant Ecology, Regulated Rivers: Mgt. and Research
1-3	Develop, calibrate and validate a model of cottonwood establishment using dynamic habitat and population models	Ecological Modelling, Conservation Biology, Ecological Applications
3-4	Develop scenarios of future climate change and management scenarios and run models to determine direction of change	Environmental Management, Climate Change; Journal of Biogeography

In conjunction with these manuscripts, we will present findings to date and overall project results at the annual CALFED Science/State of the Estuary Conference and at a minimum one other internationally-recognized conference annually, such as meetings of the Ecological Society of America, Society for Ecological Restoration, and American Geophysical Union. We will also disseminate the results of this research within local agency, restoration and stakeholder forums.

This project will allow me to fulfill important professional and research goals. My career goal is to conduct a vibrant research and teaching program in riparian ecology at the university level. This project builds on my dissertation research on riparian landscape ecology to comprise the next logical component in my research program. Through this project, I intend to expand my analytical skills both in modeling and field skills in the study of plant population processes, patterns and restoration approaches.

For Dr. Stella, my research mentor, this project reflects an opportunity to extend his theoretical and field-based research in riparian forest community ecology to population and landscape models. He will realize project benefits in co-authoring peer-reviewed articles and apply his existing research expertise to new ecosystems and resource management challenges. For Mr. Roberts and/or Dr. Golet, my community mentors (see Community Mentorship Plan), this project directly addresses their extensive experience in applying rigorous science to restoration management strategies on regulated rivers. At The Nature Conservancy They have been outspoken advocates for hypothesis-driven research on mechanisms that sustain riparian communities and for ecologically-focused and quantifiable restoration goals.

TABLES AND FIGURES

Table 1. Study hypotheses, evaluation criteria, and proposed field studies.

Task	Proposed Studies	Details	Timeframe
1a. Meander model adaptation: Simulate cross-section evolution and near-channel floodplain topography	• Compare modeled bed topography between previous and current re-surveyed cross-sections • Tie cross-section model into meander migration code to predict near-channel bar slope and height and link to GIS	• Collate channel dimensions and planform data for each survey site • Re-survey cross-sections taken at irregular intervals over the past 50 years, focusing on those surveyed in 2003 by CDWR and UC Davis • Model channel cross-sectional change from 2003 to 2008 using a hydrodynamic model	Year 1
1b. Sedimentation study: Measure floodplain sedimentation rates using dendro-geomorphology in different floodplain habitats (active vs. off-channel).	• Conduct a limited field study of floodplain sedimentation rates using dendro-geomorphology (integrated tree core and sediment core analysis) • Contrast historical sedimentation rates on floodplains created by progressive migration and abandoned channels using remotely-sensed and field data	• Locate historic abandoned channel locations using aerial photography and GIS data of channel traces • Field measure sediment and take tree-cores at base of multiple cottonwood stands within selected abandon channels • Compare LIDAR surface of relative elevation with cottonwood age classes in abandoned channels and previous mid-channel islands	Years 1 & 2
2. Analyze cottonwood establishment pathways and population structure using current and historical aerial photographs with field verification.	• Analyze the area of cottonwood forest and age class currently on surfaces created by progressive migration and channel abandonment. • Complete a rapid assessment of cottonwood presence using existing field surveyed vegetation data (UC Davis, UC Berkeley, CSU Chico)	• Analytically overlay GIS layers of vegetation and floodplain type to isolate percent cottonwood forest per floodplain type • Ground truth CSU Chico and UC Davis vegetation layers in abandoned channel and previous mid-channel bars for cottonwood presence and density • Analyze long-term dataset of cottonwood recruitment and point bar development (Data from CSU Chico, D. Wood)	Years 1 & 2
3. Develop a joint physical/biological model that simulates reach-wide cottonwood population structure over time	• Couple landscape models (meander migration and cross section evolution) and population models (age of cottonwood forest dynamics to improve overall predictability • Run model from near past date to current condition and compare modeled results to surveyed field data	• Formulate model structure and translate into computer code • Error check code and functionality • Calculate model parameters (geomorphic and biotic) from past and current datasets • Calibrate and validate model	Years 2 & 3
4. Evaluate model scenarios for current conditions, for projected climate changes, and under modified flow regimes.	• Run model using flow conditions under habitat restoration alternatives, and projected under climate change (and resulting Environmental Water scenarios).	• Generate realistic model parameters of future environments using models of climate, flow discharge and floodplain configuration • Confer with community mentors regarding scenarios	Year 3

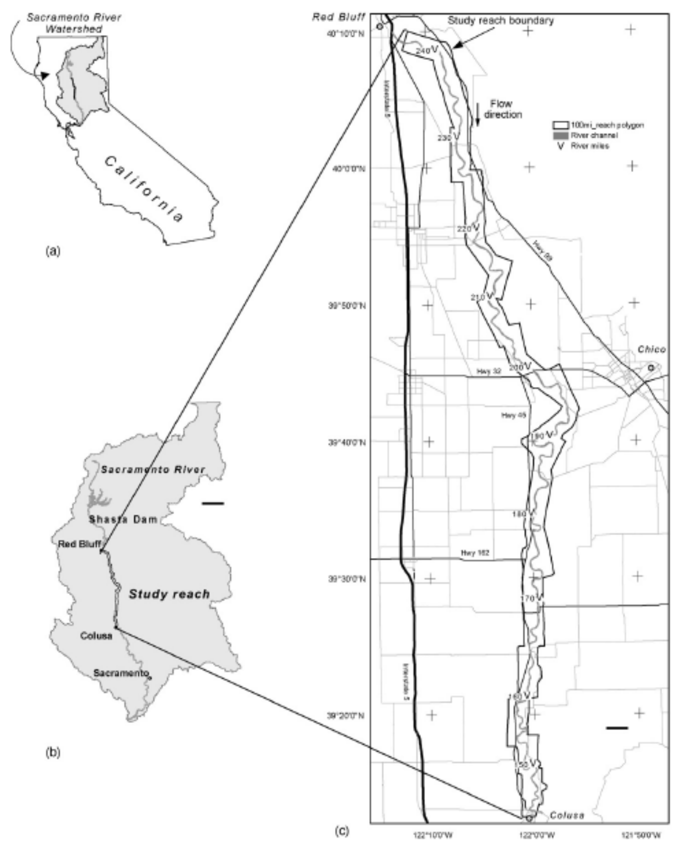


Figure 1: Central Valley river basin map with proposed study reach. Vegetation and channel mapping completed by UC Davis (2003). Plant community and seedling studies have been conducted by UC Davis and by The Nature Conservancy, CDWR, and CSU Chico on the Sacramento River. Extensive corridor restoration planning is underway within the 100-mile study reach (e.g., Stillwater Sciences 2007).

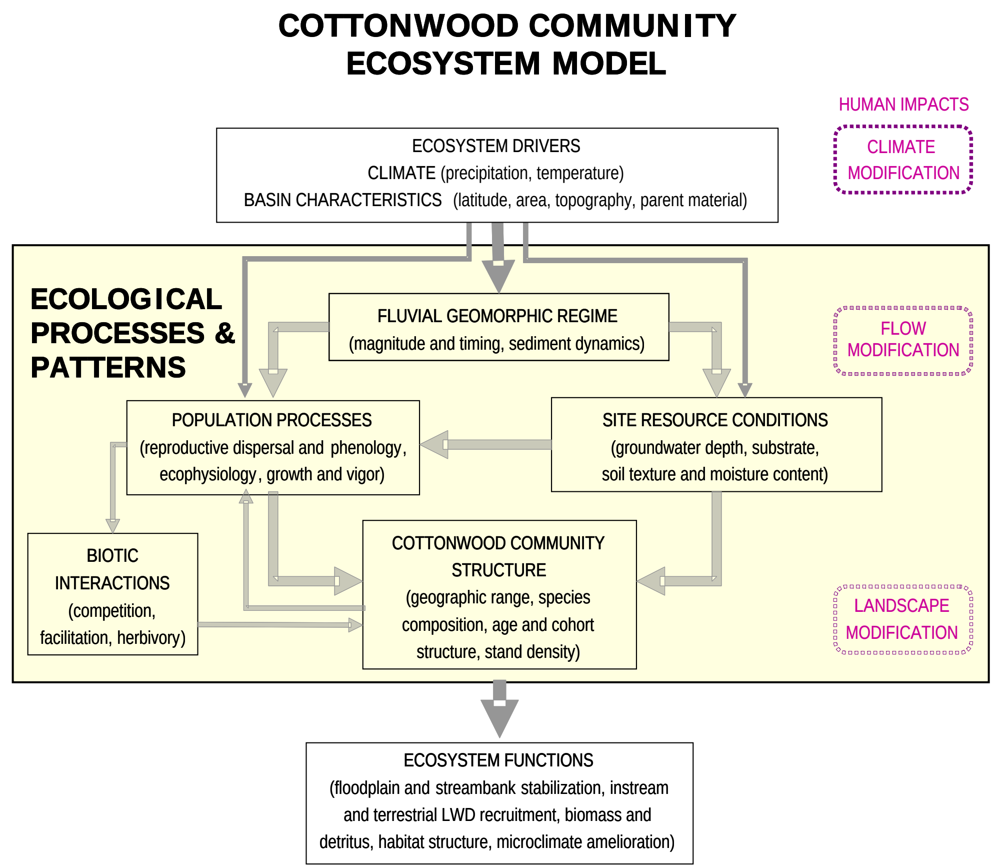


Figure 2: Conceptual model of ecosystem development in cottonwood-dominated riparian communities (modified from Strange et al. 1999). Climate and basin characteristics drive ecosystem processes, primarily through their influence on flow regime. Flow regime influences population processes and site resource conditions to create riparian community structure and landscape patterns, which in turn control riparian ecosystem functions. Biotic interactions are less important than physical factors and dispersal in this non-equilibrium, disturbance-driven ecosystem. Human impacts occur at all levels of the model by modifying drivers, processes, community structure, and landscape patterns.

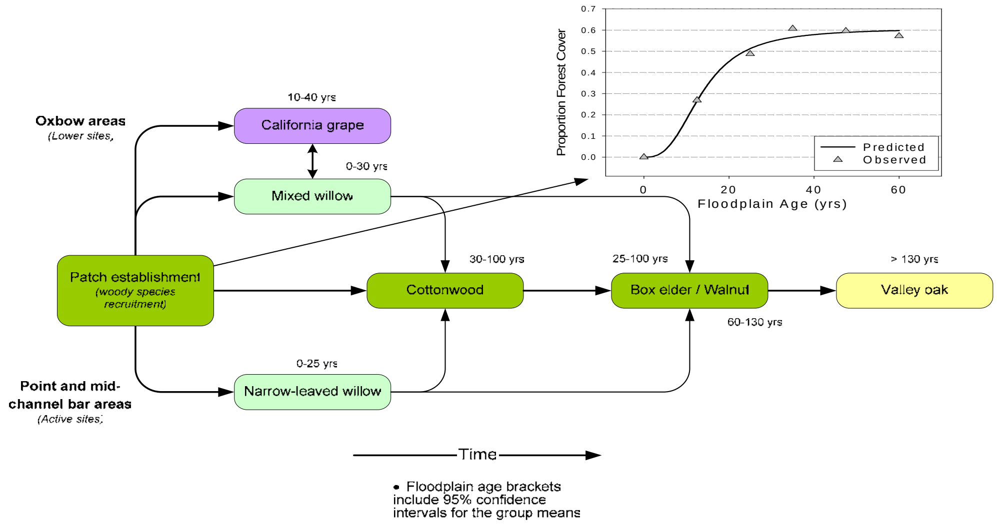


Figure 3: Conceptual model of species composition transitions over a floodplain age gradient. Year values taken from Fremier (2003) and represent the average age of the floodplain where each species were field-surveyed. Two sets of data are lacking: cottonwood establishment rates and the relative rates of establishment pathways between floodplain types (i.e. this proposal). Inset graph shows empirical rates of forest community colonization on point bars following patch creation using aerial photography and GIS layers of historic vegetation development.

Figure 4 (below): Existing dataset of aerial photo with 1999 mapped vegetation series. Red polygons are Fremont cottonwood forest type (vegetation data from CSU Chico).

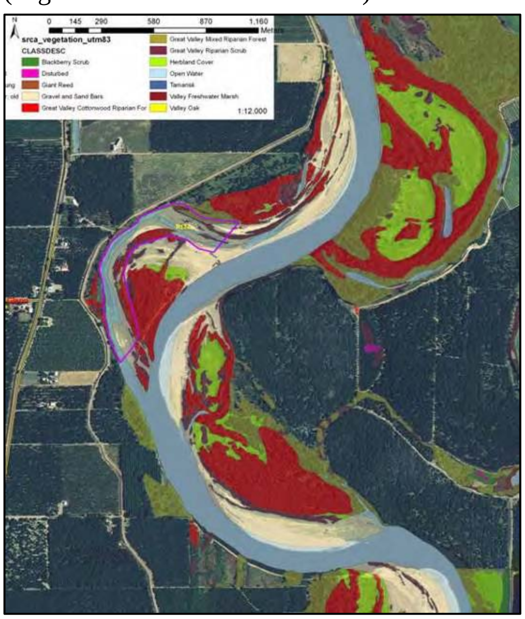
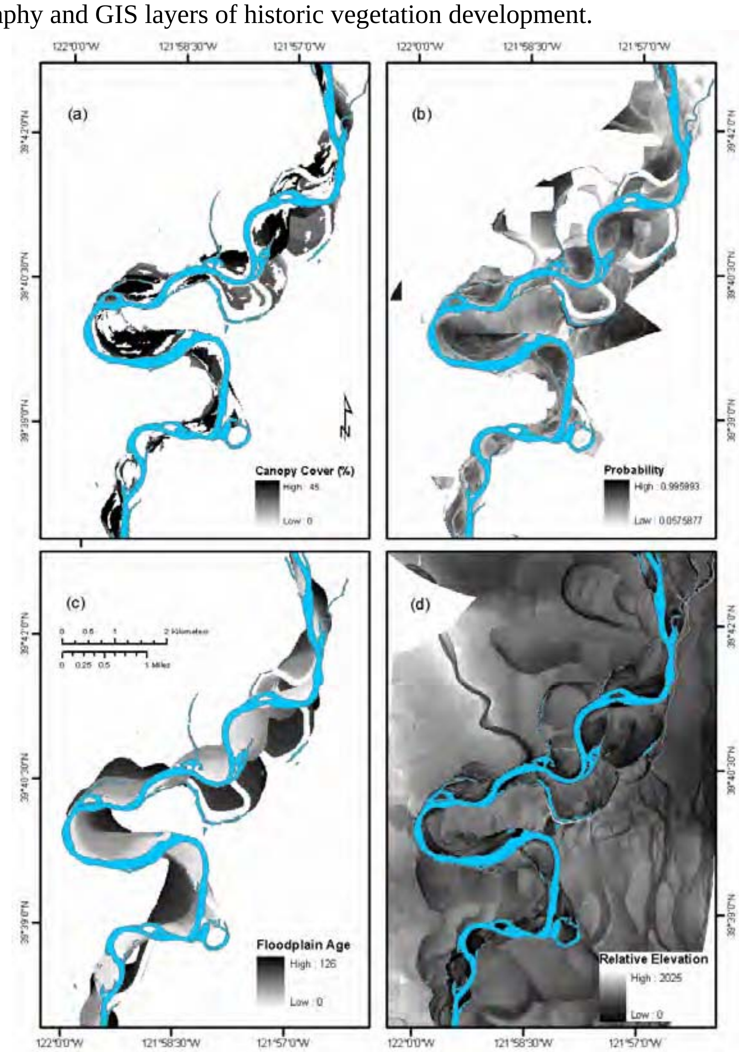


Figure 5 (right): Example statistical model of Fremont cottonwood on the Sacramento River using logistic regression and landscape predictor variables (floodplain age, relative elevation and distance to channel). a) predicted canopy cover >50%, b) probability distribution surface, c) floodplain age (past 130 years), and d) elevation relative to low flow water



REFERENCES AND LITERATURE CITED

Abbe, T. B., and D. R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers-Research & Management **12**:201-221.

Abell, D.L. (Ed.) 1989. Proceedings of the California riparian systems conference: protection, management, and restoration for the 1990s. General Technical Report PSW-110, Davis, California, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

Battles, J.J. and T.J. Fahey. 2000. Gap dynamics following forest decline: A case study of red spruce forests. Ecological Applications 10: 760–774.

Battles, J.J., J.J. Armesto, D.R. Vann, D.J. Zarin, J.C. Aravena, C. Perez and A.H. Johnson. 2002. Vegetation composition, structure, and biomass of two unpolluted watersheds in the Cordillera de Piuchué, Chiloé Island, Chile. Plant Ecology 158:5-19.

Braatne, J.H., S.B. Rood and P.E. Heilman. 1996. Life history, ecology and conservation of riparian cottonwoods in North America. Biology of Populus and its Implications for Management and Conservation. Eds. R.F. Stettler, H.D. Bradshaw, Jr., P.E. Heilman and T.M. Hinckley. NRC Research Press, National Research Council of Canada, Ottawa, ON, pp 57-86.

CALFED Bay-Delta Program. 2000. Flow regime requirements for habitat restoration along the Sacramento River between Colusa and Red Bluff. Integrated Storage Investigation. Sacramento, California.

California Department of Water Resources (CDWR). 1999. Sacramento River Atlas, Red Bluff to Colusa. Sacramento, CA.

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson. 2001. Changes in the onset of spring in the western United States. Bulletin of the American Meteorological Society 82:399-415.

Cayan, D., Luers, A., Hanemann,M. , Franco, G. and Croes, B. 2006. Climate Change Scenarios for California: an Overview. California Energy Commission PIER working paper.

Cepello, S.A. 1991. Riparian vegetation distribution along the Middle Sacramento River in releaion to flood requency. Masters thesis. California State University, Chico.

Dettinger, M.D., D.R. Cayan. 1995. Large-Scale Atmospheric Forcing of Recent Trends toward Early Snowmelt Runoff in California. Journal of Climate, 8(3):606-623.

Enright, N. J., and B. B. Lamont. 1989. Seed Banks, Fire Season, Safe Sites and Seedling Recruitment in 5 Co-Occurring Banksia Species. Journal of Ecology 77:1111-1122.

Faber, P.M. (Ed.) 2003. California Riparian Systems: Processes and Floodplains Management, Ecology, and Restoration. Riparian Habitat Joint Venture, Sacramento.

Fenner, P., W.W. Brady, D.R. Patton. 1985. Effects of regulated water flows on regeneration of Fremont cottonwood. Journal of Range Management 38(2):135-138.

Fremier, A. K. 2003. Floodplain age modeling techniques to analyze channel migration and vegetation patch dynamics on the Sacramento River, CA. Masters of Arts. University of California, Davis, CA.

Fremier, A. K., E. H. Girvetz, S. E. Greco, and E. W. Larsen. in prep_a. Quantifying a sliding baseline: comparing past and future impacts to river channel migration and riparian forests. (To submit to: Ecological Applications)

Fremier, A. K., E. H. Girvetz, S. E. Greco, and E. W. Larsen. 2006. Quantifying a sliding baseline: comparing past and future impacts to river channel migration and riparian forests. 4th Biennial CALFED Science Conference, Sacramento, CA.

Fremier, A.K. and S.E. Greco. in prep_b. Floodplain formation and riparian vegetation patterns along an alluvial meandering reach of the Sacramento River, CA USA. (To submit to: Ecological Monographs)

Fremier, A.K. and T.S. Talley. in review. Linking pattern with process to improve upper riparian restoration efforts in California. (Submitted to: Restoration Ecology)

Golet, G. H., D. L. Brown, E. E. Crone, G. R. Geupel, S. E. Greco, K. D. Holl, D. E. Jukkola, G. M. Kondolf, E. W. Larsen, F. K. Ligon, R. A. Luster, M. P. Marchetti, N. Nur, B. K. Orr, D. R. Peterson, M. E. Power, W. E. Rainey, M. D. Roberts, J. G. Silveira, S. L. Small, J. C. Vick, D. S. Wilson, and

D. M. Wood. 2003. Using science to evaluate restoration efforts and ecosystem health on the Sacramento River Project, California. Pages 368-385 *in* P. M. Faber, editor. California Riparian Systems: Processes and Floodplain Management, Ecology, and Restoration. 2001 Riparian Habitat and Floodplains Conference Proceedings, Riparian Habitat Joint Venture, Sacramento, CA.

Greco, S.E. 1999. Monitoring riparian landscape change and modeling habitat dynamics of the Yellow-billed Cuckoo on the Sacramento River, California. Ph.D. dissertation. University of California, Davis.

Greco, S. E., and C. A. Alford. 2003. Historical Channel Mapping from Aerial Photography of the Sacramento River, Colusa to Red Bluff, California: 1937 to 1997. Technical report prepared for California Department of Water Resources, Northern District, Red Bluff, California. University of California, Davis.

Greco, S. E., A. K. Fremier, R. E. Plant, and E. W. Larsen. 2007. A tool for tracking floodplain age land surface patterns on a large meandering river with applications for ecological planning and restoration design. Landscape and Urban Planning.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An Ecosystem Perspective of Riparian Zones. BioScience **41**:540-551.

Groffman, P.M., C.T. Driscoll, G.E. Likens, T.J. Fahey, R.T. Holmes, C. Eagar, and J.D. Aber. 2004. Nor gloom of night: a new conceptual model for the Hubbard Brook ecosystem study. Bioscience 54(2):139-148.

Gurnell, A. M., and G. E. Petts. 2002. Island-dominated landscapes of large floodplain rivers, a European perspective. Freshwater Biology **47**:581-600.

Jenny, H. 1941. Factors of Soil. McGraw, New York.

Johanesson, H., and G. Parker. 1989. Linear theory of river meanders. *in* S. Ikeda and G. Parker, editors. River Meandering. American Geophysical Union, Washington, D.C.

Johnson, W.C. 2000. Tree recruitment and survival in rivers: influence of hydrological processes. Hydrological Processes 14:3051-3074.

Katibah, E. F., K. J. Dummer, and N. E. Nedeff. 1984. Current condition of riparian resources in the Central Valley of California. Pages 314-321 in R. E. Warner and K. M. Hendrix, editors. California riparian systems: ecology, conservation, and productive management. University of California Press, Berkeley.

Kondolf, G.M., J. Constantine, H. Piégay. 2006. Off-channel habitats of the Sacramento River. Draft technical memo prepared for The Nature Conservancy, Chico CA. 20 Sept. 2006.

Larsen, E. W., A. K. Fremier, and E. H. Girvetz. 2006a. Modeling the effects of variable annual flow on river channel meander migration patterns, Sacramento River, California, USA. Journal of the American Water Resources Association **42**:1063-1075.

Larsen, E. W., E. H. Girvetz, and A. K. Fremier. 2006b. Assessing the effects of alternative setback channel constraint scenarios employing a river meander migration model. Environmental Management 37:880-897.

Larsen, E. W., A. K. Fremier, and S. E. Greco. 2006c. Modeling Bank Erosion and Meander Migration as a Function of River Discharge. 4th Biennial CALFED Science Conference, Sacramento, CA.

Ligon, F. K., W. E. Dietrich, and W. J. Trush. 1995. Downstream ecological effects of dams: a geomorphic perspective. 45:183-192.

Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher and R.S. Pierce. 1970 Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecological Monographs 40: 23-47.

Lytle, D. A., and D. M. Merritt. 2004. Hydrologic regimes and riparian forests: A structured population model for cottonwood. Ecology 85:2493-2503.

Mahoney, J. M., and S. B. Rood. 1992. Response of a hybrid poplar to water-table decline in different substrates. Forest Ecology and Management 54:141-156.

Mahoney, J.M. and Rood, S.B., 1998. Streamflow requirements for cottonwood seedling recruitment--an integrative model. Wetlands, 18(4): 634-645.

McBride, J.R. and J. Strahan. 1984. Fluvial processes and woodland succession along Dry Creek, Sonoma County, California. In: Warner and Hendrix (eds.). California riparian systems: ecology, conservation and productive management. University of California Press. 110-119.
Menge, B. A., and J. P. Sutherland. 1976. Species diversity gradients: synthesis of the roles of predation, competition, and temporal heterogeneity. American Naturalist **110**:351-369.
Morgan, T. L. 2005. Hydrological and physiological factors controlling Fremont cottonwood seedling establishment along the Sacramento River, CA. California State University, Chico, CA.
Patten, D. T. 1998. Riparian ecosystems of semi-arid North America: diversity and human impacts. Wetlands 18:498-512.
Piegay, H., G. Bornette, A. Citterio, E. Herouin, B. Moulin, and C. Statiotis. 2000. Channel instability as a control on silting dynamics and vegetation patterns within perifluvial aquatic zones. Hydrological Processes 14:3011-3029.
Poff, N. L., and D. D. Hart. 2002. How dams vary and why it matters for the emerging science of dam removal. Bioscience 52:659-668.
Polzin, M. L., and S. B. Rood. 2006. Effective disturbance: Seedling safe sites and patch recruitment of riparian cottonwoods after a major flood of a mountain river. Wetlands 26:965-980.
Rieger, J. P., and D. A. Kreager. 1989. Giant reed (*Arundo donax*): a climax community of the riparian zone. Pages 222-225 in D. L. Abell, editor. Proceedings of the California riparian systems conference: protection, management, and restoration for the 1990s. General Technical Report PSW-110. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, Davis, California.
Roberts, M. D., D. R. Peterson, D. E. Jukkola, and V. L. Snowden. 2002. A pilot investigation of cottonwood recruitment on the Sacramento River. The Nature Conservancy, Sacramento River Project, Chico, California.
Roberts, M. D. 2003. Beehive Bend sub-reach addendum to: a pilot investigation of cottonwood recruitment on the Sacramento River. The Nature Conservancy, North Sacramento Valley Hub Office, Chico, CA.
Rood, S. B., and J. M. Mahoney. 1990. Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. Environmental Management 14:451-464.
Rood SB, C.R. Gourley, E.M. Ammon. et al. 2003 Flows for floodplain forests: A successful riparian restoration. Bioscience 53 (7): 647-656
Sakio, H. 1997. Effects of natural disturbance on the regeneration of riparian forests in the Chichibu mountains, central Japan. Plant Ecology **132**:181-195.
Sands, A., (Ed.). 1980. Riparian forests in California: their ecology and conservation. A symposium sponsored by Institute of Ecology, University of California, Davis and Davis Audubon Society. Agricultural Sciences Publications, University of California, Berkeley.
Scott, M. L., J. M. Friedman, and G. T. Auble. 1996. Fluvial processes and the establishment of bottomland trees. Geomorphology 14:327-339.
Scott, M. L., P. B. Shafroth, and G. T. Auble. 1999. Responses of riparian cottonwoods to alluvial water table declines. Environmental Management **23**:347-358.
Stella, J. C. 2005. A field-calibrated model of pioneer riparian tree recruitment for the San Joaquin Basin, CA. University of California, Berkeley, Berkeley, CA.
Stella, J. C., J. J. Battles, B. K. Orr, and J. R. McBride. 2006. Synchrony of seed dispersal, hydrology and local climate in a semi-arid river reach in California. Ecosystems.
Stella, J.C., J.J. Battles, B.K. Orr, J.R. McBride. (in prep_a) Physiological thresholds and water relations of riparian tree seedlings in response to simulated river regimes.
Stella, J.C., J.J. Battles, B.K. Orr, J.R. McBride. (in prep_b) A field-calibrated, predictive model of riparian seedling establishment on regulated rivers in the San Joaquin Basin, CA.

Stillwater Sciences. 2001. Merced River Restoration Plan Phase II. Volume II: Baseline evaluations; geomorphic and riparian vegetation investigations. Prepared by Stillwater Sciences, Berkeley, California for CALFED, Sacramento, California.

Stillwater Sciences. 2007. Linking biological responses to river processes: implications for conservation and management of the Sacramento River-a focal species approach. Final Report. Prepared by Stillwater Sciences, Berkeley for The Nature Conservancy, California.

Strange, E.M., K.D. Fausch, A.P. Covich. 1999. Sustaining ecosystem services in human-dominated watersheds: biohydrology and ecosystem processes in the South Platte River Basin. Environmental Management 24(1):39-54.

Stromberg, J. C., B. D. Richter, D. T. Patten, and L. G. Wolden. 1993. Response of a Sonoran riparian forest to a 10-year return flood. 53:118-130.

Thompson, K. 1961. Riparian forests of the Sacramento Valley, California. Annals of the Association of American Geographers 51:294-315.

Tu, I. M. 2000. Vegetation patterns and processes of natural regeneration in periodically flooded riparian forests in the Central Valley of California. Dissertation. University of California, Davis.

Warner, R. E and K. M. Hendrix, editors. 1984. California riparian systems: ecology, conservation, and productive management. University of California Press, Berkeley.

Weltzin, J. F., and G. R. McPherson. 1999. Facilitation of conspecific seedling recruitment and shifts in temperate savanna ecotones. Ecological Monographs **69**:513-534.

Wiens, J. A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology **47**:501-515.

Wood, D. M. 2003a. Pattern of woody species establishment on point bars on the middle Sacramento River, California. Report submitted toThe Nature Conservancy, Sacramento River Project. Department of Biological Sciences, California State University, Chico.

Wood, D.M. 2003b. The distribution and composition of woody species in riparian forests along the Middle Sacramento River, California. Report submitted to The Nature Conservancy, Sacramento River Project. Department of Biological Sciences, California State University, Chico.

Young, J.A., and C.D. Clements. 2003. Germination of seeds of Fremont cottonwood. Journal of Range Management 56:660-664.