Title
Biogeography and Habitat Dynamics of California's Bank Swallows (Riparia riparia)

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Publication Date
2021

Biogeography and Habitat Dynamics of California's Bank Swallows (*Riparia riparia*)

By

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DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Geography

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

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Eric W. Larsen

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Committee in Charge

2021

Nearby is the graceful loop of an old dry creek bed. The new creek bed is ditched straight as a ruler; it has been "uncurled" by the county engineer to hurry the run-off. On the hill in the background are contoured strip-crops; they have been "curled" by the erosion engineer to retard the runoff. The water must be confused by so much advice.

- Aldo Leopold, Sketches Here and There

Acknowledgements

As I write this, it feels woefully inadequate as a means of acknowledging the community of people and the scope of experiences that have been so important to my academic journey over the last 8 years. I am truly grateful for the support, encouragement, assistance, and guidance of so many colleagues, my family, and my friends – it has been amazing to interact with you all in the context of this adventure.

I will start with a grand thank you to my comprehensive exam - and my dissertation committee members - Eric Larsen, Steve Greco, Jim Quinn, Jay Lund and Sara Kross. You have challenged me to think beyond the details of a technical analysis and to inspire, think deeply and be creative, and to look at problems and questions from a multidisciplinary lens. I am grateful for the time and critical thought you've put into this body of work and my time at school over the past many years.

Thank you, Eric Larsen for the opportunity to join your cadre of river scientists for a few years, providing a window into the world of river mechanics, and your patience as I have made my best attempt to employ a process-based model despite my empirical leanings. I aspire to someday realize a fraction of your gift of storytelling, inspiring, and leaving people excited about the things that you are working on.

Carrie Armstrong-Ruport! Thank you for your support, advice, and guidance in navigating this process. Your tireless advocacy for the graduate student body is amazing and your encouragement has been so meaningful.

Thank you, Adam Henderson, for the knowledge and wisdom regarding rivers and birds that you've shared over the years and your great friendship. Your leadership on the Bank Swallow survey is fundamental to our understanding of that bird in California.

Thank you, Mike Roberts, for your mentorship, guidance, and friendship over the past many years – and the sanity-preserving adventures on two wheels and up the sides of rock walls.

Thank you, Terri Gaines, for supporting my academic and professional endeavors, believing I could get this done, and being a tireless advocate for me as I stepped through the process from coursework to studying for my comprehensive exam to writing.

Thank you, Stacy Cepello and Ray McDowell, for the patient mentorship, knowledge, and wisdom you both have offered over the many years working on the planning processes and river systems of the Central Valley – it has been a huge learning experience.

Thank you, Gail Newton, for your willingness to support this work at the highest levels of government within our professional arena.

Thank you, Joe Silveira and Andrew Conlin, for showing me the soils and vegetation and land management approaches along the middle Sacramento River. Joe we've had great conversations about the knowns and unknowns of the Bank Swallow, and I've learned much from you about the management of the Sacramento River National Wildlife Refuge.

Thank you, John Callaway for the peer review in the professional arena – it was a learning experience to develop a science synthesis of the Delta - and the support and advocacy on my PhD pursuits.

Kate Anderson, Cory Copeland, Dan Constable, and Kaylee Griffith working with you all over the years has been an inspiration and motivating force – I've learned much from all of you.

Grayson and June Scott – thank you for your patience with Dad while he's been working on "school stuff" and I hope this affords you future inspiration for the natural world and for your academic pursuits. I love you both dearly – you can do anything you put your mind too!

Rachel – where to start? Thank you for your un-ending support, patience, interest, and advice over the years. You've been an incredible partner through all of this – and endured a lot of grumbling over the years – I love you. Thank you for your willingness to help me edit and format this thing after so many years… I'm not sure I would have been able to get it across the finish line. As with San Luis Obispo birds … you've been such a huge part of the reason I have been able to start, carry out, and finish this work. I'm looking forward to our next chapter … educating and learning from these girls.

And last, thank you to all of you who have had been so present and supportive over the years – the cumulative encouragement and energy you have given has enabled me to keep moving forward. It has been such an important dimension for me… so thank you E. & L. Hansen, A. Kalia, D. Middleton, G. & R. Elert, D. Fisher, T. Giffen, J. Tabarracci, A. Azam, L. Finch, J. Brown, J. Shaner, R. & E. Warren J. & V. Novak, D. Carlson, T. Cool, T. Holland, A. Anderson, C. Gennarelli, N. Clipperton, D. Kratville, E. Lindgren, B. Cannon, R. Phillips, D. Battaglia, and those not named.

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Introduction

Within the semi-arid west, riparian systems support more than 80% of the terrestrial biodiversity despite occupying less than 2% of the landscape (Johnson et al. 1977, Smith 1980, Cooperrider 1986, Johnson 1989, Chaney et al. 1990, Naiman et al. 1993, Ohmart 1996, Svejcar 1997, RHJV 2004). Further, they are expected to play an important role in ecological adaptation to a changing climate (Seavy et al. 2009). The Sacramento River basin (Figure I-1) supports a rich riverine ecosystem including structurally and compositionally complex riparian vegetation and a diverse landbird community (Larsen et al. 2006, Greco et al. 2007, Golet et al. 2013). Of note, the river corridor provides nesting habitat for the largest documented metapopulation of breeding Bank Swallows (*Riparia riparia*) in California (Humphrey and Garrison 1986, Garrison et al. 1987, Laymon et al. 1988, CDFW 1992, BANS TAC 2013). Within this system, the species depends specifically on riverine geomorphic processes, specifically the erosion and deposition of sediments resulting from channel migration which renew its nesting substrate, steep riverbanks of friable soils, on a nearly annual basis (Garrison 1999, BANS TAC 2013). These fluvial geomorphic processes are fundamental in the development of floodplain forest communities and associated habitats at the terrestrial-aquatic interface (USFWS 1992, Golet et al. 2003, Stillwater Sciences 2007, Florsheim et al. 2008, Greco 2013).

The function of the Sacramento River ecosystem has been impacted by flow impairment from dams, disconnection of floodplains from levees, and flood control measures such as bank stabilization, resulting in declines in the Bank Swallow population and other wildlife taxa (Katibah 1984, The Bay Institute 1998). Similar impacts to watersheds within western North

America have led to a loss of 95% of the historical Bank Swallow population, garnering conservation attention as a Partners in Flight Species of Continental Importance (Rosenberg et al. 2016). Recent significant decline of California Bank Swallow numbers has led public wildlife agencies to consider up-listing the species' status from State Threatened to State Endangered (Wright et al. 2014). Given the significance of the Sacramento River in the context of other continental habitat resources and the large metapopulation using the waterways within the Sacramento River basin, federal endangered species protections may also be warranted.

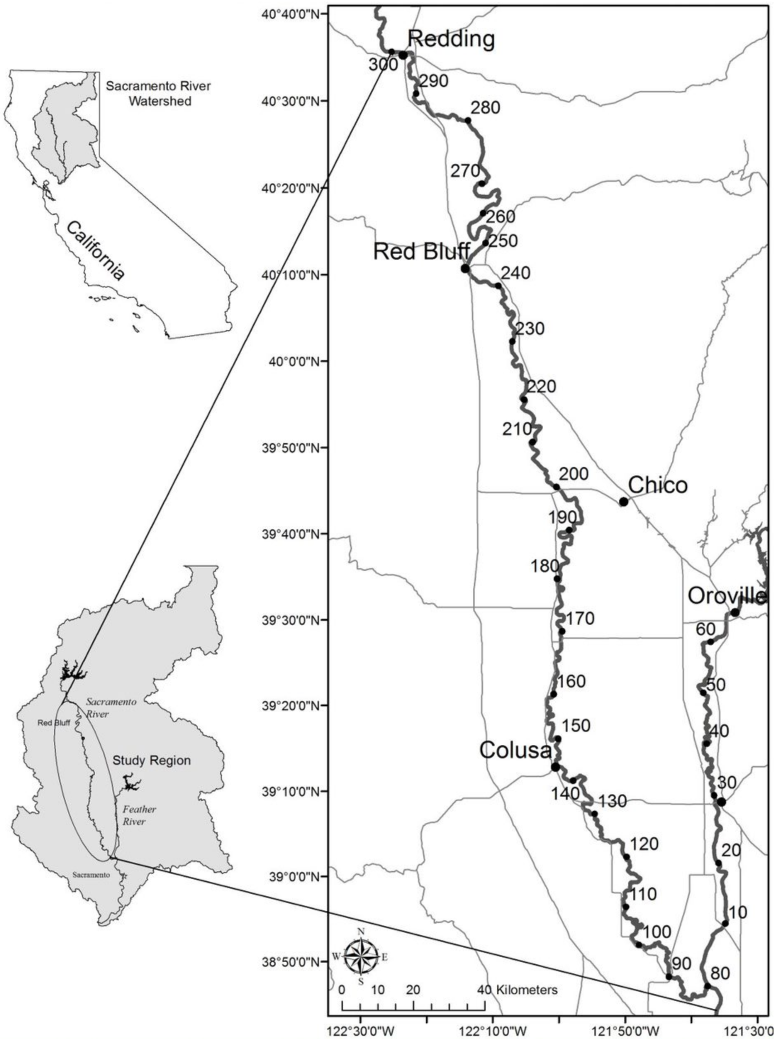

Figure I-1. Geographic extent of the Sacramento River Basin

The Bank Swallow Recovery Plan identifies stream channel restoration through bank stabilization removal as the most important management action in addressing the recovery needs of the species (CDFW 1992, Garrison 1998). Population assessments which attempt to forecast population trajectories indicate that bank restoration through bank stabilization removal will positively impact population viability (Moffatt et al. 2005, Garcia et al. 2008, and Girvetz 2010). Several significant data gaps exist which impede progress on implementing bank restoration. While Bank Swallow population surveys have been conducted along the Sacramento River since 1986 by state and federal agencies, clear and quantitative identification and spatial mapping of suitable nesting substrate (e.g. soil characteristics) is needed (BANS TAC 2013). There is also a lack of understanding regarding site-specific habitat evolution through space and time, and the constraints on habitat-forming processes within the basin (e.g. geology, infrastructure, climate change effects on streamflow; BANS TAC 2013). Additionally, the efficacy of bank restoration in creating usable Bank Swallow habitat remains untested. Entities focused on the development and implementation of environmental policy, river restoration, and environmental risk reduction actions (i.e. flood management) would benefit significantly from an improved understanding of Bank Swallow habitat and its relationship with riverine geomorphic process. The topic of geomorphic process restoration of the Sacramento River system has been identified as a restoration target in a watershed restoration context by Golet et al. (2013). That paper notes that restoration efforts on the Sacramento River have benefited native species through re-establishing native vegetation but have largely failed to address restoration of riverine geomorphic process. Focused study of geomorphic process restoration would contribute directly to: (1) California Department of Fish and Wildlife's (CDFW) Bank Swallow Recovery Plan Update, (2) multiple efforts to prioritize geomorphic process-based restoration actions (e.g. United States Army Corp of Engineer's Sacramento Bank Protection Program Phase II, III, and California Department of Water Resource's (CDWR) Central Valley Flood System Conservation Strategy (CDWR 2016), and (3) permitting and mitigation requirements of flood control agencies working within the river system.

Few land bird species are as closely tied to riverine geomorphic process as the Bank Swallow. This dependency on the function of dynamic landscape characteristics requires analyzing not only the extent of suitable landscape components (typical in bird-habitat association modeling), but also the potential for those components to interact with a dynamic river channel over time. Expected shifts in river hydrology due to climate change further complicate predictions based solely on existing conditions.

This research uses a novel combination of historical information, existing survey data, and modeling approaches, to support the information needs of the California Department of Fish and Wildlife and other public agencies, the Bank Swallow Technical Advisory Committee (BANS TAC), and non-governmental conservation organizations. It will inform efforts aimed at recovery and conservation of the Bank Swallows and riparian ecosystems in California.

Research Questions

Research questions include three major focus areas:

Bank Swallow Metapopulation and Sacramento River watershed status: What is the biogeographic/continental significance of the Sacramento River Bank Swallow metapopulation? Similarly, what is the continental significance of the breeding habitat resources that the watershed provides to the species? Are continental population estimates (e.g. Rosenberg et al. 2016) of the species consistent with observations of the species on the landscape?

Bank Swallow Habitat Associations (soils and channel meander migration): Are there specific soil attributes that correlate with colony presence? Can these attributes be identified to provide a habitat suitability framework? What is the extent and distribution of suitable soils within the floodplains of the middle and lower Sacramento River? How does flow impairment and river channel stabilization through the installation of rock revetment influence channel migration through soils modeled as suitable for Bank Swallows?

Bank Swallow Response to Restoration: Will Bank Swallows respond to efforts to restore geomorphic function (specifically lateral channel migration through rock revetment removal)? What characteristics or habitat features are present at sites where Bank Swallows have recolonized restored banks?

Based on these research questions, the specific study objectives are:

1. Evaluate the continental (biogeographic) significance of the Sacramento River Bank Swallow metapopulation.
2. Identify and map soil suitability for Bank Swallows along Sacramento River.

3. Evaluate meander migration under various scenarios including historical and current streamflow conditions and with and without stream channel constraints.
4. Empirically assess bank restoration (revetment removal) as a recovery measure for Bank Swallows.

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Status on the Sacramento River - What's the Difference Between Threatened and Endangered, and Where Do We Go From Here? Paper presented at the Sacramento-Shasta Chapter of the Wildlife Society 8th Annual Natural Resources Symposium. Sacramento, CA. November, 2014.

Chapter 1. Evaluating the Biogeographic (Continental) Significance of the Sacramento River Bank Swallow Metapopulation:

Abstract

The Bank Swallow is one of nine neotropical migrant swallow species in North America. Like other new world avian insectivores, the Bank Swallow has suffered significant range-wide declines. Breeding Bird Survey estimates indicate a 95 percent decline over the past 30 years. Standard bird survey methods are not well suited for estimating abundance of gregarious species with large home ranges, however. Thus, while historical anecdotal observations indicate the species occurred in extraordinary numbers, and the species is now local and uncommon, current estimates of abundance are not reliable. Here I evaluate the biogeographic significance of the Sacramento River which is known to support many large colonies of breeding Bank Swallows. I apply expert opinion and findings from a review of the literature to explore the species conceptual habitat associations at the landform, river reach, and site-specific scale within the Sacramento Valley of California. I collect and analyze breeding colony census data on the Sacramento and Feather River. I contrast these estimates with data from the Breeding Bird Survey and eBird for states and regions across North America and conduct an extensive literature review to further identify metapopulation data. The species has close associations with friable soils and fluvial geomorphic processes that operate at various spatial and temporal scales for its breeding substrate. These processes have been impacted by river impoundment and flood control measures. Despite these impacts on river function, the Sacramento River and its tributaries support a large metapopulation of Bank Swallows. Only Lake Ontario and Lake Huron are documented to supported larger

numbers of the species. Estimates of the species population are likely overestimated, and heightened conservation of the species is warranted, especially in California and the Great Lakes region which support significant breeding populations.

Introduction

The Bank Swallow is a Holarctic species, inhabiting Europe, Asia and North America. The species is one of nine species of swallows in North America (Garrison 1999). The Bank Swallow is a Neotropical migrant species, wintering in Central America and South America, and breeding in the North America. Like many other insectivore Neotropical migrant species, the Bank Swallow has suffered significant range-wide declines (Robbins et al. 1989). Rosenberg et al. (2016) estimate a 95% reduction in the continental population based on Breeding Bird Survey (BBS) data. COSEWIC (2013) reports a decline of 98% of its Canadian population over the past 50 years.

Despite these significant continental declines in abundance, the species has yet to garner federal protections in the United States. Currently the species is listed by Partners in Flight as a common bird in steep decline, ranking 11th out of 20 on the continental concern score (NABCI 2016).

The largest regional populations occur in California along the Sacramento River, and in the Great Lakes region. The species was listed in 1989 as threatened under the California Endangered Species Act. Within Canada, it was designated by the Canadian Wildlife Service as threatened in 2013.

The Bank Swallow is a gregarious species, nesting in colonies, and flocking during the non-breeding component of its annual cycle (Garrison 1999). Breeding colonies are highly variable in size, from 10 to more than 10,000 burrows (Garrison 1999, COSEWIC 2013). Colonies vary in size annually and have been shown to vary with environmental condition. Bent (1942) describes a migratory flock at Cedar Lake, IL consisting of more than 250,000 individuals in the early part of the 20th century. No contemporary records exist of this magnitude, but within the last 20 years flocks of 1,000-5,000 birds have been observed on migration (eBird 2019).

The aerial and gregarious nature of the species present challenges for typical bird survey techniques and population estimation on the breeding, migratory, and wintering range. The variability of cluster (i.e. flock or colony) size further complicate survey approaches. Typical methods such as mist netting, spot mapping, line transects, and point counts make assumptions about the rates at which birds are detected, and about their distribution across the landscape within discrete territories (Ralph et al. 1995, Ministry of Environment, BC 1998). Birds with large home ranges, such as swallow species, violate these assumptions. Colony nesting and flocking birds require focused survey methods at colony or roosting sites (CalPIF 2002). Thus, large-scale standardized population assessments such as the Breeding Bird Survey and the Monitoring Avian Productivity and Survivorship (MAPS) programs are unreliable approaches to assessing Bank Swallow status on the continent. They are, however, the only comprehensive surveys of breeding birds within North America.

On the breeding grounds in North America, the Bank Swallow has strong ties to friable soils and geomorphic processes, which expose steep banks where it nests during the breeding season (March – July). These conditions often occur in alluvial soils that are re-worked through river meander migration or bluffs created by lake or ocean wave wash. The species is also known to nest in anthropogenic habitats such as gravel pits and road cuts. The geomorphic processes can conflict with human land uses and infrastructure in managed systems, leaving the species habitats vulnerable to impacts from efforts to protect levees, bridges, and water supply infrastructure (James 1991, USFWS 2004, BANS TAC 2013).

These specialized habitat associations constrain the extent and distribution of available nesting substrate. Therefore, the species is often characterized as being "highly local," and observations during the breeding season tend to be limited. Further, the species is sensitive to management activities that alter flows or stabilize stream channels or lakeshores, which has led to a further reduction in the distribution of suitable habitats. For example, within California, the species is of conservation concern given the loss of suitable habitat and concomitant range contraction in Southern California (Remsen 1978). The species was listed as State threatened in 1989, due to these impacts. It has been documented that more than 85% of the observed California breeding population uses the Sacramento River and Feather River corridors (Laymon et al. 1988). A colony at the sea cliffs of Fort Funston, Golden Gate National Seashore has persisted for many years (on average approximately 360 burrows; NPS 2007). Very small (<100 burrows) populations persist on the north coast and eastern Sierra Nevada in California.

The following are questions this research seeks to elucidate: (1) What are the biogeographic habitat elements that support Bank Swallows within the Sacramento Valley of California? (2) What is the relative significance of the of the Sacramento River Bank Swallow metapopulation with regard to the continental population? (3) What is the continental significance of the breeding habitat resources the watershed provides to the species? And, (4) Are modeled population estimates broadly accepted in developing species conservation status consistent with empirical observations of the species on the landscape?

Methods

For this chapter I develop a conceptual description of the biogeographic elements of the habitat that supports Bank Swallows within the Sacramento Valley. I also contrast field gathered population survey data from the Sacramento and Feather rivers with a comprehensive synthesis of existing literature on Bank Swallows and citizen science data including the Breeding Bird Survey and eBird. These citizen science data provide both qualitative and quantitative information on the species more broadly across North America. I identify the need for a robust quantitative assessment of the continental population using appropriate methods, as the methodological assumptions of the current approaches are violated by the species' biology and distribution on the landscape. Last, using the best available data from citizen science datasets, I present a synthesis on the continental significance of the Sacramento River watershed given existing and available information.

Sacramento River Watershed

Biogeographic Elements of Bank Swallow Habitat

I conducted a review of literature on the geomorphic origins of the Sacramento Valley, the historic and current hydrology and geological characteristics of the river corridor including anthropogenic impacts, and the known habitat associations of the Bank Swallow within this geographic region. I describe these elements in three distinct temporal and spatial scales: landform (geologic time), river reach (decadal), and site specific (annual/within season).

Sacramento River Bank Swallow Population

I used annual Bank Swallow survey data from census work that has been conducted from 1986-2017 along the Sacramento River, and 1986-87, 2002-03, and 2008-2017 along the Feather River. I conducted surveys from 2011-2017 as part of an interagency effort on the Sacramento River and Feather River. In this chapter I summarize the existing survey information from the coordinated efforts, including those which I participated on, from 1986-2017. A temporal subset of these data also provides the colony location information used to model soil suitability in Chapter 2 of this dissertation.

North American Bank Swallow Assessment

Literature Review

I conducted an in-depth literature review to identify technical reports and peer reviewed publications with a focus on key words “Bank Swallow” and “Riparia”. The literature review included comprehensive search of online databases including Web of Science, ScienceDirect, JSTOR, and others. To understand how the California Bank Swallow population compared to other populations within North America, I focused my search on articles that provided information on nesting occurrences outside of the California populations I was actively studying through the Bank Swallow Technical Advisory Committee (BANS TAC). From these articles I extracted information on location, colony size, number of colonies, and the nesting substrates within which the colonies were constructed. I also queried select avian experts and surveyed online bird listservs for information on Bank Swallow nesting occurrences beyond what was captured in the peer-reviewed literature.

Population Data Synthesis

I queried two online databases, the North American Breeding Bird Survey (BBS) (https://www.pwrc.usgs.gov/bbs/about/) and eBird (https://ebird.org/about). Each is built upon citizen-science data collection efforts which allow data collection and inference at a continental scale. The BBS, which gathers data across North America where roads allow surveys to be conducted, relies on local ecological knowledge of volunteer field technicians and standardized data collection methods to ensure data quality. eBird, which gathers data at the global scale, employs multiple levels of quality control and quality assurance at pre- and post-data submission points, through observer verification, and through leveraging local ecological knowledge in data review (Kelling et al. 2015, Callaghan and Gawkik 2015). Both the BBS and eBird represent the most current, geographically comprehensive, and rigorous data on Bank Swallows throughout their North American range. Nonetheless, each has potential bias introduced by methodological assumptions or spatial or temporal coverage bias (Zhang 2020).

Breeding Bird Survey

I extracted Bank Swallow count data from the North American Breeding Bird Survey (BBS). This survey is a research program coordinated by the US Geological Survey's Patuxent Wildlife Research Center and Environment Canada's Canadian Wildlife Service. The major research objective of the BBS is to monitor the status and trends of North American bird species. This is accomplished though annual road-based point-transect surveys which occur during the breeding season (May or June). The BBS employs a point-transect survey approach to assess bird populations. Observers travel along a 24.5-mile survey route, stopping every 0.5 miles to conduct an area constrained point count survey lasting three minutes. Statistical techniques are then employed to estimate rates of detection and extrapolate population estimates from count indices (Link and Sauer 1994).

BBS data are compiled and analyzed by program researchers and made available at the following website: https://www.pwrc.usgs.gov/bbs/. I queried the Breeding Bird Survey (BBS) database by state, province, and regions based on climate/vegetation potential for long-term (1966-2015) and short-term (2005-2015) trend data on the Bank Swallow within North America (Sauer et al. 2017). These data include sample sizes (number of BBS routes), trend estimates and confidence intervals for each geographic region. I also queried raw survey data for years 2013-2017 for each state and province.

EBird Citizen Science Database

I also extracted Bank Swallow observations from eBird. eBird is a web-based real time database where observers can document bird sightings. The project was initiated in 2002 by Cornell Lab of Ornithology, and its use has grown significantly. eBird provides a venue where analysts can evaluate bird abundance and distribution based on a rich catalogue of bird observations. The primary source of data is observations recorded by birdwatchers and naturalists. Unlike the BBS, eBird requests data on how observations are made, however, it is not based on a time and space bound repeatable protocol. The research objectives of the project continue to evolve, but eBird is centered on providing a platform where bird occurrence information is continuously documented and available to the benefit of naturalists and researchers studying bird abundance, distribution, and habitat use around the globe. eBird data are available at the following website: https://ebird.org/home. I queried the eBird database by state and province for the interval of March - July from 2013-2017. These data include sample sizes (the number of user entries per year), and raw numbers of observations for each geographic region.

Results

Sacramento River Watershed

For the Sacramento River watershed, I provide results of the literature review regarding the biogeographic elements of Bank Swallow habitat, including a technical description of the regional setting and the habitat dynamics of the Bank Swallow within the study region. I then summarize the results of long-term Bank Swallow surveys of the Sacramento River and Feather River.

Biogeographic Habitat Elements of Bank Swallow

The Sacramento River is the largest river system within California, flowing from north to south in the northern portion of the Great Central Valley of California. The catchment of the Sacramento River comprises nearly 1/5th of California's land area. In total, the Sacramento

River watershed drains 60,900 km^2, with its hydrology driven by a Mediterranean climate. During the winter wet season (November-March) rain events and spring snowmelt from its headwaters and upper tributary reaches influence streamflow (Schoellhamer et al. 2012). During the summer and fall months (April-October) unimpaired flows would have been low due to the semi-arid climate, corresponding with the nesting period of the Bank Swallow. The upper reaches of the river reside at higher elevations and are incised or entrenched and constrained by volcanic deposits (Singer and Dunne 2001, Larsen et al. 2006). The middle and lower reaches of the river meander across a flat broad (~350 km) alluvial plain within the Central Valley composed of transporting and building bars of gravels, sand, clay, and silt (Singer and Dunne 2001). The two-year recurrence interval flow within the alluvial reach of the river is 2270 m^3/s, and bed material grain sizes range from 20-30 mm (WET 1988). The slope of the alluvial reach is between 0.0002 m/m to 0.0007 m/m (WET 1988). The basin and tributary characteristics result in well sorted and relatively fine sediments along the main stem of the Sacramento River (Singer 2008). The prevalence and extent of suitable soil within the basin is a key habitat resource for Bank Swallows. Throughout the middle and lower reaches, tall, cohesive, yet friable cut banks form, which are ideal nesting substrate for Bank Swallows. In reaches constrained by geologic features or levees, local erosion sites are also used by the Bank Swallows for nesting.

The Feather River is the largest tributary to the Sacramento River. It has two large tributaries, the Yuba and Bear rivers, and drains a catchment area of 10,300 km^2 above its confluence with the Yuba (James et al. 2009). The Feather River can receive significant precipitation, upwards of 2667 mm during the wet season. The two-year recurrence interval flow is 934 to

1415 m^3/s (Cain and Monohan 2008). The slope of the Feather River downstream of Oroville Dam is between 0.00012 m/m to 0.0007 m/m (Porterfield et al. 1978). The Yuba River watershed has a catchment area of 3740 km^2. The Bear River has a catchment area of 760 km^2. Like the Sacramento River, the Feather River and its tributaries are controlled by regulated flow from reservoirs created by dams. Oroville Reservoir impounds the Feather River, Englebright and New Bullard's Bar Reservoirs control flows on the Yuba River, and Camp Far West Reservoir governs flows on the Bear River. The Feather River surficial geology has been significantly impacted by mining activities in the upper watershed. Between 1848 and 1909 approximately 76.5 million cubic meters of hydraulic mining debris washed down the Feather River, and the watershed received another 524 and 192.5 million cubic meters respectively in the Yuba and Bear rivers (James et al. 2009). A legacy of deposits along the alluvial reaches of the lower Feather River remain, with lower strata being cohesive and erosion resistant, while upper strata are less cohesive and more erosion prone (GEI 2008, James et al. 2009). These clay rich deposits have reduced the availability of friable soils to Bank Swallows on the banks of the Feather River.

The surficial geology, floodplain soils, hydrology, and climate of the Sacramento Valley once supported vast riparian, wetland, oak woodland and grassland vegetation communities (Katibah 1984, TBI 1998, RHJV 2004). Dominant tree species included valley oak (*Quercus lobata*), California sycamore (*Platanus racemosa*), Fremont cottonwood (*Populus fremontii*), and several willow species (*Salix* spp.), among other species (Thompson 1980). These ecosystems supported diverse populations of invertebrates, mammals, fish, and other wildlife (TBI 1998). For the Bank Swallow, California's Mediterranean climate combined with the geography of the Sacramento and Feather rivers result in high wet season flows, seasonal river meander, and local erosion which refreshes banks at a large spatial scale.

The Sacramento River and tributary flows have been altered by dams, diversions, and levees over the past 150 years (TBI 1998). The river provides approximately 35% of California’s water supply (Buer et al. 1989). To enhance water supply and flood control purposes, levees, bank stabilization, and grade control structures have been installed, impacting fluvial channel processes. Further, the river has been engineered to connect to a flood bypass system, using system of weirs and floodways during high flows, disconnecting the main channel from floodplains on the lower river system. Land conversion has reduced wetlands by 94% and riparian vegetation by 87-89% of historical cover, respectively (Katibah 1984, GIC 2003). The remnants of riparian and wetland ecosystems along the Sacramento are considered “endangered ecosystems” within the arid and semi-arid regions of western North America (Noss et al. 1997).

The river systems within the Sacramento Valley are influenced by a Mediterranean climate with cool wet winters and hot dry summers. Historically, storm events caused high flows initiating in November and receding from March through June. The species evolved to respond to a declining hydrograph in spring as snow melted creating relatively predictable declines river water levels during the breeding season. Water development and reservoir releases for agricultural purposes have led to unstable water surface elevations during the breeding resulting in seasonal bank slumping or burrow inundation (BANS TAC 2013, R. Melcer Jr. pers obs).

A second key component of Bank Swallow habitat is the mechanism of local erosion that renews the surface of the cut bank (i.e. local erosion caused by river channel meander migration or lake wind-wave action). Cut bank renewal is important as slope degradation, vegetation colonization, and infestation by parasites degrade the quality of burrows and colony sites after approximately two seasons (Garrison and McKernan 1994, Garrison 1999, Szep and Moller 1999, Moffatt et al. 2005). Bank Swallow's habitat is renewed within the Sacramento River watershed on a nearly annual basis, even in relatively dry years that experience only a single bank-full flow (Wright et al. 2011).

Temporal and Spatial Scale

The Sacramento Valley is an important and unique landscape for the Bank Swallow, as evidenced by the presence of the largest documented population of nesting birds outside of the Great Lakes region. The species has responded to geological, hydrological, and ecological processes of the landscape that are occurring over various temporal and spatial scales – over millennia and within each nesting season, and over entire regional scales (i.e. landscape) to the scale of individual sites. These processes have been interrupted by anthropogenic activities.

Landform Considerations - Long time scales (>100 years)

Over millennia and at a landscape scale, geologic and hydrological processes operating on the northern Central Valley of California have created a landform which supports multiple key habitat dimensions of the Bank Swallow. The broad and extensive distribution of soils which are iteratively eroded and reworked by more than 644 km (~400 miles) of large meandering river channels may be the largest and most important habitat resource for the species on the western landscape. This is further complemented by the Mediterranean climate and snowmelt-driven river hydrology and extensive riparian vegetation communities. The hydrology and riparian vegetation provide the needed structure and food resources which further support the large populations of swallows nesting along the river (Garcia 2009, Girvetz 2010, Moffat et al. 2005).

The predominant phenomena acting over geologic time-scales on Northern California include basin subsidence and uplift of the northern Coast Range to the west, Klamath Mountains to the north, and Cascade Mountains and Sierra Nevada to the east. Erosion and sedimentary processes acting on the uplifting mountain ranges have filled the basin, along with volcanic flows, and formed a very wide, low gradient valley. This wide and low gradient valley resulted in main stem channels with tributaries and distributaries that were and are situated far from their sediment production zones, and ultimately low sediment loads compared to other river systems exiting montane landscapes (Schumm 1981, Singer 2008). During high water events, sediment deposition may occur at the reach or river scale. During lower flows sediment movement and deposition occurs locally, within a single bend or riffle-pool complex. The resulting well sorted deposits of silt, sand, clay, and cobble along hundreds of miles of tributary and river channel are significant to the Bank Swallows. Given the seasonal hydrology of the channels, these deposits include fine-scale features such as horizontal striations in the deposits where variation in silt, sand, and clay content provide the cohesiveness for burrow construction (Figure 1.1). While the presence of Bank Swallows colonies along the Sacramento River demonstrates the suitability of floodplain deposits, no quantitative evaluation of the suitability or extent of suitable soils has been undertaken (BANS TAC 2013).

Figure 1.1. Fine-scale features such as horizontal striations in silt, sand, and clay deposits provide substrate for burrow construction.

The sedimentary processes and connections between the sediment production, transfer, and deposition zones of the watersheds have been significantly impacted over the past 200 years by mining, water development and flood control (Singer and Dunn 2001). Large dams which impound sediment and bank stabilization which hardens the stream channel banks interrupt these fundamental processes at a watershed scale. This has led to shifts in meander dynamics and destabilization of erosion processes (Micheli et al. 2004).

Under current conditions, sediment inputs are limited from tributaries and headwaters due to dams, and sediment dynamics are now largely dependent on existing deposits within the transfer zone below these impoundments (Buer et al. 1989, Singer 2008). Long-term sustainability of the river deposits will be impacted if the river impoundment persists. The magnitude of impact of these stressors on Bank Swallows has not been quantitatively evaluated and would provide information key to restoration of Bank Swallow habitats and conservation of the species (Girvetz 2010, BANS TAC 2013).

River Reach Considerations and Decadal Time Scales (>10 years)

The sediment deposits described above are not available to Bank Swallows for nesting until the river channel erodes laterally and forms steep cut banks (BANS TAC 2013). At the reach scale, lateral channel migration and cutoff processes form cut banks exposing suitable soils where Bank Swallows can excavate burrows. Lateral channel migration also drives vegetation dynamics, including vegetation recruitment, and loss of older stands of vegetation (Greco et al. 2007). Flooding which occurs on the 10-year recurrence interval time scale provides extensive resurfacing of banks, which rejuvenates cut banks from slump, vegetation colonization, and parasite infestation.

Existing sediment deposits with characteristics suitable for Bank Swallow burrow construction are widespread within the floodplain of the Sacramento River. The stream channel migrates up to 4.8 meters per year (Micheli et al. 2004), therefore bend translation over 5- and 10-year time periods forms steep cut banks accessible by Bank Swallows.

Bank and channel stabilization (rock revetment, grade control structures, other hard points) impacts hydrologic, geomorphic, and ecological processes that occur at the reach scale. Rock revetment placed on banks halts local erosion and deposition processes, alters channel depth, and increases velocities (Buer et al. 1989, DeHaven 1989, USFWS 2004). River impoundment and water extraction through diversions have altered sediment supply, stream power, and hydrological timing (Larsen et al. 2006). These effects alter river meander dynamics, destabilize the riverbed, and lead to losses in vegetation community dynamics and species habitats both upstream and downstream of the site of stabilization (Larsen et al. 2006). Removal of natural vegetation for agriculture or flood control actions has significantly affected the rate of river meander migration and reduced the complexity and function of the riparian ecosystem (Katibah 1984, TBI 1998, Micheli et al. 2004, USFWS 2004).

Site Specific Considerations and Annual Time Scales (within season)

At the site scale, Bank Swallow habitat models demonstrate a preference for friable yet cohesive soils, steep banks clear of vegetation, and appropriate adjacent land cover that support terrestrial insect populations (Moffat 2005, Garcia 2009, BANS TAC 2013). Riparian vegetation and grasslands correlate with the presence of large Bank Swallow colonies. Annually, hydrologic variations influence what sites are available for nesting - water levels in a given year may make some banks inaccessible to Bank Swallows. Bank saturation from increases in water level during the nesting season can also cause local bank slump and influence the quality of the habitat (Habersack et al. 2007). These processes tend to occur at the bend scale or more locally depending on channel form and local hydraulics.

Similar to effects at the reach scale, bank and channel stabilization infrastructure impact habitat availability at the site scale. Rock revetment prevents the formation of cut banks, and blocks Bank Swallow access to suitable soils. The removal of vegetation affects prey availability, loafing, foraging, and roosting activities. Hydrological impacts result in unnatural water surface elevation increases and decreases which can inundate colonies or cause bank slumps and mass colony failures (BANS TAC 2013, R. Melcer pers obs).

Sacramento River Bank Swallow Population Estimate

The Sacramento River and Feather River support a large metapopulation of Bank Swallow colonies. Field surveys conducted along the Sacramento River from river mile 300 downstream to river mile 80 between 1986 and 2017 have documented 11,000 – 25,000 burrows annually (BANS TAC 2013, BANS TAC unpublished data 2017). The Feather River, a major tributary of the Sacramento River has provided habitat for 7-24 colonies composed of 1,000 to 6,500 burrows in any given year (BANS TAC 2013, BANS TAC unpublished data 2017). Table 1.1 summarizes the number of colonies and burrows for the Sacramento and Feather rivers by year from 1986-2016, as documented through multi-agency led annual census surveys of both of these waterways. Appendix A, *Bank Swallow Survey Methods for the Sacramento and Feather Rivers, California, Version 1.0, January 2017,* provides a detailed methodology for these census surveys.

As of November 2020, there is no documentation of river systems within North America supporting Bank Swallow populations of this size. Throughout North America, only the glacial deposits and wind-wave action of the Great Lakes region support Bank Swallow colonies of similar or greater magnitude. The climate, landform characteristics, river hydrology, and geomorphic processes of California's Central Valley are unique and are well recognized in providing significant habitat resources for the Bank Swallow within California (Garrison et al. 1987, Humphrey and Garrison 1987, Laymon et al. 1988, CDFW 1992, BANS TAC 2013). The significance of the Sacramento River watershed as a significant habitat resource for the species is not well recognized, however, at the continental scale (Garrison 1999, DeSante pers. comm. Sept. 17, 2015, Panjabi pers. comm. Sept. 16, 2015). A comprehensive review of the published literature, technical reports, and citizen science databases is summarized in Table 1.2.

Table 1.1. Colonies, burrow counts, from empirical studies of Sacramento River.

	Sacramento River				Feather River				Region	
Year	Colony Count	Burrow Count	Mean Burrow Count	Max Burrow Count	Colony Count	Burrow Count	Mean Burrow Count	Max Burrow Count	Total Colony Count	Total Burrow Count
1986	69	29399	426	3000	7	3140	449	2000	76	32539
1987	65	24903	383	1630	*	6592	*	*	65+	31495
1988	30	10330	344	2330	NO DATA				30	10330
1989	23	7230	314	1740					23	7230
1990	49	20658	422	1920					49	20658
1991	41	15899	388	2440					41	15899
1992	49	15520	317	3440					49	15520
1993	42	12587	300	1620					42	12587
1994	37	15391	416	2250					37	15391
1995	39	9659	248	700					39	9659
1996	47	11530	245	1150					47	11530
1997	47	10330	220	1400					47	10330
1998	37	9700	262	1260					37	9700
1999	52	16960	326	1540					52	16960
2000	34	18130	533	2770					34	18130
2001	38	19170	504	1800					38	19170
2002	44	16160	367	1720	8	2274	284	925	52	18434
2003	47	17600	374	1640	15	3594	240	1164	62	21194
2004	43	17040	396	1570	NO DATA				43	17040
2005	39	13990	359	1840					39	13990
2007	38	17640	464	3640					38	17640
2008	56	19023	340	1920	18	3787	151	825	74	22810
2009	74	16051	217	2533	20	2807	140	393	94	18858
2010	50	9529	191	1376	14	1832	131	465	64	11361
2011	57	9991	175	1126	24	2516	105	861	81	12507
2012	58	11994	207	838	14	2322	166	506	72	14316
2013	69	11136	161	1212	13	2111	162	442	82	13247
2014	78	12363	159	2162	7	2425	346	503	85	14788
2015	43	9468	220	955	11	2790	254	542	54	12258
2016	48	8906	186	1252	13	1753	135	564	61	10659
2017	52	10846	209	976	15	1097	73	255	67	11943

North American Bank Swallow Assessment

Information on North American Bank Swallow populations is available from several sources. The species' association with habitat features that are limited on the landscape, along with the gregarious behavior of the bird, create methodological challenges for robust estimation of population size and trends. Below I provide a summary of the results of my review of published literature and technical reports, the BBS, and eBird databases. Limitations to each of these bodies of information are described.

Literature Review

A comprehensive literature review of the nesting ecology, location, and colony size of Bank Swallows in North America resulted in the identification of peer reviewed journal articles (n=65), a technical report (n=1), a doctoral dissertation (n=1), and master's theses (n=2) as summarized in Table 1.2. Publications primarily focused on behavioral or ecological research other than documenting the number and size of colonies. However, information on these aspects of the species were available in many articles. The articles span a date range of 1884 through 2019. The geographic range of these articles included all provinces in Canada, and locales within the Great Lakes region and north-eastern U.S. Notably, information is lacking on the species from Alaska and western states. Within these regions, the species is rare and carries heightened conservation status (e.g. State threatened in California, State sensitive in Oregon). The species is listed a species of special concern in Kentucky.

Collectively these publications give insight on the narrow set of nesting substrates used by the species and provide insight on the relatively low abundance of the species across the

Canadian Provinces. They show that Bank Swallows nest along lakeshores (n=9), rivers (n=23), cliffs (n=3), and manmade features (n=3) including road cuts, sand or gravel mines, and even sawdust piles at a mill. Of note, the Great Lakes region of the continent supports the largest collection of birds with upwards of 200,000 burrows in the glacial deposits along Lake Ontario and Lake Erie. This is contrasted with the fact that Erskine (1979) documented population estimates within Canadian provinces, and found that the maritime provinces, prairie provinces, and British Columbia each hosted a province-wide estimate of less than 10,000 pairs, with human activities impacting the species. Colonies of more than 1,000 burrows are uncommon, with most colonies having less than 100 burrows. In summary, large colonies and metapopulations beyond those on the shores Great Lakes are not well documented. In areas that have received surveys intended to estimate populations, hundreds of small colonies (mean <100) are documented in the literature indicating low abundance, for example British Columbia had 145 colonies and a mean colony size of 60 burrows (Erskine 1979).

Table 1.2. Summary of literature reviewed for information on the nesting ecology, location, and colony size of Bank Swallows in North America.

Author	Year	Article Title	Journal Title	Issue(Volume): Page	Nesting Substrate	Number of Colonies	Notes	Location	Estimate of Burrows
Cooke, W.W. and O.Widman	1884	Bird Migration in the Mississippi Valley.	American Field	21(1):9	*no data*	*no data*	*no data*	*St. Lo* uis, MO	*no data*
Toppan, G.L.	1887	List of birds found breeding within corporate limits of Mt. Carmel, Illinois.	Ridgway Ornithological Club Bulletin	2:26-35	Road Cut	4	no burrow count given; just noting their occurrence	Mt Carmel, IL	*no data*
Barnes, R.M.	1890	List of birds breeding in Marshall County, Illinois	Ornithologist and Oologist	15(8): 113-116	*no data*	3	Several large colonies in the county	Marshall County, IL	300
Strong, R.M.	1898	Bank swallow habits	Wilson Bulletin	10(4):50	Lake Shore	1		Lake Michigan	*no data*
Widmann, O	1907	A preliminary catalog of the birds of Missouri.	Academy of Science of St. Louis Transactions.	17(1) 288 p	River	*no data*	Missouri and Mississippi Rivers; discusses "small and large" colonies	MO	*no data*
Ford, E.R.	1915	Recollections of city bird-nesting	Oologist	32(10):156-157	Gravel Pits; Rivers	*no data*	describes dynamic nature of banks	Chicago, IL	*no data*
Musselman, T.E.	1921	The birds of Illinois	Journal of the Illinois State Historical Society	14: 75p	*no data*	*no data*	flocks of hundreds	IL	*no data*
Schantz, M.O.	1923	The charm of ravines	Audubon Bulletin	Fall 1923:47-48	Road Cut	1	loess river bank	IL	*no data*
Potter, L.B.	1924	Badger digs for Bank Swallows	Condor	26:191	River	1	depredation account	Frenchman River, SK	6
Stoner, D.	1925	Observations and Banding Notes on the Bank Swallow, Plate VIII	Auk	42(1): 86-94	Sand Pits	5	50, 75, 3, 20, 6	Miller's Bay, West Okoboji Lake, IA	154
Stoner, D.	1926	Observations and Banding Notes on the Bank Swallow, Plate II	Auk	43:198-213	Sand Pits	5	50, 75, 3, 20, 6	Miller's Bay, West Okoboji Lake, IA	154
Stoner, D.	1928	Observations and banding notes on the Bank Swallow, Plate III	Auk	45:41-45	Sand Pits	5	50, 75, 3, 20, 6	Miller's Bay, West Okoboji Lake, IA	154
Stoner, D.	1928	Observations and banding notes on the Bank Swallow, Plate IV	Auk	45:310-320	Sand Pits			Miller's Bay, West Okoboji Lake, IA	154
Stoner, D.	1936	Studies on the Bank Swallows Riparia riparia riparia (Linnaeus) in the Oneida Lake Region	Roosevelt Wildlife Bulletin	4:122-233	Sand pits; Creeks	12	13 colonies and 1729 burrows total; other small sites but not many swallows present	Onieda Lake, Ontario	1729
Stoner, D.	1937	Ten years return from banded Bank Swallows	N.Y. State Museum Circ	18:1-21	Lake Shore	3	conducted banding at 3 locations	Okoboji Lake, IA	*no data*
Stoner, D.	1937	The house rat as an enemy of the Bank Swallow	Journal of Mammalogy	18:87-89	Lake Shore	1	documented depredation by cat	Oneida Lake, ON	*no data*
Beyer, L.K.	1938	The Nest Life of the Bank Swallow	Wilson Bulletin	50(2):122-137	Sand Pits	3	small colonies; 10s; anecdotally reported hundreds in years past	Milton, PA	105
Fawks, E.	1938	Bird-Lore's second breeding bird census. Second-growth hardwood.	Bird Lore	40(5):359	Cliff	1	Largest colony found; 1939	Rock Island, IL	6000
Stoner, D.	1938	Longevity in Bank Swallow	Bird Banding	9:173-177	Lake Shore	3	conducted banding at 3 locations	Okoboji Lake, IA	250
Stoner, D. and L. Stoner	1941	Feeding of nestling Bank Swallows	Auk	58:52-55	Road Cut	1	21 burrows	Albany, NY	21
Stoner, D.	1941	Homing instinct in the Bank Swallow	Bird Banding	12:104-108	Lake Shore	3	conducted banding at 3 locations	Okoboji Lake, IA	250
Beecher, W.J.	1942	Nesting birds and the vegetation substrate.	Chicago Ornithological Society, Chicago.	vii; 69pp	Gravel Pits	1		IL	20
Bent, A.C.	1942	(Riparia Riparia Riparia) Bank Swallow	Life Histories of North American Flycatchers, Larks, Swallows, and Their Allies.	400-424	River	*1*	21 nests Brunswick Maine	Brunswick, ME	20
Bent, A.C.	1942	(Riparia Riparia Riparia) Bank Swallow	Life Histories of North American Flycatchers, Larks, Swallows, and Their Allies.	400-424	Lakeshore	*1*	90 nests at Oneida Lake, NY	NY	89
Bent, A.C.	1942	(Riparia Riparia Riparia) Bank Swallow	Life Histories of North American Flycatchers, Larks, Swallows, and Their Allies.	400-424	River	*1*	23 nests Androscogin River, ME	ME	22
Bent, A.C.	1942	(Riparia Riparia Riparia) Bank Swallow	Life Histories of North American Flycatchers, Larks, Swallows, and Their Allies.	400-424	Sawdust piles	*1*	Ostego Lake, MI; Franconia, NH	NH	20
Bent, A.C.	1942	(Riparia Riparia Riparia) Bank Swallow	Life Histories of North American Flycatchers, Larks, Swallows, and Their Allies.	400-424	Gravel Pits	*1*	201 in St Clair County, IL	IL	200
Bent, A.C.	1942	(Riparia Riparia Riparia) Bank Swallow	Life Histories of North American Flycatchers, Larks, Swallows, and Their Allies.	400-424	*no data*	*1*	discusses flights in migration of 10,000 in 1929	*no data*	*no data*
Bent, A.C.	1942	(Riparia Riparia Riparia) Bank Swallow	Life Histories of North American Flycatchers, Larks, Swallows, and Their Allies.	400-424	*no data*	*no data*	1932 Little Cedar Point marsh- 250,000 individuals.	Lake Erie, OH	*no data*
Morris, W.A.	1942	A trap for Bank Swallows.	Bird Banding	13:83-84	Gravel Pits	1	na	Ontario	95
Cooke, M.T.	1950	Returns from banded birds.	Bird Banding	21(1):11-18	*no data*	*no data*	Record of dead banded bird from Peru	*no data*	*no data*
Bergstrom, E.A.	1951	The South Windsor Bank Swallow Colony	Bird Banding	22:54-63	River	1	Connecticut River; 6 years of surveys; colony supported 285 through 910 burrows	CT	910
Petersen, A.J.	1955	The breeding cycle of the Bank Swallow	Wilson Bulletin	67:235-286	River	8	several hundred	Madison, WI	300
Sargent, T.D.	1962	A study of homing in the Bank Swallow (Riparia riparia)	The Auk	79(2):234-246	*no data*	8	418 birds used in experiment… no discussion of colony size	Madison, WI	250
Mayhew, W.W.	1963	Homing of Bank Swallows and Cliff Swallows	Bird Banding	34:179-190	Sand Pits	1	banded and removed from colony	Clearwater County, MN	13
Fawks, E.	1966	Field notes- Sept. 1966	Audubon Bulletin	139:22-23	Cliff	1	same colony as 1938…	Rock Island, IL	250
MacBriar Jr., W.N.	1970	Eight-year-old Bank Swallow (Riparia riparia)	Bird Banding	41:130	*no data*	*no data*	banded 6781 birds over 13 year period	WI	*no data*
Ginevan, M.E.	1971	Chipmunk predation on bank swallows	Wilson Bulletin	83:102	River	1	>5 burrows	Sunderland, MA	5
Graber, R.R., J.W. Graber, & E.L. Kirk	1972	Illinois Birds: Hirundinidae	Illinois Natural History Survey	80:9-13	River	N/A	Statwide breeding population < 3000 birds	Statewide, IL	1500
Greenlaw, J.S.	1972	The use of sawdust piles by nesting Bank Swallows	Wilson Bulletin	84:494-496	Sawdust piles	2	50-100 burrows	Aroostook County, ME	150
Morlan, R.E.	1972	Predation at a Northern Yukon Bank Swallow Colony	Canadian Field Naturalist	86:376	River	3	a hundred or more; large colony described as 140 holes	Old Crow River, YK	250

Table 1.2. Cont'd.

Author	Year	Article Title	Journal Title	Issue(Volume): Page	Nesting Substrate	Number of Colonies	Notes	Location	Estimate of Burrows
Emlen, S.T. and N.J. Demong	1975	Adaptive significance of synchronized breeding in the Bank Swallow	Science	188(4192):1029-31	*no data*	15	401 nests total over 15 colonies; cover 12-20 square miles during foraging	Tompkins County, NY	400
Windsor, D. and S.T. Emlen	1975	Predator-prey interactions of adult and prefledgling Bank Swallows and American Kestrels	Condor	77:359-361	Gravel Pits	16	501 burrows total	Ithica, NY	500
Hoogland, J.L. and P.W. Sherman	1976	The Advantages and Disadvantages of Bank Swallow (Riparia riparia) coloniality	Ecological Monographs	46:33-58	Gravel Pits	54	1-50 active nests in 60% of colonies; maximum colony size 451 active nests	Ann Arbor, MI	2881
MacBriar Jr., W.N. and D.F. Stevenson	1976	Dispersal and survival in the Bank Swallow (Riparia riparia riparia) in Southeastern Wisconsin	Contributions in Biology and Geology	No. 10; 14pgs	Gravel Pits	28	banded 6781 birds over 13 year period	WI	*no data*
Freer, V.M.	1977	Colony Structure and Function in the Bank Swallow Riparia riparia.	PHD Dissertation at State University of New York	312 pp	Gravel Pits	7	401 birds banded annually… 2816 birds total banded over 11 years	Ulster County, NY	*no data*
Plummer, M.V.	1977	Predation by Black Rat Snakes in Bank Swallow Colonies	South Western Naturalist	22:147-148	River	4	other colonies described as larger…	Douglas County, KS	1600
Beecher, M.D, and I.M. Beecher	1979	Sociobiology of Bank Swallows: reproductive strategy of the male	Science	205(4412): 1282-1285	Rivers; Gravel Pits	12	Discusses colonies containing "hundreds to thousands" of individuals	Statewide MI, MA	120
Blem, C.R.	1979	Predation of black rat snakes on a Bank Swallow colony	Wilson Bulletin	91(1):135-137	River	1	James River; 1 of 3 sites in the state; 3 years sampled; 435, 388, 71 burrows respectively for 1975-1978	Chesterfield County, VA	435
Erskine, A.J.	1979	Man's Influence on potential nesting sites and populations of swallows in Canada.	Canadian Field Naturalist	93:371-377	All types	147	Maritime Provinces; colony number based on mean number of burrows per colony; mean colony size 57	Maritime Provinces	8207
Erskine, A.J.	1979	Man's Influence on potential nesting sites and populations of swallows in Canada.	Canadian Field Naturalist	93:371-377	All types	261	Quebec and Ontario; nest surveys through 1974; mean colony size 39	Quebec and Ontario	9934
Erskine, A.J.	1979	Man's Influence on potential nesting sites and populations of swallows in Canada.	Canadian Field Naturalist	93:371-377	All types	102	Prairie Provinces; mean colony size 6	Prairie Provinces	509
Erskine, A.J.	1979	Man's Influence on potential nesting sites and populations of swallows in Canada.	Canadian Field Naturalist	93:371-377	All types	145	British Columbia; mean colony size 60	British Columbia	8568
Freer, V.M.	1979	Factors affecting site tenacity in New York Bank Swallows	Bird Banding	50:349-357	Gravel Pits	7	401 birds banded annually… 2816 birds total banded over 11 years	Ulster County, NY	400
Hickman, G.R.	1979	Nesting ecology of Bank Swallows in interior Alaska.	Masters Thesis. University of Alaska, Fairbanks,	78 pp.	River and Lakes	11	7-204 active burows across 11 colonies	Fairbanks, AK	580
Marsh, R.L.	1979	Development of endothermy in neslting bank swallows (Riparia riparia).	Physiological Zoology	52: 340-353	Sand pits	2	78 burrows over 2 colonies	Ann Arbor, MI	78
Petersen, P.C. and A.J. Mueller	1979	Longevity and Colony Loyalty in Bank Swallows	Bird Banding	50(1):69-70	Road Cut; Gravel Pit	7	4208 birds banded over 15 years; 7	Scott County, IA	500
Beecher, M.D., I.M. Beecher, and S. Hahn	1981	Parent-offspring recognition in bank swallows (Riparia riparia): I. Natural History	Animal Behaviour	29(1):86-94	Rivers; Gravel Pits	5	Colonies studied ranged from 12 to over 1000 active nests; typically 100 active nests	MA, MI, WA	1312
Beecher, M.D., I.M. Beecher, and S. Hahn	1981	Parent-offspring recognition in bank swallows (Riparia riparia): II. Development and acoustic basis	Animal Behaviour	29(1):95-101	Rivers; Gravel Pits	5	Studied 93 nests over these 5 colonies over 2 years	MA, MI, WA	93
Wickler, S.J. and R.L. Marsh	1981	Effects of nestling age and burrow depth on CO2 and O2 concentrations in the burrows of bank swallows (Riparia riparia)	Physiological Zoology	54(1):132-136	Sand pits	*no data*	37 samples measured; no discussion of colony size	IL	*no data*
Ellis, J.H.	1982	The thermal nest environment and parental behavior of a burrowing bird, the bank swallow	Condor	84:441-443	River	1	5 burrows monitored in colony	Missoula, MT	*no data*
Marsh, R.L. and S.J. Wickler	1982	The role of muscle development in the transition to endothermy in nestling bank swallows, Riparia riparia	Journal of Comparative Physiology	149:99-105	Sand pits	2	78 burrows over 2 colonies	Ann Arbor, MI	78
Beecher, I.M. and M.D. Beecher	1983	Sibling Recognition in Bank Swallows (Riparia riparia)	Z. Tierpsychology	62(2)145-150	*no data*	*no data*	No details provided	*no data*	*no data*
Hjertaas, D.G.	1984	Colony site selection in bank swallows	Thesis; Dept of Biology; University of Saskatchewan	138 pp.	Rivers; Gravel Pits	60	48 of 60 were on manmade sites; colonies were between 1 and 48 burrows; 764 nests total throughout the study area	Qu'Appelle River, Saskatchewan	764
Hjertaas, D.G., P. Hjertaas, and W.J. Maher	1988	Colony size and reproductive biology of the Bank Swallow, Riparia riparia, in Saskatachewan	Canadian Field Naturalist	102:465-470	Rivers; Gravel Pits	40	290 burrows in 1980 over 40 colonies; 322 burrows over 39 colonies in 1981	Qu'Appelle River, Saskatchewan	322
MacBriar Jr., W.N.	1988	Weights of Bank Swallows (Riparia riparia) from Southeastern Wisconsin	North American Bird Bander	10:1-14	Gravel Pits	*no data*	banded 6781 birds over 13 year period	Waulkesha County, WI	261
Stutchbury, B.J.	1988	Evidence that Bank Swallow Colonies Do Not Function as Information Centers	The Condor	98:953-955	Sand and Gravel Pits	3	1987; total burrows 111	Dickson County, IA	110
John, R.D.	1991	Observations of Soil Requirements for nesting Bank Swallows, Riparia riparia	Canadian Field Naturalist	105:251-254	Gravel Pits	3	not much detail; good discussion of sediment and morphology of banks	Ottawa, Ontario	30
Shelden, F.H. and D.W. Winkler	1993	Intergeneric phylogenetic relatshionships of swallows estimated by DNA-DNA hybridization.	Auk	110:798-824	*no data*	*no data*	*no data*	*no data*	*no data*

Table 1.2. Cont'd.

Author	Year	Article Title	Journal Title	Issue(Volume): Page	Nesting Substrate	Number of Colonies	Notes	Location	Estimate of Burrows
Ghent, A.W.	2001	Regular spatial patterns of Bank Swallow (Riparia riparia) tunnel entrances, with some possible evolutionary implications	The American Midland Naturalist	146(2): 414-423	Sand pits	6	Colonies over 12 years including: 14, 24, 27, 27, 44, 99	Sundridge, Ontario	99
Ghent, A.W.	2001	Importance of a low talus in location of Bank Swallow (Riparia riparia) colonies.	American Midland Naturalist	146(2): 447-449	Sand pits	2	54 burrows; 7 burrows	Sundridge, Ontario	53
Silver, M. and C.R. Griffin	2009	Nesting habitat characteristics of Bank Swallows and Belted Kingfishers on the Connecticut River	Northeastern Naturalist	16(4)519-534	Rivers; Gravel Pits	12	91.6 km of river distance; censused; 5 colonies at 1-49, 1 colony with 50-99 paris, and 3 colonies with 100-149, and 2 colonies with 200-250 pairs	CT_River	1049
Cadman, M. and Z. Lebrun-Southcott	2013	Bank Swallow colonies along the Saugeen River, 2009-2013	Ontario Birds	31(3): 137-147	River	7	Saugeen River; 7 colonies; 2500 maximum annual count	Toronto, Ontario	2500
COSEWIC	2013	COSEWIC assessment and status report on the Bank Swallow Riparia riparia in Canada.	Committee on the Status of Endangered Wildlife in Canada. Ottawa.	Ix + 48 pp.	Lake Shore	*no data*	also 97,750; occupancy ~60%; 2010, 2012	Lake Erie	121, 450
COSEWIC	2013	COSEWIC assessment and status report on the Bank Swallow Riparia riparia in Canada.	Committee on the Status of Endangered Wildlife in Canada. Ottawa.	Ix + 48 pp.	Lake Shore	*no data*	2011	Lake Ontario	20500
COSEWIC	2013	COSEWIC assessment and status report on the Bank Swallow Riparia riparia in Canada.	Committee on the Status of Endangered Wildlife in Canada. Ottawa.	Ix + 48 pp.	Gravel Pits	27	Aggregate pits; no natural nest sites	Wellington, Ontario	5467
Falconer, C.M., G.W. Mitchell, P.D. Taylor, and D.C. Tozer.	2016	Prevalence of Disjunct Roosting in Nesting Bank Swallows (*Riparia riparia*)	The Wilson Journal of Ornithology	128(2):429-434	Lake Shore	2	Colonies had ~300 each; paper discusses 50,000 pairs of bank swallows nesting along the north shore of Lake Erie.	Port Burwell, Ontario	50,000
Saldanha, S.	2016	Foraging and Roosting Habitat Use of Nesgting Bank Swallows In Sackville, NB	Master's Thesis; Dalhousie University	99 pp.	River	2	2 colonies; 76, 54 burrows each	Trantramar River, New Brunswick	130
Implay, T.L., K.A. Hobson, A. Roberto-Charron, M.L. Leonard	2018	Wintering areas, migratory connectivity and habitat fidelity of three declining Nearctic-Neotropical migrant swallows	Animal Migration	5:1-16	River	1	No information provided; 110 birds banded	Trantramar River, New Brunswick	*no data*
Kelly, J.F., and S.M. Pletschet	2018	Accuracy of swallow roost locations assinged using weather surveillance radar	Remote Sensing in Ecology and Conservation	4(2):166-172	*no data*	*no data*	No information on colonies	*no data*	*no data*

Population Data Synthesis

Breeding Bird Survey

A summary of the regional trends and raw detections for Bank Swallow within the BBS database by state, province, and regions are summarized in Table 1.3. These trends are organized by climate/vegetation potential types and states and provinces for long-term (1966-2015) and short-term (2005-2015) within North America (Sauer et al. 2017). These data include sample sizes (number of BBS routes), trend estimates and confidence intervals for each geographic region. Table 1.4 provides a summary of the raw survey data for years 2013-2017 for each state and province in North America.

Two important conservation plans have used BBS data to assess the status of Bank Swallows. These analyses are often referenced in considering organisms for provincial, state, or federal listing as threatened or endangered species.

Rosenberg (2016) uses BBS data to conduct a vulnerability assessment of land birds and sets 10-year conservation priorities for Joint Ventures and Bird Conservation Regions. The document reports a 95% decline in population size of the Bank Swallow. The current Bank Swallow population is estimated to be 7,700,000 individuals throughout North America. The document provides a species assessment to prioritize species conservation based on population size, breeding and non-breeding distribution, threats to breeding, threats to non-breeding, and population trends. The Bank Swallow was identified as a common species in steep decline. The species is described as a “habitat generalist” (Rosenberg et al. 2016), despite its strong ties to very specific and limited distribution of specific landscape features as described above.

The State of North America’s Birds report (NABCI 2016), using the same data ranks the conservation priority of landbird species on population size and a suite of threats, distribution, and habitat characteristics. Within this assessment, the Bank Swallow received a score of 11 on a scale of 1-20, warranting a species of “moderate” conservation concern (Panjabi et al. 2012).

Table 1.3. Breeding Bird Survey region trends for Bank Swallow based on surveys conducted 1966-2015 (Sauer et al. 2017).

Region	N	1966-2015 Trend Estimates	1966-2015 Credible Interval for Trend Estimate	2005-2015 Trend Estimates	2005-2015 Credible Interval for Trend Estimate
Northwestern Interior Forest	47	-5.93	(-9.15, -2.60)	-6.25	(-11.58, -1.75)
Northern Pacific Rainforest	13	-0.47	(-9.07, 8.59)	1.44	(-12.41, 19.99)
Boreal Taiga Plains	50	-4.24	(-7.37, -0.99)	-2.58	(-10.01, 7.46)
Boreal Softwood Shield	25	-6.46	(-11.44, -0.89)	-3.7	(-13.96, 20.48)
Great Basin	129	1.42	(-1.18, 3.82)	0.19	(-19.12, 9.54)
Northern Rockies	130	-4.44	(-7.32, -2.28)	-1.15	(-5.24, 3.59)
Prairie Potholes	225	-2.52	(-3.74, -1.24)	-0.54	(-3.33, 3.98)
Boreal Hardwood Transition	174	-11.27	(-13.30, -9.29)	-8.69	(-13.50, -4.41)
Lower Great Lakes/ St. Lawrence Plain	154	-7.27	(-8.86, -5.84)	-6.1	(-8.55, -3.28)
Atlantic Northern Forest	213	-9.43	(-11.74, -6.24)	-7.05	(-11.12, 0.81)
Southern Rockies/colorado Plateau	39	0.8	(-7.32, 7.09)	5.09	(-9.20, 21.50)
Badlands and Prairies	69	-0.78	(-3.84, 2.62)	2.8	(-5.55, 14.85)
Shortgrass Prairie	17	-4.5	(-11.61, 2.99)	-10	(-35.26, 7.64)
Central Mixed Grass Prairie	44	0.1	(-3.39, 4.26)	0.78	(-12.37, 17.92)
Oaks and Prairies	9	1.23	(-14.99, 21.65)	8.32	(-49.18, 125.11)
Eastern Tallgrass Prairie	160	-0.49	(-2.42, 1.60)	0.14	(-5.53, 5.46)
Prairie Hardwood Transition	120	-3.86	(-6.29, -1.98)	-1.3	(-4.51, 2.09)
Central Hardwoods	26	3.82	(-1.08, 9.07)	9.08	(-5.51, 27.01)
Appalachian Mountains	112	-5.49	(-7.89, -3.07)	-4.4	(-12.37, 3.41)
Piedmont	20	-5.84	(-13.40, 1.78)	3.81	(-20.44, 42.86)
New England/mid-atlantic Coast	73	-4.4	(-7.02, -1.61)	-2.83	(-9.79, 5.00)
Coastal California	11	-6.3	(-11.59, -1.04)	-6.34	(-14.85, 3.52)
Tamaulipan Brushlands	9	1.94	(-7.11, 12.45)	19.73	(-17.22, 100.72)
Alberta	86	-5.05	(-9.06, -2.16)	-1.97	(-7.84, 6.57)
British Columbia	47	-5.31	(-7.71, -2.90)	-4.81	(-9.73, 0.70)
California	23	-4.84	(-7.90, -1.55)	-3.92	(-10.29, 5.30)
Colorado	32	1.65	(-4.95, 7.45)	2.86	(-11.13, 16.92)
Connecticut	14	-0.95	(-4.81, 2.90)	-1.11	(-7.95, 4.92)
Delaware	8	-0.34	(-5.50, 5.48)	0.02	(-8.05, 15.89)
Iowa	33	-1.95	(-5.29, 0.82)	-1.51	(-11.05, 6.29)
Idaho	35	3.39	(-0.15, 6.77)	6.34	(-0.03, 16.49)
Illinois	56	-2.81	(-5.78, 0.73)	-0.41	(-9.49, 11.49)
Indiana	41	-0.64	(-4.54, 3.09)	-0.95	(-12.47, 5.96)
Kansas	34	-4.75	(-7.61, -1.81)	-4.32	(-11.62, 3.55)
Kentucky	6	-2.06	(-9.43, 6.09)	-2.24	(-26.09, 25.42)
Manitoba	47	-4.35	(-8.08, -1.54)	-2.51	(-8.06, 2.37)
Massachusetts	23	-5.77	(-9.05, -2.35)	-5.59	(-15.33, 1.92)
Maryland	26	-6.22	(-9.90, -2.67)	-2.47	(-12.41, 16.05)
Maine	48	-10.93	(-13.23, -8.57)	-10.83	(-15.36, -5.67)
Michigan	78	-0.8	(-2.94, 1.17)	-0.31	(-5.27, 3.09)
Minnesota	69	-4.99	(-7.59, -2.42)	-1.52	(-6.65, 4.76)
Missouri	21	5.12	(0.22, 10.83)	7.26	(-1.60, 22.22)
Montana	45	0.68	(-2.44, 4.17)	4.12	(-6.12, 18.99)
New Brunswick	30	-9.35	(-11.69, -6.49)	-8.09	(-16.58, 6.04)
North Dakota	49	-3.73	(-5.48, -1.94)	-3.43	(-6.24, -0.13)
Nebraska	33	-1.2	(-6.52, 2.97)	-1.13	(-18.23, 7.50)
Nevada	8	4.75	(-12.82, 21.03)	-24.77	(-62.90, 20.72)
New Hampshire	23	-9.69	(-12.17, -6.85)	-9.02	(-14.54, -0.80)
New Jersey	14	-11.23	(-18.10, -4.12)	-10.01	(-29.49, 17.93)

Table 1.3. Cont'd.

Region	N	1966-2015 Trend Estimates	1966-2015 Credible Interval for Trend Estimate	2005-2015 Trend Estimates	2005-2015 Credible Interval for Trend Estimate
Nova Scotia	30	-8.97	(-11.32, -6.70)	-8.66	(-14.11, -1.87)
New York	108	-7.69	(-9.38, -5.91)	-6.53	(-12.23, -0.45)
Ohio	45	-2.89	(-6.16, 0.45)	-2.31	(-12.61, 4.03)
Oklahoma	13	2.49	(-7.30, 11.75)	-2.62	(-33.51, 34.45)
Ontario	111	-7.51	(-10.26, -5.62)	-5.68	(-8.52, -2.27)
Oregon	38	0.37	(-3.06, 3.75)	1.07	(-4.00, 6.79)
Pennsylvania	58	-2.79	(-6.09, 0.52)	-2.86	(-12.92, 6.08)
Prince Edward Island	4	-6.21	(-11.82, -0.32)	-5.92	(-13.37, 5.94)
Quebec	100	-9.57	(-12.23, -5.75)	-5.84	(-13.06, 11.06)
Saskatchewan	57	-1.48	(-4.69, 1.51)	-0.01	(-5.36, 10.47)
South Dakota	37	1.92	(-1.92, 6.46)	7.12	(-3.69, 22.25)
Tennessee	4	0.4	(-11.31, 13.53)	-2.3	(-39.27, 18.30)
Texas	18	1.89	(-6.70, 12.05)	19.28	(-15.57, 94.15)
Utah	22	-2.15	(-9.34, 5.85)	7.94	(-9.13, 37.65)
Virginia	10	-5.77	(-14.06, 2.31)	-4.44	(-31.30, 31.03)
Vermont	24	-6.14	(-9.16, -3.18)	-5.96	(-11.91, -1.02)
Washington	47	2.11	(-0.63, 4.84)	2.46	(-2.58, 7.03)
Wisconsin	82	-3.83	(-5.09, -2.60)	-3.89	(-6.68, -1.42)
West Virginia	15	-5.93	(-15.83, 5.69)	-5.95	(-39.58, 48.95)
Wyoming	70	1.53	(-4.64, 5.05)	3.24	(-2.37, 9.92)
Eastern BBS Region	1059	-7.48	(-8.91, -5.64)	-3.47	(-6.47, 3.07)
Central BBS Region	441	-1.85	(-3.16, 0.35)	1.11	(-2.99, 12.47)
Western BBS Region	322	-1.36	(-4.03, 0.69)	0.1	(-17.28, 7.78)
Canada	512	-7.56	(-9.04, -5.65)	-3.49	(-6.78, 3.45)
United States	1310	-2.18	(-3.75, -0.52)	0.48	(-12.91, 8.33)
Survey-wide	1822	-5.33	(-6.65, -3.80)	-0.77	(-11.36, 5.83)

eBird Citizen Science Database

Table 1.4 summarizes raw eBird data, and for comparison includes raw BBS data by state and province for the years 2013-2017. During the selected 5-year period, eBird detections sum to a total of 2,062,756 individual detections encountered during 144,230 field visits by observers across the continent. Annual total detections ranged from 251,263 to 487,380. On average, observers detect approximately one to two Bank Swallows during outings where the species is encountered.

As described above, the BBS are point transect surveys, with each transect surveyed once annually within a constrained date range. Over the same selected 5-year period, a total of 14,473 detections were made across 2,440 sampling points. Annual total detections ranged from 2,394 to 3,413. That results in an average detection rate of approximately six Bank Swallows per sampling point.

The effort and number of documented Bank Swallow occurrences is multiple orders of magnitude greater within the eBird dataset. Problematically, however, eBird records are not standardized, and may include multiple visits to the same location within a season, and potentially within a given day, by observers. The BBS is more rigorous with coordinated survey timing, locations, and sampling protocols. At the continental scale, there is little agreement between raw annual detections of Bank Swallows in the BBS and eBird datasets over the selected 5-year period (R-square=-0.522, p = 0.367, n=5; Figure 1.2, Table 1.4). Similarly, BBS and eBird surveys had little agreement within California from 2013-2017, where an average of 4,782 detections were made through eBird but BBS failed to capture any detections (Table 1.4).

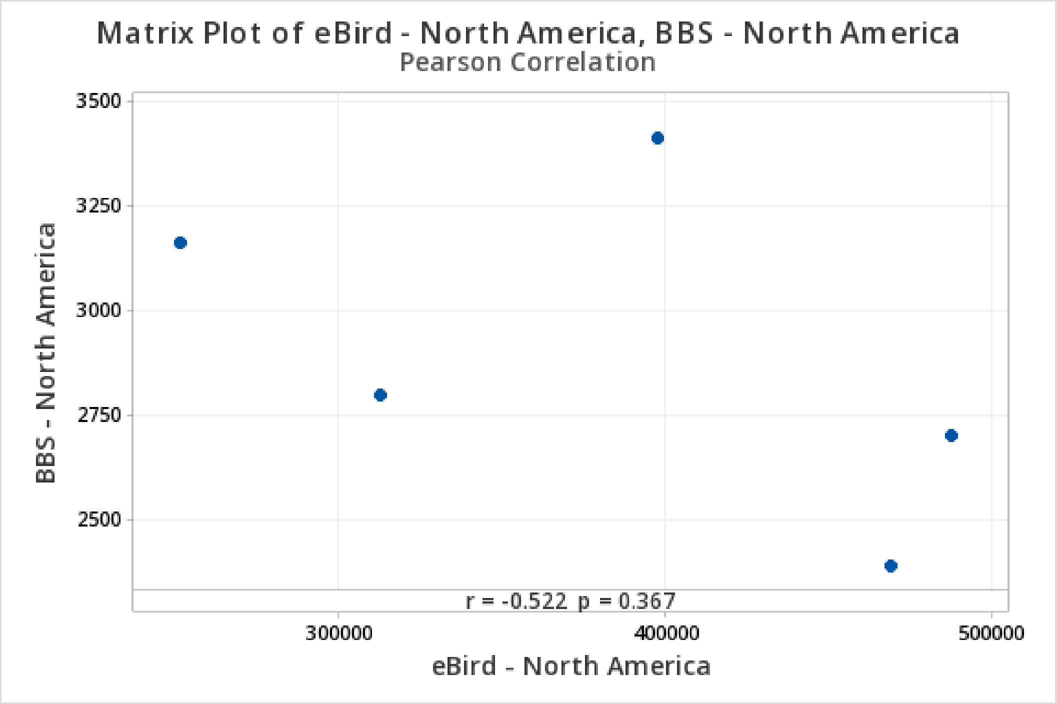

Figure 1.2. Pearson's correlation of annual detections of Breeding Bird Survey (BBS) versus eBird for North America (2013-2017).

Table 1.4. Summary of raw Bank Swallow observations from eBird and Breeding Bird Survey databases for by region for 2013-2017.

	EBIRD								BREEDING BIRD SURVEY (BBS)							
STATE/PROVINCE	2013	2014	2015	2016	2017	N	TOTAL	ANNUAL AVERAGE	2013	2014	2015	2016	2017	N	TOTAL	ANNUAL AVERAGE
Alaska	3807	7312	5319	6064	12610	3106	35112	7022	0	0	0	0	0	0	0	0
Alberta	11549	20988	13852	21679	17738	2975	85806	17161	0	0	0	0	0	0	0	0
British Columbia	3438	2779	5900	7971	5191	2210	25279	5056	0	0	0	0	0	0	0	0
California	3111	4326	5590	4826	6059	3016	23912	4782	0	0	0	0	0	0	0	0
Colorado	7733	5969	7487	12689	12418	4464	46296	9259	0	0	0	0	0	0	0	0
Connecticut	1189	1522	2971	1796	2162	1895	9640	1928	0	0	0	0	0	0	0	0
Delaware	633	992	3670	52759	1936	1009	59990	11998	12	3	37	8	12	12	72	14
District of Columbia	36	22	39	56	240	166	393	79	0	0	0	0	0	0	0	0
Idaho	7372	6326	9681	9405	11562	2740	44346	8869	82	342	560	348	137	121	1469	294
Illinois	6644	6082	8396	14007	9760	5583	44889	8978	160	67	91	114	15	57	447	89
Indiana	3674	5603	5801	10406	10413	2536	35897	7179	14	6	6	1	3	20	30	6
Iowa	846	1532	1848	2601	3086	1113	9913	1983	221	8	20	7	3	26	259	52
Kansas	865	4324	14322	7909	10840	1635	38260	7652	7	11	8	8	3	17	37	7
Kentucky	614	482	644	2282	1714	484	5736	1147	1	4	0	3	0	5	8	2
Maine	1444	1475	2239	1652	2459	1498	9269	1854	515	484	381	404	257	159	2041	408
Manitoba	2364	941	2360	12192	11630	889	29487	5897	0	0	0	0	0	0	0	0
Maryland	2448	2642	5136	6684	4443	2562	21353	4271	13	3	5	5	12	26	38	8
Massachusetts	5047	4920	5356	7231	7454	5297	30008	6002	2	6	0	20	3	20	31	6
Michigan	12616	11793	24862	16811	21366	9205	87448	17490	34	62	82	90	56	120	324	65
Minnesota	2357	2794	3294	4990	7336	2585	20771	4154	171	134	218	157	78	218	758	152
Missouri	3259	5303	4793	11152	9385	1638	33892	6778	7	5	45	2	3	15	62	12
Montana	4742	7330	7008	10392	10558	2964	40030	8006	57	103	212	96	79	136	547	109
Nebraska	1162	1675	1529	1094	2366	899	7826	1565	87	79	97	130	53	29	446	89
Nevada	1366	956	920	1359	1670	928	6271	1254	22	39	17	42	26	43	146	29
New Brunswick	765	1344	644	1457	1754	472	5964	1193	0	0	0	0	0	0	0	0
New Hampshire	1285	2204	1663	1763	1655	1265	8570	1714	11	7	8	5	10	16	41	8
New Jersey	1305	2958	2303	2409	2669	3466	11644	2329	0	0	1	6	0	2	7	1
New Mexico	1350	1767	2187	2225	2835	1456	10364	2073	0	0	0	0	0	0	0	0
New York	25443	27309	19709	29031	24697	11534	126189	25238	60	38	9	57	25	42	189	38
Newfoundland and Lab	113	123	198	590	1665	192	2689	538	0	0	0	0	0	0	0	0
North Dakota	2346	3515	18421	4806	9913	1699	39001	7800	543	309	364	284	271	267	1771	354
Northwest Territories	410	2178	790	683	57	267	4118	824	0	0	0	0	0	0	0	0
Nova Scotia	1372	1864	5106	4508	5850	1106	18700	3740	0	0	0	0	0		0	0
Ohio	12608	21879	23520	16261	20328	6852	94596	18919	66	108	66	111	78	77	429	86
Oklahoma	262	557	233	229	445	368	1726	345	198	157	582	108	231	214	1276	255
Ontario	42541	49348	55123	72798	68988	15137	288798	57760	0	0	0	0	0		0	0
Oregon	12206	7723	5572	4883	17807	2798	48191	9638	39	50	20	25	74	39	208	42
Pennsylvania	2477	3600	2650	6530	4601	3125	19858	3972	47	7	6	12	4	20	76	15
Prince Edward Island	738	1230	1195	3122	1233	351	7518	1504	0	0	0	0	0	0	0	0
Quebec	9725	17828	21590	26283	29335	7302	104761	20952	0	0	0	0	0	0	0	0
Rhode Island	721	786	1076	884	1126	727	4593	919	146	216	71	107	136	90	676	135
Saskatchewan	2963	1710	1935	2064	3779	778	12451	2490	0	0	0	0	0		0	0
South Dakota	1976	887	2702	3061	6162	748	14788	2958	22	28	63	78	40	61	231	46
Tennessee	122	2506	3485	930	555	461	7598	1520	0	2	0	0	0	1	2	0
Texas	5021	3145	6004	3826	4943	4402	22939	4588	16	0	4	0	0	6	20	4
Utah	9690	17009	32645	21976	14281	3276	95601	19120	21	0	25	25	365	23	436	87
Vermont	1562	1089	1834	1770	1234	1211	7489	1498	17	14	16	27	0	14	74	15
Virginia	420	528	1168	2802	842	803	5760	1152	0	0	1	0	0	1	1	0
Washington	13930	19579	16627	22569	24433	5251	97138	19428	427	307	204	148	221	231	1307	261
West Virginia	97	199	47	135	97	172	575	115	0	0	0	0	0		0	0
Wisconsin	7533	9214	23104	15276	21036	6144	76163	15233	88	99	118	133	106	183	544	109
Wyoming	1249	1184	856	2374	2689	877	8352	1670	58	100	76	143	93	129	470	94
Yukon Territory	2717	1610	2346	4128	9767	593	20568	4114	0	0	0	0	0	0	0	0
	251263	312961	397750	487380	469172	144230	2062756	383705	3164	2798	3413	2704	2394	2440	14473	2895

Summary

Bank Swallows are unique among Neotropical migrant insectivore species given their specific breeding habitat requirements which are geographically limited on the North American landscape. Despite an extensive breeding range, this localized distribution and colonial nesting behavior result in a poor understanding of their population status. While acknowledging the likely bias in population estimates, datasets such as the BBS have indicated significant continent-scale declines consistent with other insectivore species (Nebel et al. 2010; Smith et al. 2015).

There are limitations on the BBS survey as a tool for assessing gregarious colony nesting species, and those with habitat whose distribution is limited. Point count surveys require estimation of multiple detection probability parameters in order to assess abundance from count data, including availability and detectability (Farnsworth et al. 2003). For gregarious birds which occur in groups, an estimate of cluster size is also required (Bibby et al. 2000, Buckland et al. 2001, Buckland 2006, Geissler and Sauer 1990). Fundamentally, birds that nest colonially, and have limited distributions on the landscape are not well surveyed by point count methods (Bibby et al. 2000). The BBS is challenged in providing robust information on Bank Swallow due to the fact that the encounter rates for the species are low, and estimating the group size of foraging Bank Swallows is difficult given flight behavior and their uneven and constrained distribution over the landscape. These are two critical issues which lead to bias in population estimation in point sampling techniques (Bibby et al. 2000).

Further, the natural history characteristics of some species violate basic assumptions of point count methods. For example, swallows tend to forage over large areas, and may be detected at two or more survey points. This violates the assumption of sampling independence between point count locations. Further, cluster size is highly variable in species such as the Bank Swallow, where colonies can range from five burrows to more than 2,000 burrows in California. Therefore, estimating population size is best accomplished by conducting census surveys rather than sampling. These are typically employed at colony sites (Bibby et al. 2000). Birds that are rare and scarcely distributed on the landscape (i.e. restricted ranges) are also more effectively counted using census techniques.

Bibby et al. (2000) notes that bird colonies and aggregations are best surveyed and studied through focused census or sampling at colony sites. A more defensible assessment framework would be based on estimating the distribution and abundance of colonies, including a parameter that assesses the number of individuals at each colony.

Given that point transect surveys are not well suited to survey colonial nesting birds, estimates of continental populations should be interpreted with caution. Based on the population estimate of 7,700,000 in Rosenberg et al. (2016), it would be reasonable to expect that each North American state or province within the Bank Swallow range would support upwards of 110,000 pairs of Bank Swallows. Incorporating an occupancy rate of 0.61 to extrapolate to colony and burrow counts expected, this number increases to more than 180,000 burrows (Wright et al. 2011). This would be analogous to nine times the number of colonies and burrows supported by the Sacramento River. The empirical accounts of the species over the past 100 years do not support this population estimate.

Population and trend estimation techniques are being explored using eBird data, but to date have been challenged by the non-standard nature of eBird data (Horns et al. 2018, Walker and Taylor 2017). The models of population size and spatial distribution which are parameterized by BBS data are based on low encounter rates which rarely exceed the number of birds observed at a typical colony. These methods do not allow for robust estimation of cluster size, and the localized distribution of suitable habitat makes extrapolation using BBS data susceptible to significant bias. Further, Table 1.4 demonstrates a lack of detections of Bank Swallows throughout important regions of the continent, leaving population indices and trend analyses vulnerable to spatial bias.

In summary, the best available information for the species' population status relies on methods that are not well suited for the Bank Swallow. The resulting modeled population estimates and distribution maps are not well supported by empirical observations as documented by eBird and other more local survey efforts. The Sacramento Valley and the Great Lakes regions of North America provide habitat for the largest known breeding populations, however, the available data for other regions of the continent do not support a population estimate of 7,700,000. Continent-wide coordinated surveys which target nesting sites may provide a method for more robust understanding of the species status. These methods could be implemented through a platform such as eBird. Conservation concern for the Bank Swallow on the continental scale should be elevated given the observed significant declines as indicated by the BBS. On a local scale where large metapopulations exist, careful management of habitats is needed. The Sacramento River and its tributaries support a large metapopulation of Bank Swallows. Only Lake Ontario and Lake Huron are documented to supported larger numbers of the species. River management and restoration efforts ought to consider impacts to habitats through flood control and other activities on floodplains, and restoration potential for the existing populations.

The following chapter (Chapter 2) provides an analysis of soil suitability within the Sacramento Valley, based on soil characteristics at existing Bank Swallow nesting colonies. Maps of suitable soils are then used to assess geologic, geomorphic, and anthropogenic constraints on the availability of these habitat resources to Bank Swallows.

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Chapter 2. Bank Swallow Habitat Associations (soil suitability, surficial geology, and river meander migration):

Abstract

The floodplains of the Sacramento River support the largest documented population of Bank Swallows (*Riparia riparia*) west of the Great Lakes region. Bank Swallows depend upon fluvial geomorphic processes to create and maintain their nesting substrate of steep vertical banks and friable soil. These processes also drive the complexity and overall biodiversity of riparian ecosystems. Bank Swallows have declined significantly within the watershed. Conservation efforts call for improved understanding of the distribution and condition of habitat resources, and identification of recovery measures. Here I present a novel analysis that links soil-suitability mapping to a physics-based model of river meander (IRIC JP). I correlated colony locations with key soil characteristics derived from the SSURGO database (USDA-NRCS 2018). I also evaluated the incremental effects of flow impairment and flood control infrastructure on the interactions of river meander and suitable soils. Both soil suitability and river meander extent have extremely limited overlap on the landscape over 20-year modeling scenarios and vary significantly by river reach due to local geology, river planform, levees, and bank stabilization. Dam operation has reduced historical suitable soil-river meander interactions by 24%, and flood control infrastructure has further limited these interactions by 24%, for overall habitat reductions of 48%. These findings provide a fundamental understanding of habitat suitability and river process which can be used to prioritize locations where process-based restoration of the Sacramento River and Feather River corridors should occur in order to ensure species persistence and recovery.

Introduction

The breeding habitat of the Bank Swallow (*Riparia riparia*), a Neotropical migrant, is locally distributed in discrete patches across its broad continental summer range (Chapter 1). The largest metapopulations of the species occurring in North America rely upon erosion processes acting on large-scale glacial or river basin deposits (Chapter 1, BANS TAC 2013, COSEWIC 2013). Bank Swallows require soil that is cohesive enough to support the construction of burrows, but friable such that the birds are able to excavate burrows. Within California, the more than 85% of the Bank Swallow population nests along a combined 380 river miles of the Sacramento River and Feather River. Of the documented breeding sites in North America, this is the second most important habitat resource given the number of Bank Swallows nesting annually (Chapter 1). The lake shore bluffs of the Great Lakes region supports the largest metapopulations of Bank Swallows (COSEWIC 2013).

Two aspects of the Sacramento Valley make the landscape a critical resource for Bank Swallows – the extensive presence of well sorted and erodible alluvial sediment deposits, and a continual source of steep cut bank formation from river channel meander migration. The surface geology and soil deposits within the valley are heterogeneous, however, with consolidated formations that do not support Bank Swallow nesting without disturbance by physical processes. Channel evolution and meander migration occur as a function of streamflow, sediment and bed characteristics, and floodplain surficial geology (Larsen et al. 2006). Streamflow, sediment supply, and bank erodibility have been altered by large dams and the placement of bank stabilization (Singer and Dunne 2001).

Bank Swallow conservation efforts have recognized the need to better understand the extent and distribution of soils suitable for nesting, and where these soils will interact with erosion and river meander migration. The Bank Swallow Recovery Plan (CDFW 1992: page 15) as part of: "Management and Acquisition Actions", directs the CDFW, CDWR, and the Army Corps of Engineers to "Inventory suitable nesting habitat to determine the most suitable locations for development of a preserve system that will ensure viable populations in perpetuity." Stillwater (2007: page viii) identifies the following research needs to better understand and enhance populations of Bank Swallows that nest on the Sacramento River: "a GIS analysis to identify potential for meander migration in soils that are suitable for bank swallow nesting, and use the analysis to prioritize conservation or bank armor removal projects." Similarly, the Bank Swallow (*Riparia riparia*) Conservation Strategy for the Sacramento River Watershed, California (BANSTAC 2013: page 34) includes the following research need: "Correlate soil mapping with expected bank erosion to prioritize locations for potential Bank Swallow colonies. A quantitative and spatially explicit analysis that combines expected patterns of river channel migration and soil types is needed. This information will help guide the acquisition of floodplain parcels and easements. It will also help identify areas where benefits to Bank Swallows may be maximized when riprap is removed or allowed to degrade."

Considerations of spatial scale are important dimensions of avian habitat association models (Knopf and Samson 1994, Saab 1999). Moore et al. (2005) have developed a hierarchal conceptual model for stopover site selection by migratory birds that includes consideration of large geographic, regional, local, and habitat scales which provides a useful framework for evaluating Bank Swallow habitat associations.

Bank Swallow Soil Suitability Assessment

The Sacramento River and Feather River provide the most important and extensive nesting habitat resource for Bank Swallows within California (Chapter 1). A key aspect of the Sacramento Valley is the extent of the alluvial plain, composed of well sorted and relatively fine sediments, which is ideal for the formation of cohesive, yet friable cut banks where Bank Swallow nesting occurs.

In this paper, I develop a series of quantitative and spatially explicit maps of suitable soils by modeling the relationship between soil characteristics using NRCS soils data, and Bank Swallow colony locations mapped during annual population surveys. This analysis provides a quantitative understanding of the location of soils suitable for Bank Swallow nesting habitat.

Geomorphic Process - Meander Migration Modeling

River channel meander migration is a key phenomenon in the creation of Bank Swallow nesting habitat. It is the primary mechanism that renews the surface of steep river (cut) banks, offsetting the effects of slope degradation, vegetation colonization, and infestation by parasites which degrade the quality of burrows and colony sites after approximately two seasons (Garrison and McKernan 1994, Garrison 1999, Szep and Moller 1999, Moffatt et al. 2005). California's Mediterranean climate combined with the geography of the watershed result in increases wet season flows, seasonal river meander, and local erosion which provides a mechanism which refreshes banks at a landscape scale. Bank Swallow habitat is renewed within the Sacramento River watershed on a nearly annual basis, even in relatively dry years that experience only a single bank-full flow (Wright et al. 2011).

In this analysis, I use a physics-based meander migration model (Larsen et al. 2006) to develop a series of quantitative and spatially explicit maps which model the locations and extent of lateral channel migration and combine these results with maps of soils suitable for Bank Swallow nesting. I explore the constraints on river meander migration through multiple scenarios including pre-Shasta Dam hydrology, post-Shasta Dam hydrology, and with and without rock revetment on the river banks. These scenarios allow a quantification of the effects of both river impoundment and bank stabilization on the interaction of river meander migration and Bank Swallow habitat. This analysis serves as a geographically comprehensive reconnaissance of areas where rock revetment removal may lead to potential Bank Swallow nesting habitat.

The main research questions to examine the Bank Swallow's habitat associations are the following: (1) Are there specific soil attributes that correlate with colony presence? (2) Can these attributes be identified to provide a habitat suitability framework? (3) What is the extent and distribution of suitable soils across the Sacramento and Feather river corridors? And, (4) what proportion of suitable soils are subject to erosion through lateral channel migration under historical and existing hydrological conditions?

Methods

Study Area

I conducted modeling of soil suitability within the Sacramento Valley in Northern California. Bank Swallow colony locations were selected from survey data from the lower Sacramento River and lower Feather River. The selected river corridors for this analysis support more than 80% of California's Bank Swallow population during the breeding season (Laymon et al. 1988, BANS TAC 2013). A detailed discussion of the watershed and river system characteristics, and their importance to Bank Swallows within California are provided in Chapter 1.

The Sacramento River flows from north to south within the northern Central Valley across sedimentary, volcanic rocks, basin deposits, and recent alluvium to its terminus with the San Francisco Bay (Larsen et al. 2006, Singer 2008). The river is bounded by the Cascade Mountains and Sierra Nevada to the east, and the California Coast Ranges to the west. The Feather River is the lower Sacramento River's largest tributary, flowing west out of the Sierra Nevada and north to south to the confluence at Sacramento river mile (RM) 80. Both the Sacramento River and Feather River hydrology and meander migration dynamics have been altered by large man-made structures including Shasta and Oroville dams, respectively, and water diversions and associated grade control structures, and flood control infrastructure including levees and bank stabilization. Peak flows are truncated by river impoundment during the winter wet season, and summer base flows during the semi-arid summer and fall have been increased to meet agricultural irrigation demands throughout both the Sacramento and San Joaquin valleys (CALFED 2000). A detailed discussion of the watershed and river system characteristics, and their importance to Bank Swallows within California are provided in Chapter 1.

I conducted modeling of river meander migration on both the Sacramento River and Feather River. For the Sacramento River, I analyzed five separate reaches between RM 274 downstream to RM 80 based on tributary inputs and differences in slope, sediment size, and channel geometry (Table 2.1 and Table 2.2). I modeled three reaches of the lower Feather River between RM 60 and the confluence with the Sacramento River at RM 0, again based on tributary inputs and differences in river channel characteristics (Table 2.1 and Table 2.2). The selected river corridors for this analysis support more than 80% of California's Bank Swallow population during the breeding season (Laymon et al. 1988, BANS TAC 2013).

Bank Swallow Soil Suitability Assessment

Bank Swallow Surveys

Bank Swallow surveys were conducted once annually during the breeding season from 1986-2017 for the Sacramento River, and 1987, 2002-2003, and 2008-2017 for the Feather River (BANS TAC, unpublished data). Surveys were conducted by 2-4 observers from watercraft using an area search method (Appendix A, *Bank Swallow Methods for the Sacramento and Feather Rivers, California, Version 1.0, January 2017*). When colonies were detected, burrow counts were conducted by two observers from the watercraft and averaged to estimate the total number of burrows. Colony locations were mapped by handheld global positioning system (GPS) prior to 2009 or using a mobile GPS unit and laptop in the field after 2009. After 2009, survey data were entered by an analyst directly into a computer geographic information system (GIS). For each colony site, river reach, river mile, colony number, activity status, the number of Bank Swallows observed, burrow counts and colony burrow estimate, elevation above water, and elevation above bank slope break were recorded. A detailed description of the count history and purpose, count methods, and data management is documented in Appendix A, *Bank Swallow Methods for the Sacramento and Feather Rivers, California, Version 1.0, January 2017*.

Soil Mapping

The US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) has complied soil mapping data from the past century for the United States. Mapping efforts included field surveys, soil sampling, and laboratory work (USDA-NRCS 2018). The data include soil classifications based on a comprehensive soil taxonomy, and additional information on soil characteristics, including sand, silt, and clay composition, and other attributes such as organic content. These soil attributes are reported for each of three soil stratigraphic horizons, A, B, and C. The A horizon represents the topmost layer (i.e. topsoil) which directly supports and hosts plant growth. The B horizon represents the underlying subsoil which is typically mineral rich. The C horizon is the deepest strata and is often composed of the foundational sediment or parent material from which the upper strata have evolved. Within the river corridor, these strata are often comprised of alluvial floodplain deposits which occur on an annual basis as a result of the hydrology with the Sacramento Valley, and can vary significantly in composition and physical attributes, varying from each other in grain size and silt, sand, or clay composition. The data format includes both spatial maps in 10-meter grid cell raster format and tabular data. I used the Gridded Soil Survey Geographic (gSSURGO) Database developed by the USDA - NRCS (2018). The gSSURGO data are compiled in the Environmental Systems Research Institute, Inc. (ESRI) file geodatabase format. I used the gSSURGO Database for California, Version 2.2, December 2016, accessed from the USDA-NRCS Geospatial Data Gateway (GDG) website located at https://gdg.sc.egov.usda.gov/.

Model Building and Assessment

I mapped soil suitability using MaxEnt (Version 3.3.3e; Phillips et al. 2006) to explore and map the relationship of Bank Swallow colonies and soil characteristics within the Sacramento Valley. MaxEnt is a machine learning algorithm which models habitat-species envelops, including datasets with small sample sizes and presence-only information (Phillips et al. 2006). MaxEnt analyzes raster data, and scores the probability of presence or habitat suitability within each raster cell between 0 and 1. The maximum entropy approach employed by MaxEnt has been used to resolve species-habitat associations of multiple taxa including birds (Elith et al. 2006, Hernandez et al. 2006, Pearson et al. 2007, Wisz et al. 2008, Benito et al. 2009, Kumar and Stohlgren 2009, Kumar et al. 2006). MaxEnt applies a non-parametric approach, and accounts for non-linearity by accounting for interactions between predictor variables (Phillips et al. 2006).

I defined an analysis extent of the Sacramento Valley which included the floodplains and channel meander belts of the Sacramento River and Feather River, and tributary streams (Figure 2.1). I developed the full extent to be consistent with the Central Valley Joint Venture (CVJV) 2019 Implementation Plan, the study area used by Dybala et al. (2017) study. For Dybala et al. (2017), we developed avian population and habitat objectives for Central Valley riparian ecosystems as part of the CVJV Implementation Plan 2019 Update. The geographic scope of the CVJV planning area includes the floor of the Central Valley based on Jepson ecoregion boundaries for the Central Valley (Hickman 1993). I extended the northern extent of the CVJV study area at its northern extent to include the Sacramento River and its topographically constrained floodplain between Shasta Dam and Redding, CA.

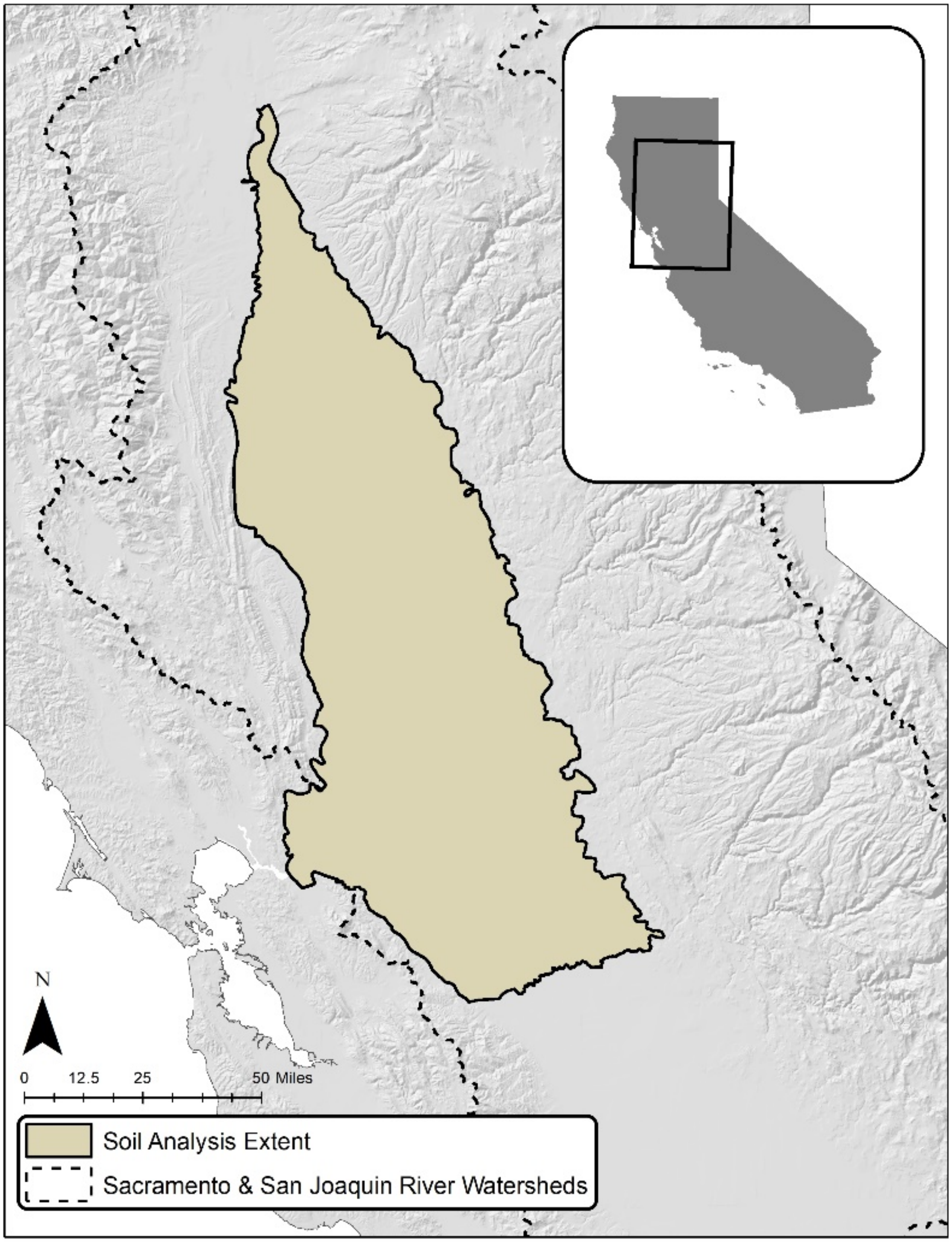

Figure 2.1. Maxent soil suitability analysis extent which includes the Sacramento Valley and upper San Joaquin Valley.

I used Bank Swallow colony locations from surveys conducted in 2008 and 2009 (BANS TAC, unpublished data). Surveys during these calendar years detected 103 discrete locations on the Sacramento River, and 33 locations on the Feather River. I selected these years (i.e. 2008 and 2009) because they correspond with environmental datasets that could be used in derivative analyses such as the vintage of National Agricultural Imagery Program (NAIP) aerial imagery land cover mapping for the Central Valley (VegCAMP 2009). I used 2009 NAIP aerial imagery and heads up digitized channel centerlines for the Sacramento and Feather rivers.

For habitat variables, I developed 1 m raster grid maps derived from soil attributes from the California gSSURGO database (USDA-NRCS 2018). I created nine separate ASCII grids for input into Maxent as covariate data. To develop these grids, I derived three 1 m grids from the gSSURGO raster, one for each of three soil horizons, A, B, and C. I conducted a spatial join based on the spatial identifier to attributed each grid cell within the analysis extent with its corresponding tabular soil component information for percent of sand, clay, and, silt. The resulting grids were projected in ArcGIS (version 10.4.1, ESRI, Redlands, CA) and symbolized based on percent of each soil component (Appendix B, *MaxEnt Input Model Input Development*, Figure B-2 through Figure B-10).

Given a robust sample size of Bank Swallow colony presence locations (n=136), I used the MaxEnt cross validation function to estimate the error of model fit and predictive performance across the replicates (Merow et al. 2013, Elith et al. 2011). I used five replicates (five-fold cross validation), in which case MaxEnt partitions the dataset into five independent data folds, and then uses four folds (n=108) to train the model, and one fold (n=27) as a testing dataset. Soil suitability results include spatially explicit maps which display mean relative occurrence rate values (i.e. between 0-1) for each raster cell. The relative occurrence rate is the probability that a given cell value is included in the occurrence dataset. A separate map is created using the standard deviation of the mean values for the five folds.

I used "Area Under the Receiver Operating Characteristic Curve" (AUC), a threshold-independent measure of model accuracy that ranges from 0 to 1, to assess the predictive ability of the model (Fielding and Bell 1997). AUC estimates the probability that a randomly selected occurrence raster cell is ranked higher than a raster cell from the background which is selected randomly. Accurate models exhibit an AUC value close to 1, and values approaching 0.5 or less indicate models with no better than random discrimination.

I used both the "percent variable contribution" and "jackknife estimation functions" model functions to examine the relative importance of each predictor variable. MaxEnt produces response curves for each predictor variable which allow assessment of suitability across the predictor space for each of the nine variables (Phillips et al. 2006).

MaxEnt allows several approaches to identify a suitability threshold, which is the value above which, a given raster cell was considered suitable as nesting substrate, and below which it was considered unsuitable. For this analysis, I selected the Minimum Training Presence Logistic Threshold, which is based on the lowest suitability in the training dataset. This threshold results in the inclusion of all habitat cells that are at least as suitable as those with the lowest suitability in the training dataset. I also selected a user defined threshold of 0.80 to delineate very suitable habitat.

River Meander Migration Model

I used the Johannesson-Parker River Meander Migration Solver (MeanderJP) within the International River Interface Cooperative (iRIC) Modeling Platform to predict river channel movement over time (Larsen et al. 2017). The MeanderJP Solver implements a numeric model which resolves equations approximating fluid mechanics and sediment transport phenomena which drive river meander migration (Johannesson and Parker 1989, Larsen 1995). This modeling framework has been applied to multiple river systems as detailed in Larsen et al. (2006).

The fundamental premise of the model is that bank erosion at a given location is proportional to the velocity of the streamflow, and dependent on the erodibility of the bank substrate at that point, as defined here:

$$M = E_o u_b$$

where M is the erosion rate (in meters per year), E_o is a dimensionless bank erodibility coefficient of the order 10^{-8}, and $\underline{u_b}$ (meters per second) is a velocity factor equal to the difference between the velocity near the bank and the reach average velocity (Larsen and Greco 2002). Higher u_b values result in greater shear stress on the bank and increased erosion potential in conjunction with the erodibility of the bank substrate E_o. The erodibility coefficient is parameterized from an erosion field which contains spatially variable values which are derived from on observed surficial geology datasets. For more detailed discussion of the model as applied to the Sacramento River, see Larsen and Greco (2002).

The model considers additional parameters in solving for stream flow velocity including slope, sediment size (D50), channel width and depth, channel planform (curvature at a given model node) and bank full flow (cubic meters per second, CMS).

Using the Eroded Area output from MeanderJP, I evaluated the amount of channel migration which overlapped with soils meeting the suitability threshold criteria in the Bank Swallow soil suitability analysis above. I made the assumption that locations where the river channel moved through suitable soil were locations where Bank Swallow nesting substrate (cut banks) could form in order to quantify the cumulative amount of river geomorphic process lost to changes in hydrology and bank stabilization efforts. This metric also allows the identification of locations where lateral channel migration intersects with potentially or highly suitable soils. At these locations more in depth modeling with MeanderJP involving more fine-scale mapping of geology and vegetation effects on erosion, variable hydrology, and could elucidate expected river dynamics at a granular scale.

Model Building and Assessment

I assembled model inputs using ArcGIS and I used the NAD 1983 UTM Zone 10 coordinate system for all data inputs including centerlines and erosion fields. Data input files were derived from existing vector or raster datasets or digitized from aerial imagery or historical maps. For each of three selected scenarios, I modeled a time period of 50 years, from 2009 to

2059. I assumed no change in the conditions for each reach and scenario beyond the changing geometry of the centerline as undertaken by the model. For each river system, modeling was undertaken within river reaches delineated based on the specific reach characteristics including bed slope, D50, and hydrological differences due to tributary inputs. The Sacramento River was segmented into six reaches as summarized by river mile in Table 2.1 and Table 2.2. The Feather River was divided into three reaches as summarized by river mile in Table 2.1 and Table 2.2.

Management Scenarios

I developed three scenarios based on significant management actions that have been taken on the rivers – river impoundment from large dams and bank stabilization through the placement of revetment on river banks. I modeled the following:

> **Pre-dam Hydrology:** a scenario using pre-dam hydrology and no bank stabilization. This scenario was intended to demonstrate the total potential for lateral channel migration based on unimpaired hydrology and the surficial geology only.
>
> **Current Hydrology:** a scenario using current hydrology (i.e. post-dam construction) and no bank stabilization. This scenario was intended to demonstrate the impact of river impoundment on lateral channel migration given only surficial geology constraints.

Current Hydrology + Revetment: a scenario using current hydrology (i.e. post-dam construction) and bank stabilization throughout the study area. This scenario was intended to demonstrate the existing condition including impaired river flows and hardened and stabilized banks which constrain river meander.

Hydrology

MeanderJP uses the 2-year or bank full discharge stream flow in cubic meters per second as a model input (Leopold et al. 1964, Larsen et al. 2017). I used constant flow rates estimated for each river reach in pre- and post-dam scenarios for each reach of river as summarized in Table 2.1 and Table 2.2. (Larsen et al. 2006, Larsen and Greco 2002). Hydrological Inputs for the Sacramento River were adapted from Larsen (2012), Larsen (2007), Micheli et al. (2004), and WET (1988). Inputs for the Feather River were adapted from James et al. (2009), Cain and Monohan (2008), and GEI (2008).

Table 2.1. Model inputs for scenarios using historical (pre-dam) hydrology and corresponding channel characteristics.

River Segment	River Miles (RM)	Q Discharge (m^3s^{-1})	Average Width (m)	Average Depth (m)	Slope (m/m)	Median bed grain size (D50)(mm)
Sacramento River						
Shasta	274-243	3300	335	5.5	0.00045	25
Red Bluff	243-225	3300	335	5.5	0.00045	25
Woodson Bridge	225-210	3300	335	5.5	0.00045	25
Hamilton City	210-190	3300	332	7	0.00033	25
Ord Ferry	190-146	4097	380	9	0.00033	20
Verona	146-80	3500	330	6	0.00033	
Feather River						
Oroville	60-29	1400	180	4.5	0.0006	20
Marysville	29-12	2000	200	5	0.00033	20
Bear	12-1	2000	200	5	0.00033	20

Table 2.2. Model inputs for scenarios using existing (post-dam) hydrology and channel characteristics.

River Segment	River Miles (RM)	Q Discharge (m^3s^{-1})	Average Width (m)	Average Depth (m)	Slope (m/m)	Median bed grain size (D50)(mm)
Sacramento River						
Shasta	274-243	2200	264	4.7	0.00045	25
Red Bluff	243-225	2200	220	5	0.00045	25
Woodson Bridge	225-210	2200	218	5	0.00045	25
Hamilton City	210-190	2181	281	5	0.00033	25
Ord Ferry	190-146	2707	268	6.2	0.00033	20
Verona	146-80	2707	268	6.2	0.00033	20
Feather River						
Oroville	60-29	300	80	2.2	0.0008	20
Marysville	29-12	350	85	2.2	0.00065	20
Bear	12-1	350	85	2.2	0.00065	20

Heterogeneous Erosion Fields

I created simplified erosion fields for both the Sacramento and Feather rivers using ArcGIS. For the Sacramento River, I used “The Surface Geology Along the Sacramento River GIS dataset” (CDWR 2013, CDWR 1995) which combined surface geology mapping by Helley and Harwood (1985) and further refinement by Koll Buer, DWR – Northern District for the River Bank Erosions Investigation. For the Feather River, I used the vector dataset “Feather River Geology Mapping Atlas” and associated SPG2 Task 6 Report and augmented the geographic coverage downstream of the Bear River by rectifying and tracing the original Helley and Hardwood (1985) geologic map within the vector dataset (CDWR 2004). I then used the geologic deposit descriptions to group geologic units into one of three categories: erodible, resistant, and non-erodible. I attributed each of the geologic units with an erosion coefficient (i.e. erodible = 300, resistant = 8888, and non-erodible = 9999) and created ASCII raster grid files for input into MeanderJP. Heterogeneous erosion raster grid files are symbolized by erosion coefficient in Appendix C, *IRIC Inputs: Erosion Fields and Centerlines*.

Revetment and bank condition were assessed and mapped on-site using mobile GIS units. Datasets were reviewed and augmented annually in the field during Bank Swallow survey efforts. I incorporated the location of bank stabilization using the "Areas of Revetment and Riprap Along Major River Reaches in California's Central Valley" (CDWR 2012). Locations of bank revetment are symbolized for the Sacramento and Feather rivers in Appendix C-2, *IRIC Input: Erosion field and centerline – EO with Revetment*.

Channel Centerlines and Geometry

I digitized centerlines from 2009 NAIP aerial imagery in ArcGIS. I selected this vintage of NAIP imagery to be consistent with other important environmental datasets such as the fine-scale land cover mapping for the Central Valley (CDFW 2013). I digitized a separate center line for each of six reaches on the Sacramento River, and three on the Feather River. I then used the Editor toolbox in ArcMap to densify points along centerlines, standardizing distance to 10 meters between nodes to ensure consistent treatment of line geometry when MeanderJP builds its computation grid. I attributed point files with X and Y coordinates for input into MeanderJP. Centerlines for each river reach for the Sacramento and Feather rivers are mapped in Appendix C, *IRIC Inputs: Erosion Fields and Centerlines*. Channel geometry and bed characteristics for the Sacramento River were adapted from Larsen (2012), Larsen (2007), Micheli et al. (2004), and WET (1988). Inputs for the Feather River were adapted from James et al. (2009), Cain and Monohan (2008), and GEI Consultants (2008).

Estimating Erosion Footprint

I used the MeanderJP eroded area output to analyze the location and extent of channel migration along each modeled reach of the Sacramento and Feather rivers. For each year that is modeled, MeanderJP outputs a polygon file created by intersecting the previous year's centerline with the current year's centerline (Larsen et al. 2017). The width of the polygon corresponds with the extent of erosion. To estimate the cumulative extent of erosion I used the merge function in the ArcMap Editor toolbox to combine polygons and create a single polygon. I then used the Extract/Clip function in the ArcMap Analysis toolbox to clip the MaxEnt soil suitability output raster with the 50-year cumulative erosion extent for each modeled reach of the Sacramento and Feather rivers for each of the management scenarios. I then calculated the number of hectares (ha) of each soil classification (i.e. highly suitable, potentially suitable, unsuitable) within the meander extent.

Identifying Bank Restoration Potential on Protected Lands

I used the California Protected Areas Database (CPAD, www.calands.org) June 2020 dataset to evaluate the potential for river process restoration through revetment removal on public lands. The CPAD 2020a dataset is a vector GIS dataset that includes public lands set aside for conservation purposes. I intersected the combined results from the Bank Swallow Soil Suitability and the River Meander Migration Modeling (specifically the areas where revetment was preventing meander migration through suitable and potentially suitable soils) with the polygons of public conservation lands. I then summarized the results of this analysis by management unit name, responsible agency, access type, county, and area of suitable soils (i.e. potential magnitude of restoration).

Results

Bank Swallow Soil Suitability Assessment

The MaxEnt five-fold cross-validation analysis resulted in a model with strong predictive ability. The average test AUC value was 0.937 (SE = 0.007). The diagnostics for each of the five-folds are summarized in Appendix D, *MaxEnt 5-fold Cross Validation Model Fit and Accuracy Diagnostics*. The relative contributions of each predictor variable are summarized in Table 2.3, with the multi-predictor MaxEnt model most informed by percent clay in the B horizon (30.2%, SE = 0.98), percent sand in the A horizon (28.8%, SE = 1.52), and percent sand in the C horizon (10.5%, SE = 0.85). The MaxEnt model was least informed by percent silt in the B horizon (3.1%, SE = 0.44) and C horizon (2.2%, SE = 0.35).

Table 2.3. Relative contribution of each predictor variable to the MaxEnt model.

Covariate	Percent Contribution	Permutation Importance
Percent Clay B	30.2	29.8
Percent Sand A	28.8	2.6
Percent Sand C	10.5	15.2
Percent Silt A	9.6	7.7
Percent Clay A	6.6	6.8
Percent Clay C	4.9	11.4
Percent Sand B	4.2	13.3
Percent Silt B	3.1	8.5
Percent Silt C	2.2	4.7

The response curves for each of the predictor variables are complex, non-linear, and non-monotonic (*Appendix D-3, Maxent Variable Response Curves*). They demonstrate that there are complex relationships between the percent of a soil component and its suitability, likely including issues of covariance.

Figure 2.2 shows the results of the jackknife test of variable importance using model training gain. Appendix D-4, *MaxEnt Tabular Diagnostic Outputs*, provides a comprehensive summary of the diagnostic values for each of these model runs including the mean and standard error across the folds. The predictor with highest training gain when used in a univariate model is percent sand in the A horizon, with a mean training gain of 0.88 (SE=0.04). Therefore, percent sand in the A horizon appears to provide the most information regarding suitability of a grid cell by itself. The predictor that decreases the gain the most when it is omitted from a model is percent sand in the C horizon, with a mean training gain of 1.97 (SE=0.02) when left out. Percent sand in the C horizon appears to have the most information when compared to the other predictors. Mean values over the five replicate runs are reported.

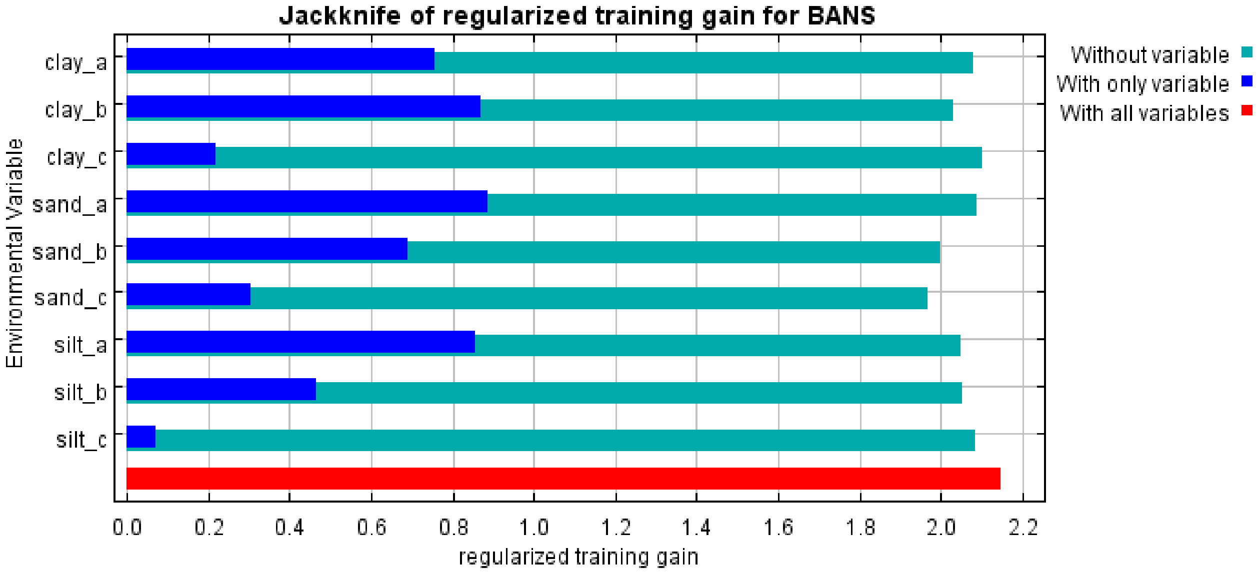

Figure 2.2. Bar chart of the jackknife test of variable importance on training gain with and without predictor variables.

Figure 2.3 shows the results of the jackknife test of variable importance derived from the cross-validation test gain. Appendix D-4, *MaxEnt Tabular Diagnostic Outputs*, provides a comprehensive summary of the diagnostic values for each of these model runs including the mean and standard error across the folds. The predictor with highest test gain when used in a univariate model is percent silt in the A horizon, with a mean test gain of 1.34 (SE=0.15). Therefore, percent silt in the A horizon appears to provide the most information regarding suitability of a grid cell by itself. The predictor that decreases the test gain the most when it is omitted from a model is percent sand in the C horizon, with a mean test gain of 1.93 (SE=0.11) when left out. Percent sand in the C horizon appears to have the most information when compared to the other predictors. Mean values over the five replicate runs are reported.

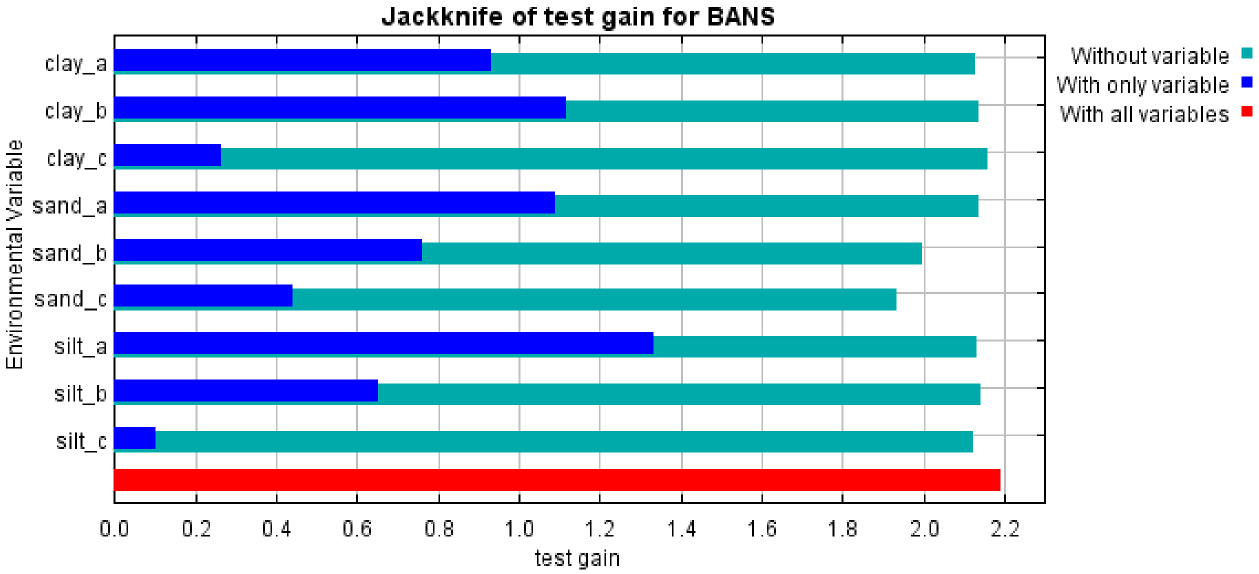

Figure 2.3. Bar chart of the jackknife test of variable importance on test gain with and without predictor variables.

The MaxEnt model produced spatially explicit maps of soil suitability based on the relative occurrence rate of Bank Swallow colonies as pictured in Figure 2.4. Suitability estimates across grid (raster) cells ranged between 0 to 0.912 with standard deviations ranging from 0 to 0.30 (Figure 2.5).

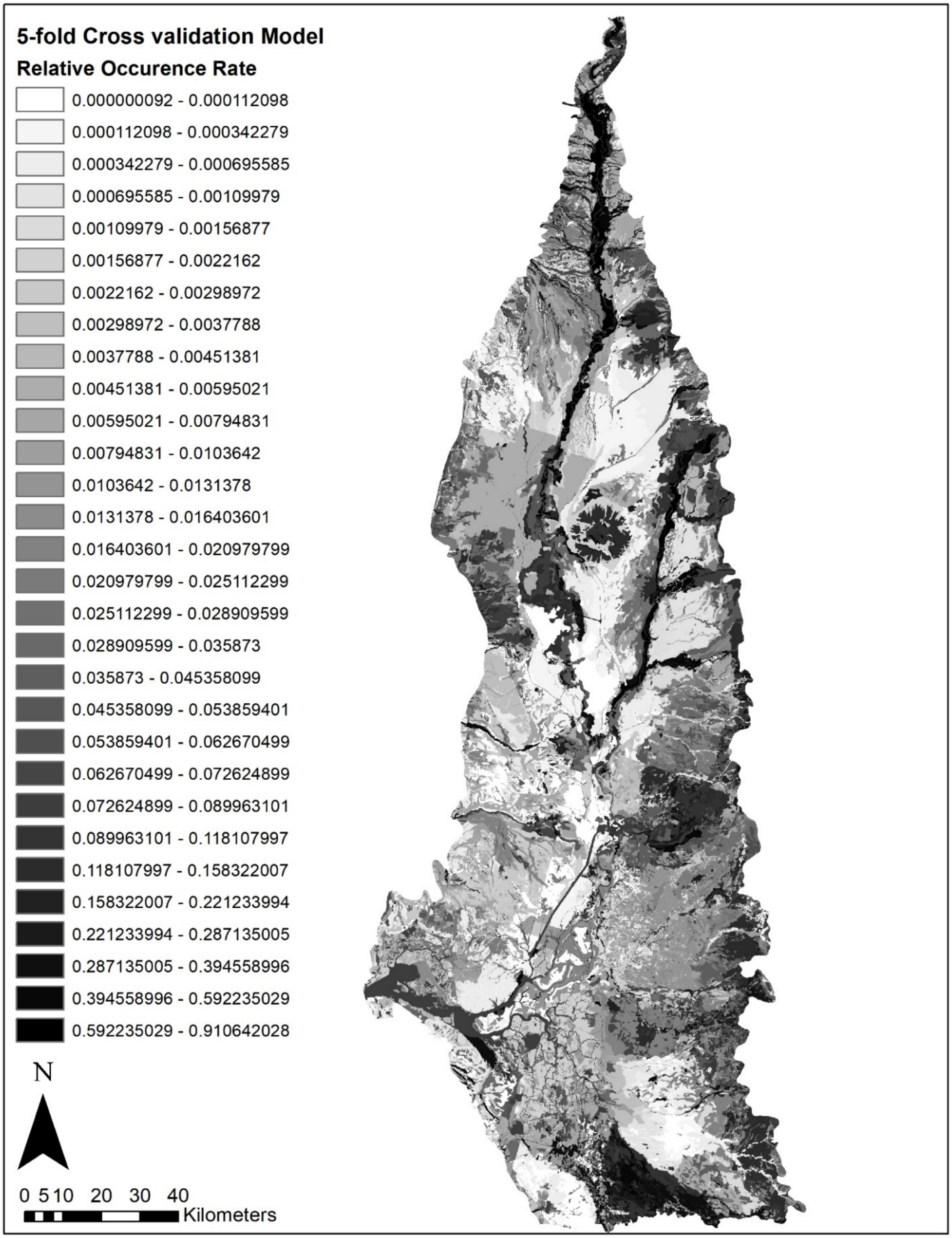

Figure 2.4. Suitability of soils throughout the analysis extent-based percent sand, silt, and clay in the A, B, and C horizons and the occurrence of Bank Swallow colonies.

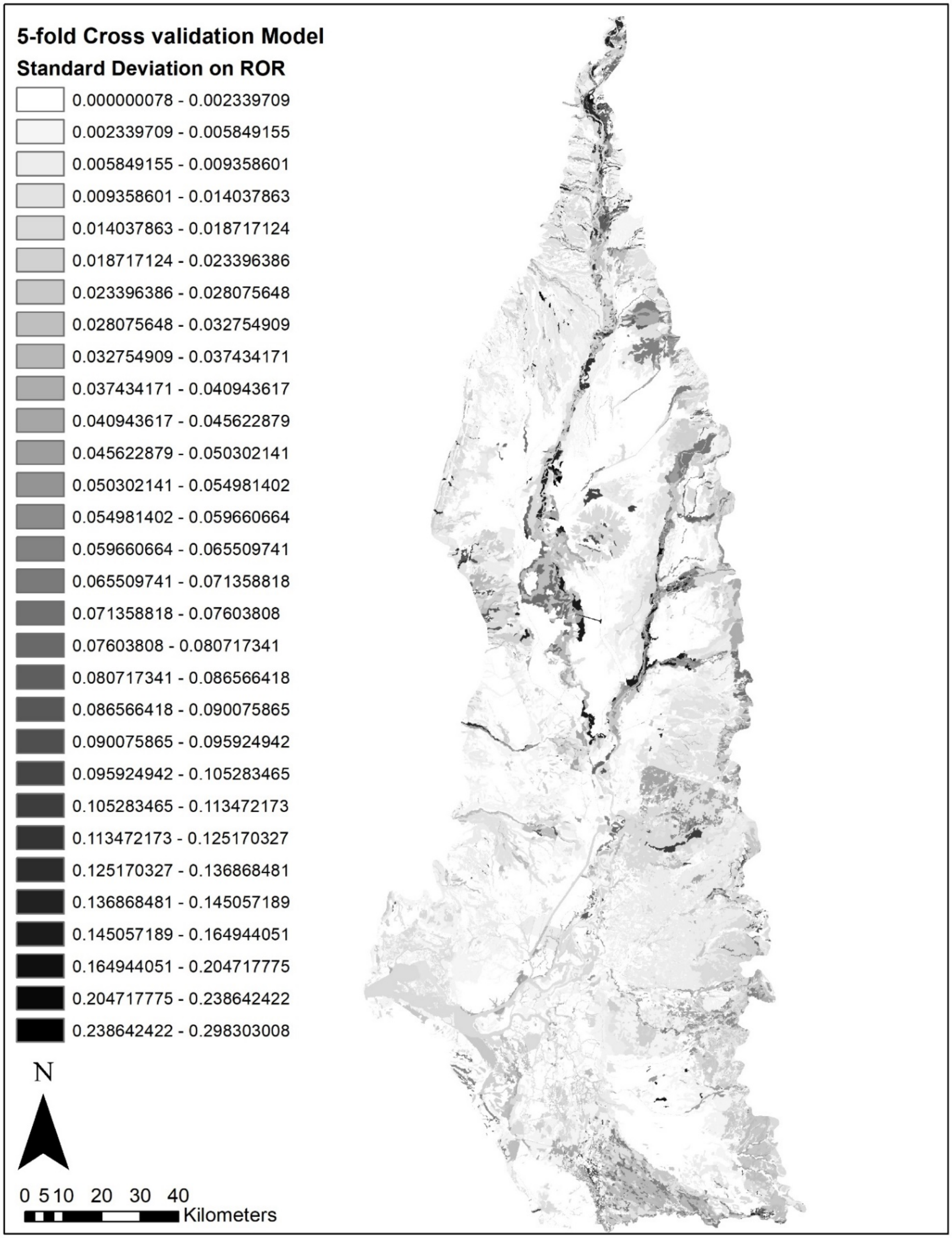

Figure 2.5. Standard deviation of the mean relative occurrence rate derived from 5=fold cross.

I developed a habitat threshold suitability map using the MaxEnt Minimum Training presence Logistic Threshold (>0.026), and an additional "user defined" threshold of 0.8 intended to delineate highly suitable raster cells. Figure 2.6 depicts three categories of raster cells: (1) unsuitable raster cells which include values below the Minimum Training Presence Logistic Threshold (<0.026), (2) potentially suitable raster cells which include values above Minimum Training Presence Logistic Threshold (>0.026) but below the user defined threshold (<0.80), and (3) highly suitable raster cells based on values above the user defined threshold (>0.80).

Potentially suitable soils (between <0.026 but <0.80 suitability) were limited within the analysis extent to the floodplain deposits associated with the geologic footprints multiple creeks and rivers including the American, Feather, and Sacramento rivers (Figure 2.6). This included Putah Creek, Cache Creek, and the broad floodplains of the lower San Joaquin River. Highly suitable soils were primarily limited to the historic meander belts of the Sacramento and Feather rivers. Soils with high suitability were also found within the floodplain deposits of tributaries of the upper Sacramento River including Stony Creek, Burch Creek, Sour Grass Creek, Jewett Creek, Singer Creek, Thomes Creek, McClure Creek, Dye Creek, Oat Creek, Coyote Creek, Redbank Creek, Reeds Creek, Dibble Creek, Blue Tent Creek, and Paynes Creek (Figure 2.6). Soils with high suitability are present along Yankee Slough and Bear Creek within the Feather River watershed (Figure 2.6).

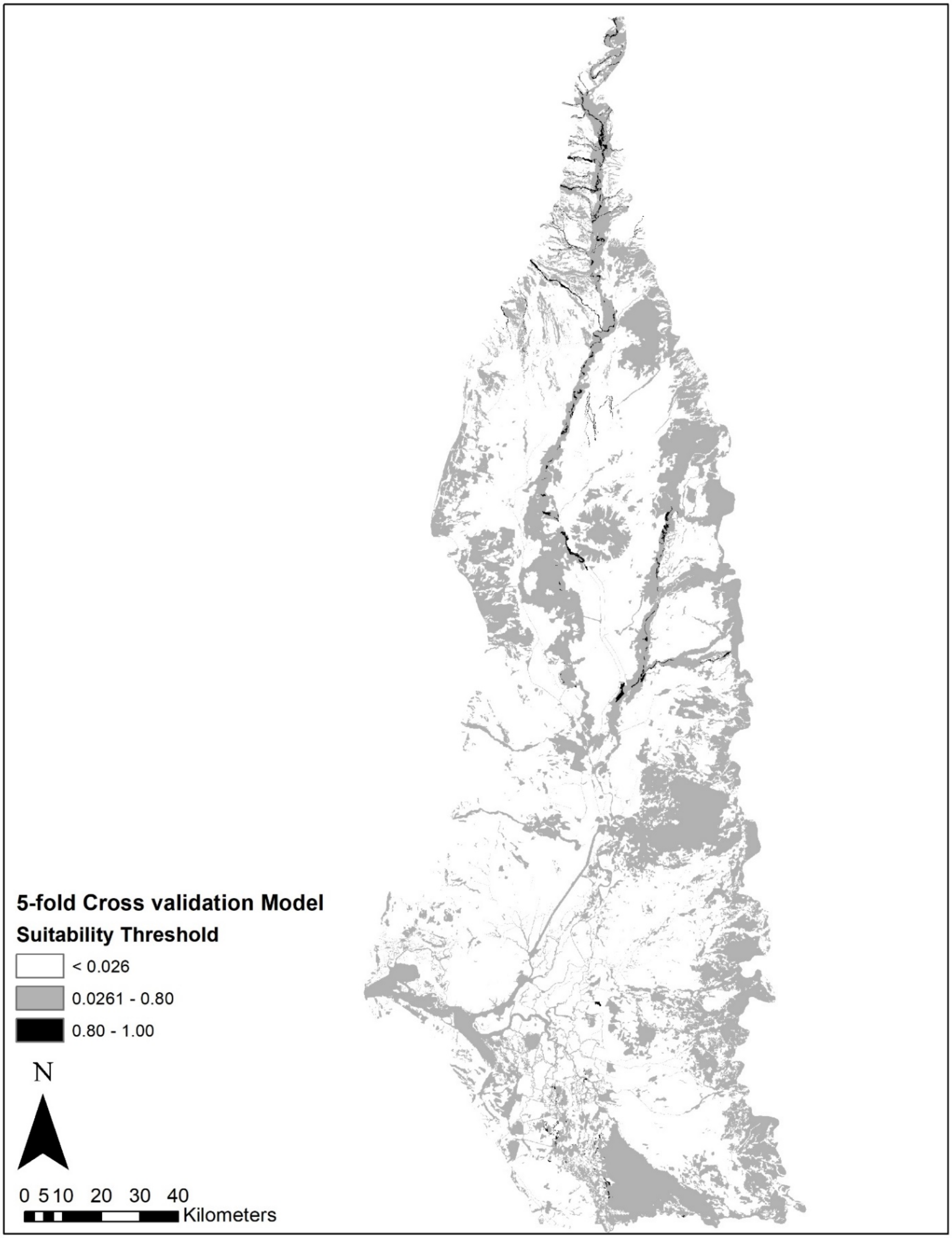

Figure 2.6. Map of suitability classifications including unsuitable, potentially suitable, and highly suitable grid cells based on the MaxEnt model Minimum Training Presence Threshold and a user.

Meander Migration Model

The 50-year meander extent for the Sacramento River, Feather River, and Sacramento and Feather rivers combined for each of the three management scenarios are summarized in Table 2.4 through Table 2.6 and Figure 2.7 through Figure 2.9 respectively. Spatial representations of these model outputs are summarized with a series of maps in Appendix E. IRIC & MaxEnt Results. Figure E-1 through E-3.

The 50-year total meander extent predicted for the Sacramento River is as follows: Pre-Dam Hydrology scenario is 3023.5 ha, Current Hydrology is 2499.7 ha, and Current Hydrology + Revetment is 1653.3 ha. Based on the model inputs and assumptions, the Sacramento River meander extent is reduced by 17% due to hydrological flow impairments, and a combined 45% of reduction due to the combined effects of both river impoundment and bank stabilization. Considering existing hydrology, 846.4 ha (34%) of landscape are unavailable to river meander due to the presence of bank stabilization (Table 2.4, Figure 2.7). The cumulative impacts of hydrological flow impairment and bank stabilization have reduced river meander through highly suitable soils by 113 ha (39%). Similarly, cumulative impacts of hydrological flow impairment and bank stabilization have reduced river meander through potentially suitable soils by 1172.3 ha (44%).

Table 2.4. Land area (ha) of Highly Suitable, Potentially Suitable, and Unsuitable soils, and area (ha) of soils unavailable to the river meander due to rock revetment. These estimates were derived from intersecting the Bank Swallow Soil Suitability raster with the MeanderJP 50-year meander extent under three management scenarios for the Sacramento River.

Sacramento River	Pre-Dam Hydrology	Current Hydrology	Current Hydrology + Revetment	Unavailable Due to Revetment
Highly Suitable (ha)	287.1	209.4	174.3	35.1
Potentially Suitable Soils (ha)	2616.3	2198.9	1454.0	744.9
Unsuitable Soils (ha)	120.2	91.4	25.1	66.4
Total Meander Potential (ha)	3023.5	2499.7	1653.3	846.4

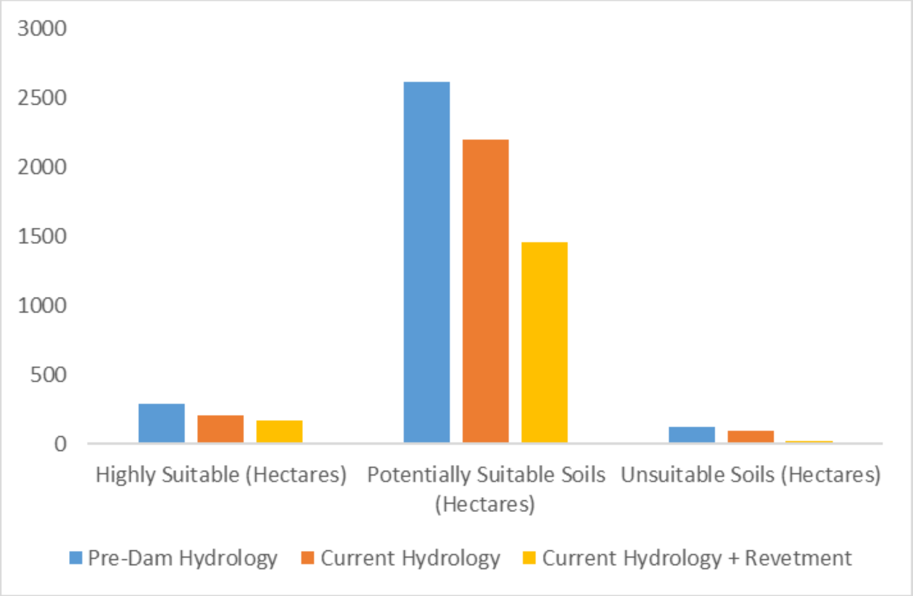

Figure 2.7. Bar graph of the land area (ha) of Highly Suitable, Potentially Suitable, and Unsuitable soils. These estimates were derived from intersecting the Bank Swallow Soil Suitability raster with the MeanderJP 50-year meander extent under three management scenarios for the Sacramento River.

The 50-year total meander extent predicted for the Feather River is as follows: Pre-Dam Hydrology scenario is 679.7 ha, Current Hydrology is 332.3 ha, and Current Hydrology + Revetment is 269.2 ha. Based on the model inputs and assumptions, the Feather River meander extent is reduced by 51% due to hydrological flow impairments, and a combined reduction of 60% due to the combined effects of both river impoundment and bank stabilization. Considering existing hydrology, 63.1 ha (19%) of landscape are unavailable to river meander due to the presence of bank stabilization (Table 2.5 and Figure 2.8). The cumulative impacts of hydrological flow impairment and bank stabilization have reduced river meander through highly suitable soils by 73.5 ha (78%). Similarly, cumulative impacts of hydrological flow impairment and bank stabilization have reduced river meander through potentially suitable soils by 332.6 ha (58%).

Table 2.5. Land area (ha) of Highly Suitable, Potentially Suitable, and Unsuitable soils, and area (ha) of soils unavailable to the river meander due to rock revetment. These estimates were derived from intersecting the Bank Swallow Soil Suitability raster with the MeanderJP 50-year meander extent under three management scenarios for the Feather River.

Feather River	Pre-Dam Hydrology	Current Hydrology	Current Hydrology + Revetment	Unavailable Due to Revetment
Highly Suitable (ha)	94.1	31.0	20.6	10.4
Potentially Suitable Soils (ha)	578.0	297.4	245.4	52.1
Unsuitable Soils (ha)	7.7	3.8	3.3	0.6
Total Meander Potential (ha)	679.7	332.3	269.2	63.1

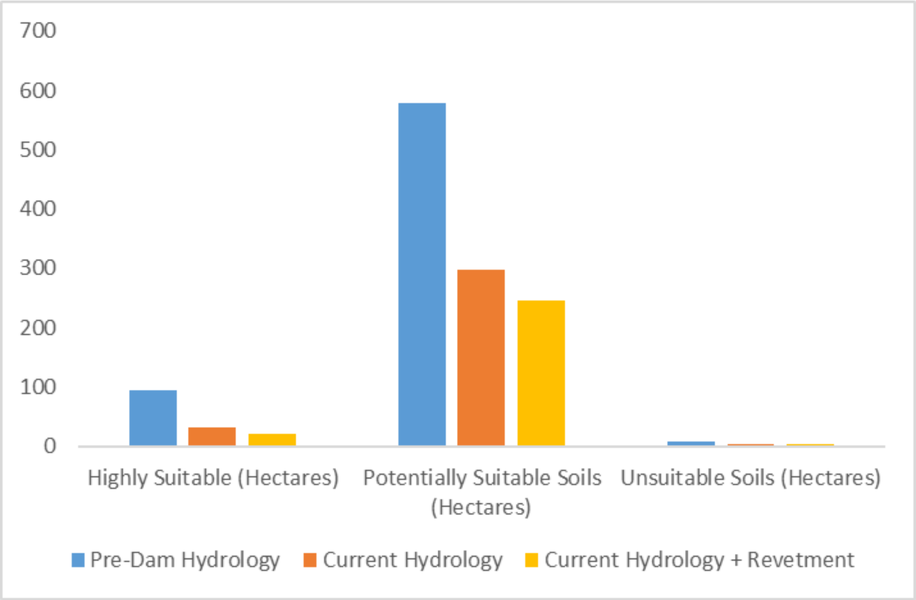

Figure 2.8. Bar graph of the land area (ha) of Highly Suitable, Potentially Suitable, and Unsuitable soils. These estimates were derived from intersecting the Bank Swallow Soil Suitability raster with the MeanderJP 50-year meander extent under three management scenarios for the Feather River.

The 50-year total meander extent predicted for the Sacramento and Feather rivers considered together is as follows: Pre-Dam Hydrology scenario is 3703.3 ha, Current Hydrology is 2832.0 ha, and Current Hydrology + Revetment is 1922.5 ha. Based on the model inputs and assumptions, the Sacramento and Feather River meander extent is reduced by 24% due to hydrological flow impairments, and a combined reduction of 48% due to the combined effects of both river impoundment and bank stabilization. Considering existing hydrology, 909.5 ha (32%) of landscape are unavailable to river meander due to the presence of bank stabilization (Table 2.6 and Figure 2.9). The cumulative impacts of hydrological flow impairment and bank stabilization have reduced river meander through highly suitable soils by 186.3 ha (49%). Similarly, cumulative impacts of hydrological flow impairment and bank stabilization have reduced river meander through potentially suitable soils by 1494.9 ha (47%).

Table 2.6. Land area (ha) of Highly Suitable, Potentially Suitable, and Unsuitable soils, and area (ha) of soils unavailable to the river meander due to rock revetment. These estimates were derived from intersecting the Bank Swallow Soil Suitability raster with the MeanderJP 50-year meander extent under three management scenarios for both the Sacramento and Feather River combined.

Sacramento + Feather River	Pre-Dam Hydrology	Current Hydrology	Current Hydrology + Revetment	Unavailable Due to Revetment
Highly Suitable Soils (ha)	381.2	240.4	194.9	45.5
Potentially Suitable Soils (ha)	3194.2	2496.3	1699.3	797.0
Unsuitable Soils (ha)	127.9	95.3	28.3	67.0
Total Meander Potential (ha)	3703.3	2832.0	1922.5	909.5

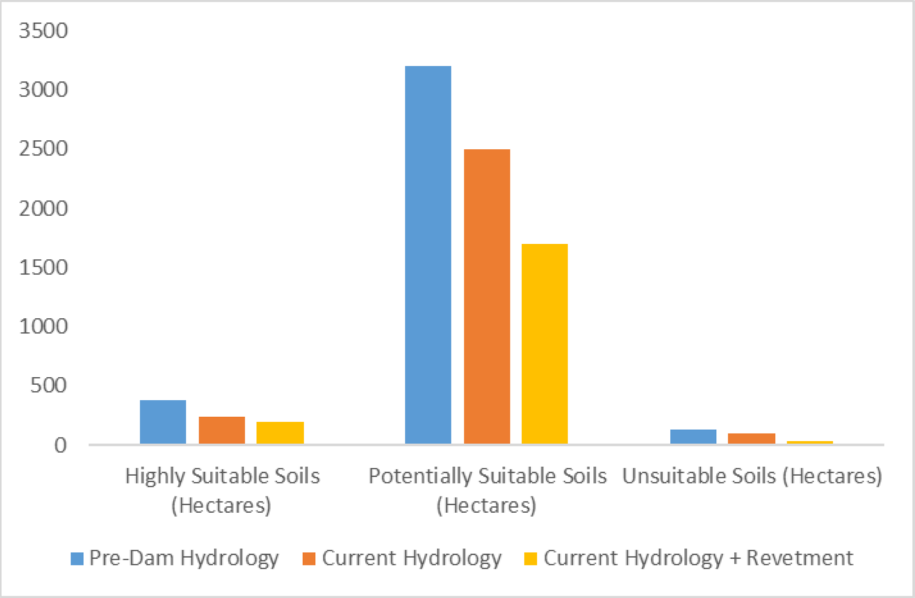

Figure 2.9. Bar graph of the land area (ha) of Highly Suitable, Potentially Suitable, and Unsuitable soils. These estimates were derived from intersecting the Bank Swallow Soil Suitability raster with the MeanderJP 50-year meander extent under three management scenarios for the Sacramento River and Feather River Combined.

An intersect of the results of the soil suitability and river process modeling with the CPAD 2020 dataset identified 38 locations with potential restoration opportunities on public conservation lands (Appendix F. Summary of California Protected Areas Database [CPAD] holdings with potential for bank restoration through bank revetment removal). On average management units have approximately 1.8 ha of potential restoration, with a cumulative potential of 67.5 ha of total potential for restoration.

Discussion

These results represent the first quantitative and spatial assessment of soil suitability for nesting substrate of the Bank Swallow. The soil characteristics and associated maps provide a validated dataset based on a geographically extensive sample, with which to identify and prioritize locations for restoration and conservation activities.

While a legacy of studies have investigated the soil types at Bank Swallow colonies in North America and Europe, the results have been qualitative and generic in nature. Studies have identified sandy, loamy, or silty soils including loamy sand, sandy loam, and coarse sandy soils based on field observation or sampling undertaken at a limited number of colonies (Cadman et al. 1987, Cramp et al. 1988, Grinnell and Miller 1944, Hickman 1979, Josefik 1962, Morgan 1979, Oelke 1968, Petersen 1955, Spencer 1962). Along the Sacramento River, Garrison (1989) sampled soils at a number of colonies (n=29) and described a typology of suitable soils consisting of sand, loamy sand, sandy loam, loam, and silty loam. These results provide a generic characterization but have proved difficult to meaningfully apply at a landscape scale. Garrison (1989) also estimated percent sand, silt and clay, but lacked a predictive spatial component and validation. Thus, these estimates have been difficult to apply beyond a site-specific context where a soil sample has been collected.

The results of the MaxEnt soil suitability mapping above provide a predictive model that provides watershed wide mapping of the extent and distribution of suitable soils based on a geographically comprehensive sample of 136 colonies along the Sacramento and Feather rivers. Appendix E. *IRIC and Maxent Results*, Figure E-1 through Figure E-3 provide understanding of the total potential landscape for Bank Swallow habitat and can be used in combination with other datasets to identify and target geographies for reserve design, conservation easement placement, and restoration activities such as bank stabilization removal.

The large and geographically comprehensive sample of colonies (n=136) and high predictive capabilities as demonstrated in the five-fold cross-validation results provide confidence in the model's ability to identify potentially and highly suitable soils. It should be acknowledged, however, that the sample is distinctly built upon colonies in the river banks of the Sacramento and Feather rivers. No sites from off river colonies were used, and thus it should be expected that the soil characteristics and extents are potentially biased towards soil types within the floodplains of river and stream corridors. Inference should therefore probably be limited to the floodplain deposits within the study extent.

For birds of riparian systems, individual species-habitat associations are known to vary by region, as described identified by Melcer (2012), and Nur et al. (2008). Considering the fact that colony locations were limited to those in cut banks along rivers within the Sacramento Valley of California, the generalizability of the results of this analysis is likely limited to the floodplain deposits of the same region. The analysis framework, including the analytical tool, use of census survey data, and the application of gSSURGO soil component attributes is of broader utility, and the approach used here could be used to understand the relationship between Bank Swallow colony locations and the soil characteristics in other model systems.

It is important to note that soil characteristics are one dimension of the reproductive habitat niche of the Bank Swallow. It is necessary to include other important dimensions of the habitat to achieve a more robust understanding of the areas on the landscape that are available to the species (Garrison 1989, Stillwater Sciences 2007). For the river systems of the

Sacramento Valley, a fundamental phenomenon is the annual interaction of the river systems with these suitable soils and the formation of steep river banks.

While conducting Bank Swallow population surveys, I observed an anecdotal but apparent relationship between burrow locations and the presence of soil lenses or soil strata where overlying and or underlying soils had differences in soil properties. Comprehensive data on the presence of these stratifications was lacking, however, and I was unable to use this in my analysis. Future work on the Sacramento and Feather river systems may explore this characteristic to better understand Bank Swallow colony placement with regards to these local soil properties.

The results of this modeling provide reconnaissance level insight into the systemwide cumulative impacts of flow impairment and bank stabilization on the potential for river meander processes to renew cut banks for Bank Swallow reproductive habitat over a 50-year period for the Sacramento River and Feather River. These findings are assembled from modeling at the river reach scale, and therefore can be explored in more detail within each reach. Importantly, the management scenarios can also be used to understand the potential for restoration of these processes, such as flow restoration and bank restoration through revetment removal.

The intersection of the Bank Swallow soil suitability raster with the river channel meander extent under the management scenarios illustrates a quantitative and spatially explicit understanding of the total potential and projected locations of future Bank Swallow nesting habitat given impaired hydrology and extensive bank stabilization. A review of the model outputs in conjunction with the California Protected Areas Database (2020) reveals 37 locations where rock revetment is preventing lateral channel migration through either potentially or highly suitable Bank Swallow soils along the Sacramento River. These locations present a prioritization scheme for public agency action on Bank Swallow conservation planning, reserve design, and restoration.

These results demonstrate the incredibly limited spatial extent of Bank Swallow nesting habitat over a 50-year period. When the amount habitat available to the Bank Swallow population is considered in an annual context, it becomes clear that river channel movement interacts with suitable soils over very small portions of the landscape which are distributed longitudinally along the river channels. Annually, the Sacramento River channel meanders through approximately 3.5 ha of highly suitable soils, and 29 ha of potentially suitable soils distributed over 200 linear miles of channel. The Feather River, on average, meanders annually through 0.4 ha of highly suitable soils, and 4.9 ha of potentially suitable soils distributed over 60 linear miles. This indicates the Bank Swallow is very much a habitat specialist dependent on an incredibly limited part of the landscape despite being characterized in Rosenberg et al. (2016) as a habitat generalist (Chapter 1). Conservation assessments must consider the rarity of the birds breeding habitat, the specialist aspect of the species natural history, and the observed declines of the species in determining the need for legal protections for the species (e.g. listing under state or federal endangered species acts).

These findings also highlight the importance of conserving the limited extent of the specific habitat features (i.e., suitable soils, steep eroding banks) and the processes (i.e., hydrology and erosion) that create them, if the California population is to persist.

While the total reduction of river process on the Feather River is impacted by 60%, Bank Swallow habitat is impacted asymmetrically, and the species has realized a more than 78% impact of highly suitable soils. The erodible soils the species depends upon are often the areas of the bank that are targeted for bank stabilization given their tendency to erode and move laterally. This represents a major stressor on this species' ability to survive, and an important area to focus conservation efforts.

The meander modeling undertaken in this study used large river reaches, generalized inputs of bank full discharge, and generalized erosion fields. Further, this work leveraged coefficients and channel geometries that have been used in validated and QA-QC applications of the model within the watershed (Micheli et al. 2004, Larsen et al. 2007, Micheli et al. 2011). This approach is likely appropriate at the watershed scale for reconnaissance level identification of river channel behavior, tendencies, and patterns. Therefore, a limitation of this study is that reach and site-scale inference should be drawn from more refined modeling approaches that apply site specific and variable hydrology, and a more fine-scale approach to developing erosion fields that considers a granular set of erodibility coefficients assigned to both geological and vegetation features on the landscape (Micheli et al. 2004). Using historical aerial photographs, hydrograph data, and rock revetment data, more granular simulations should be validated to ensure the most robust model is being applied for future projections.

It is notable that the results from this study agree with previous studies that have examined process limitations on ecosystem development on the Sacramento River. A study by Greco (2013) examined the riparian habitat dynamics of the federally threatened Neotropical migrant bird species, the Yellow-billed Cuckoo (*Coccyzus americanus*). Using a similar, but slightly smaller linear river channel extent, that study found a 52% reduction in the production of new land due to reductions in hydrologic flow (loss of stream power) and bank revetment as compared to 45% in this study. In another related study, Fremier et al. (2014) found a 25% reduction in channel migration rate due to cumulative flow reductions (loss of stream power) as compared to pre-dam conditions, while this study found 17%. All of these studies support the need for conservation of the ecosystem processes (flow and floodplain erosion and deposition) that create and maintain crucially important habitats (i.e., nesting and feeding) for threatened and endangered species dependent on the dynamic cut banks and floodplains of the Sacramento River ecosystem.

Climate change is expected to further alter hydrologic patterns of flow on rivers in California (Dettinger 2016, Knowles and Cayan 2004). Modeling scenarios beyond 20-30 years will likely require considering shifts in the hydrograph. For the Sacramento River, and the magnitude of flows over the winter are expected to increase as climate shifts towards warm storms (Cloern et al. 2011, Dettinger 2016). Projections of net rainfall are uncertain however, and thus cumulative stream power over the course of a year may remain static (Cloern et al. 2011, Dettinger 2016). More consideration of these factors is required in modeling of long time periods.

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Chapter 3. Bank Swallow Response to Stream Channel Restoration

Abstract

The meandering portions of the middle Sacramento River and lower reaches of the Feather River provide the most significant breeding habitat resources to more than 70% of California's State Threatened Bank Swallow (*Riparia riparia*) population. Throughout these river reaches, river bank stabilization efforts have degraded and reduced the amount of suitable eroding banks, and Bank Swallow use of the river corridors has been in decline. The Bank Swallow Recovery Plan, many scientific papers, and, recent modeling efforts have suggested that removal of rock revetment along banks of the Sacramento River would contribute to the persistence and recovery of Bank Swallows, however, the large-scale efficacy of this activity in benefiting Bank Swallows is untested. Using historical aerial photography, rock revetment spatial datasets, and Bank Swallow colony survey data, I evaluated Bank Swallow response at locations where revetment along the Sacramento River from Colusa to Redding was unintentionally removed through high water scour events, or is no longer serving its designed purpose on the river bank. I found 18 instances where rock revetment no longer remained in place, and at all but two locations, Bank Swallow colonies were re-established. These instances were located within the 100-year meander belt, where rock revetment had been placed on alluvium. At nine locations, colonies were re-established within 1-2 years, and in five cases, Bank Swallows returned between 3 and 6 years. At the two locations where Bank Swallows did not return, the revetment failed, however, steep cut banks were not formed. Given the nearly universal response throughout the study area, we find this compelling empirical evidence that removing rock revetment will provide an

increase in useable nesting habitat and has the potential to contribute to the persistence and recovery of the species.

Introduction

The Bank Swallow is a Neotropical migrant species, wintering in Central America and South America, and breeding in the North America. Like many other insectivore Neotropical migrant species, the Bank Swallow has suffered significant range-wide declines. Rosenberg et al. (2016) estimate a 95% reduction in the continental population based on Breeding Bird Survey (BBS) data. On the breeding grounds in North America, the Bank Swallow has strong ties to steep river banks or lake or ocean bluffs composed of friable soils where it excavates burrows during the breeding season (March – July). In these settings, a geomorphic mechanism such as river channel meander migration or lake or ocean wave wash refreshes the steep banks which are subject to degradation from slumping, vegetation colonization, and parasite infestation over time. Bank Swallows are sensitive to management activities that alter flows or stabilize stream channels or lakeshores (CDFW 1992, BANS TAC 2013).

Within California, the Sacramento River and the Feather River support more than 85% of the breeding population of Bank Swallows (Laymon et al. 1988). Surveys of breeding Bank Swallows conducted from 1986-2017 have recorded between 7,000 and 32,000 burrows annually (BANS TAC, unpublished survey data). The sediment contributions from montane headwaters combined with the flat topography of the valley have resulted in extensive alluvial deposits of well-sorted and suitable surface geology and soils. River flows, driven by a Mediterranean climate, erode and resurface stream channel banks during winter flooding, and recede during summer months when the birds construct burrows and nest (Garrison et al. 1987, Garrison 1999, Schoellhamer et al. 2012).

Anthropogenic activities have impacted Bank Swallow habitats along the Sacramento and Feather rivers (CDFW 1992, BANS TAC 2013). Large dams control flow, reducing peak flows during the wet season, and interrupting sediment supply and stream channel dynamics (Singer and Dunn 2001, Micheli et al. 2004, Larsen et al. 2006b, Singer 2008,). Flow regulation has a significant impact on lower magnitude flooding that occurs at frequencies biologically relevant to Bank Swallows that would have resurfaced cut banks every other year (Cain and Monohan 2008, Williams et al. 2009). Levees have disconnected stream flood flows from river floodplains (Opperman et al. 2010, Opperman 2012). Activities undertaken to halt river channel meander migration and local erosion, such as rock revetment (“riprap”), have reduced the extent of cut banks and halted the processes which form these floodplain features. Approximately one-third (387 km) of the banks of the main stem Sacramento River, and approximately one-tenth (26 km) of the Feather River has been stabilized with revetment (CDWR 2012). Conceptually, a meandering river has stable, eroding, and depositing segments of bank, approximately equally distributed through a meander bend. While some natural river bank remains on the Sacramento River and Feather River, revetment is typically placed on the eroding component of the channel, thus having more impact on the proportion of banks used by the Bank Swallow for nesting.

Bank Swallows were listed as a State Threatened Species under the California Endangered Species Act (Remsen 1978). The populations on the Sacramento River and Feather River have experienced declines as habitat extent and quality has been impacted by alterations in river flows and bank stabilization activities (Garrison et al. 1987, Laymon et al. 1988, CDFW 1992). Multiple conservation planning efforts have identified the need to remove bank stabilization to restore both stream channel banks and re-establish geomorphic processes such as river meander migration (DFW 1992, BANS TAC 2013, Dybala 2017). Golet et al. (2013) recognizes that restoration efforts have failed to realize improvements in river conditions relating to flows, bank condition, and resulting geomorphic processes. Stream bank restoration remains untested as a management action to address declining use of Bank Swallows on the Sacramento and Feather rivers.

Both construction of artificial nesting colonies and restoration of stream channel banks through revetment removal have been suggested as management actions to address declining trends in Bank Swallows and their habitats within the Sacramento Valley. Only development of artificial habitat has been studied in the field. From 1988 - 1990, the California Department of Fish and Wildlife (CDFW) constructed and evaluated the performance of artificial nest sites on the Sacramento River (Garrison 1991). The findings of this assessment indicated higher observed depredation at artificial nest sites, and lower use by Bank Swallows when compared to river bank reference sites. Artificial sites were also expensive to construct and difficult to maintain limiting their temporal contribution as habitat, thus they have been deemed an unsuitable management action for addressing the species conservation (Garrison 1991, CDFW 1992).

Restoration of natural banks by removal of revetment has been suggested as an important solution to the recovery of the species (Schlorff 1997, Garcia et al. 2008, BANSTAC 2013). Modeling investigations have assessed the potential effects of bank restoration on colony dynamics and population viability (Moffat et al. 2005, Girvetz 2010). Moffat et al. (2005) found that restoration of natural banks could lead to the increases in Bank Swallow population size through increases in the number of colonies found on the river. The spatially explicit population viability analysis of Girvetz (2010) showed that revetment removal produced significant reductions in the probability of extinction on the Sacramento River. These studies and conservation documents which have recommended bank restoration as a management action (DFW 1992, Garcia et al. 2008, BANS TAC 2013, Dybala et al. 2017) have assumed that Bank Swallows would respond by re-colonizing banks that had revetment removed. Similar assumptions were associated with the development of artificial habitat. When artificial banks were developed on the Sacramento River, however, species response was muted and habitat quality was low (Garrison 1991). Similarly, while large-scale restoration efforts on the Sacramento and Feather rivers have increased riparian forest land cover to enhance the habitat of the Yellow-billed Cuckoo (*Coccyzus americanus*), the species has not responded to these increases in riparian land cover (Dettling et al. 2015). Thus, there is uncertainty surrounding the potential to benefit Bank Swallows through bank restoration. Despite the recommendations of Schlorff (1997), Garcia et al. (2008), and the modeling work of Girvetz (2010) and Moffat et al. (2005), no deliberate removal of revetment as a conservation or recovery management action for Bank Swallows has occurred, making it difficult to assess whether this action would actually benefit the species within the Sacramento Valley.

In this paper, we take an observational approach in testing the assumption that Bank Swallows would re-colonize sites after revetment was removed on the Sacramento and Feather rivers. Specifically, our objectives were to review historical river maps and Bank Swallow survey datasets in order to: (1) identify locations where revetment has been "orphaned" (i.e., abandoned by river channel movement processes), degraded, or eroded out by high water events, and (2) evaluate the response of Bank Swallows to these changes. We also review soil types, surface geology, land cover, and location on the meander belt and suggest an approach for identifying sites that may be appropriate for revetment removal for the purposes of Bank Swallow recovery.

Methods

Study Area

For this study we limited our analysis extent to the river reaches which support most of the Bank Swallow population within the Sacramento Valley of California. This includes the reaches of the middle Sacramento River from Red Bluff, CA (River Mile [RM] 243), to Colusa, California (RM 143). We also investigate the reaches of the lower Feather River from Oroville, California (RM 67) to the confluence with the Sacramento River in Verona, California (RM 0). The river mile (RM) designation system was developed by the US Army Corps of Engineers in the early 20th century and is used to indicate distances upstream from the confluence with the San Joaquin River for locations on the Sacramento River, and upstream from the confluence with the Sacramento River for locations the Feather River. The Sacramento and Feather rivers have meandered over time, and the number designations no longer accurately reflect channel length, but continue to be used to designate geographic locations in a variety of scientific literature.

The Sacramento River watershed drains 60,900 km^2 including tributaries within the coast range, Trinity, Cascade and Sierra Nevada mountain ranges (Singer and Dunne 2001, Larsen et al. 2006a). Within the study reach of the Sacramento River, the channel is quite wide, meanders actively forming cut banks, point bars, and gravel islands (Michalkova et al. 2011). Channel cut-off processes form oxbow lakes and new channel alignments. The floodway and floodplain support both agriculture and structurally diverse vegetation including cottonwood (*Populus fremontia*) and willow (*Salix* spp.) dominated riparian forests. The geology of this reach of the river primarily consists of alluvial deposits with intrusions of clay rich (e.g. Modesto and Laguna formations) or consolidated (e.g. riverbank formation) deposits which are resistant to erosion. The Feather River has significant erosion resistant mining deposits (slickens) due to legacy mining (James et al. 2009, CDWR 2004). Shasta Dam regulates flows on the main stem of the Sacramento River. Bank full discharge is approximately 2270 m^3/s, and unimpaired tributary flows (e.g. Cottonwood Creek) can have a significant effect on the hydrograph of the river depending on the centering storm events (WET 1988). The lower 50 km of the study area along the Sacramento River (RM 144 - RM 186) is bounded by flood control levees. These levees are set back from the river channel allowing meander bend migration processes to occur.

The upper portions of the lower Feather River (from RM 27 to RM 67) actively migrate, braid and form gravel islands similar to the Sacramento River. Downstream of RM 27, the river meanders less, with broad sparsely vegetated alternating sand bars forming meanders within the low flow channel. The floodway between levees primarily supports agriculture, and riparian forests dominated by cottonwood and willow can be found adjacent to the river channel. The surficial geology of the Feather River has been impacted by mining activities in the upper watershed, and alluvium has consolidated with mining debris in erosion resistant formations called slickens. The reach also has intrusions of clay rich deposits resulting from mining sediment input and is overall less active than the Sacramento River. While the Feather River is bound by state and federal levees throughout the study reach, they are set back from the channel in most locations, and generally does not impede river geomorphic processes. The river channel is partially rocked with revetment, however, and flows are impaired by the Lake Oroville Dam with bank full events reduced to 934 - 1415 m^3/s (Cain and Monohan 2008). Model projections of the effects of rock revetment over a 50-year (i.e. 2009-2059) time period indicate that meander potential is reduced more than 33% on the Sacramento River, and approximately 19% on the Feather River (Chapter 2). Flood control agencies continue to implement large scale bank stabilization projects. As of 2020, the Sacramento River Bank Protection Program has conducted environmental review on Phase II of a program to place a cumulative total of 24.4 linear km of rock revetment on the Sacramento and Feather river (USACE 2020). This is in addition to the bank stabilization currently on the rivers.

Identification of Revetment Removal Sites

Within the study area on the Sacramento and Feather rivers we reviewed multiple data sources to obtain channel alignments and compared these with mapped locations of revetment to identify locations where revetment was orphaned, degraded, or removed. Orphaned revetment is the situation when river channel processes migrate the channel away from the revetment and leave it abandoned. We relied primarily on computer-based geographic information systems (GIS) catalogues of aerial photos developed by state and federal agencies, non-governmental agencies, and universities for environmental planning, assessments, land-use mapping, surveying, public references, and ownership. Analyses were conducted using ArcGIS (version 10.4.1, ESRI 2020). Aerial photos were available from historical photo mapping efforts as summarized in Table 3.1.

Table 3.1. Historical datasets used to evaluate rock revetment locations and instances of rock revetment failure.

California Department of Water Resources (CDWR). 2005. 2004 Sacramento River Aerial Atlas, Colusa (River Mile 144) to Redbluff (River Mile 243). Photographic Atlas. State of California, The Resources Agency, CDWR Northern District, Redbluff, CA.
California Department of Water Resources (CDWR). 2002. 1999 Sacramento River Aerial Atlas, Red Bluff (River Mile 243) to Keswick Dam (River Mile 302). Photographic Atlas. State of California, The Resources Agency. CDWR Northern District, Redbluff, CA.
Harmon, H. and A. Henderson. 1999. 1997 Sacramento River Aerial Atlas. Photographic Atlas. California Department of Water Resources, Northern District, Redbluff, CA.
U.S. Army Corps of Engineers. 1991. Sacramento River, Sloughs, and Tributaries, California - 1991 Aerial Atlas, Collinsville to Shasta Dam. Photographic Atlas. U.S. Army Corps of Engineers, Sacramento, CA.
U.S. Army Corps of Engineers (USACE). 1984. 1984 Sacramento River Aerial Atlas. Photographic Atlas. U.S. Army Corps of Engineers, Sacramento, CA.
U.S. Army Corps of Engineers (USACE). 1980 Sacramento River Aerial Atlas, Collinsville to Shasta Dam, California. Photographic Atlas. U.S. Army Corps of Engineers, Sacramento, CA.
U.S. Army Corps of Engineers (USACE). 1973. 1973 Sacramento Aerial Atlas. Photographic Atlas. U.S. Army Corps of Engineers, Sacramento, CA.
The CDWR updated revetment catalogues in 2013. GIS-based catalogues of field verified revetment locations were developed by the CA Department of Water Resources. Revetment locations

Bank Swallow Population Monitoring

For the Sacramento River, we used the Bank Swallow monitoring data collected within the study area from 1986 to 2015. Between the towns of Red Bluff (at RM 245) and Colusa (at RM 144), the California Department of Fish and Wildlife, the California Department of

Water Resources, and the U.S. Fish and Wildlife Service have conducted surveys from jet boat in early June each year using a river census area search methodology (Appendix A, *Bank Swallow Survey Methods for the Sacramento and Feather Rivers, California, Version 1.0, January 2017*). For this study, we focus on active colonies within survey datasets (i.e. colonies with birds present and nesting in the season they were mapped).

Double observers count burrow numbers for consistency, while a third technician performed mapping and photographic work. Colony locations were mapped using a global positioning system (GPS) unit (1996-2008), and later mapped using a mobile GIS on a laptop (2008-2017). Monitoring data provide a consistent and uniform assessment of the study area. During the study period, a total of 1,352 colonies were recorded. The mean number of colonies per year are 48.3 (SE=2.5). Mean burrow counts for the middle Sacramento River are 14,997 (SE=942.5). Colony and burrow numbers increased early in the study period through 2001, however have exhibited overall declines during the latter years of the study period (2002-2014) from a high count of 19,023 active burrows to a low of 9,529 (Table 3.2).

Table 3.2. Colonies, burrow counts, from empirical studies of Sacramento River.

	Sacramento River				Feather River				Region	
Year	Colony Count	Burrow Count	Mean Burrow Count	Max Burrow Count	Colony Count	Burrow Count	Mean Burrow Count	Max Burrow Count	Total Colony Count	Total Burrow Count
1986	69	29399	426	3000	7	3140	449	2000	76	32539
1987	65	24903	383	1630	*	6592	*	*	65+	31495
1988	30	10330	344	2330	NO DATA				30	10330
1989	23	7230	314	1740					23	7230
1990	49	20658	422	1920					49	20658
1991	41	15899	388	2440					41	15899
1992	49	15520	317	3440					49	15520
1993	42	12587	300	1620					42	12587
1994	37	15391	416	2250					37	15391
1995	39	9659	248	700					39	9659
1996	47	11530	245	1150					47	11530
1997	47	10330	220	1400					47	10330
1998	37	9700	262	1260					37	9700
1999	52	16960	326	1540					52	16960
2000	34	18130	533	2770					34	18130
2001	38	19170	504	1800					38	19170
2002	44	16160	367	1720	8	2274	284	925	52	18434
2003	47	17600	374	1640	15	3594	240	1164	62	21194
2004	43	17040	396	1570	NO DATA				43	17040
2005	39	13990	359	1840					39	13990
2007	38	17640	464	3640					38	17640
2008	56	19023	340	1920	18	3787	151	825	74	22810
2009	74	16051	217	2533	20	2807	140	393	94	18858
2010	50	9529	191	1376	14	1832	131	465	64	11361
2011	57	9991	175	1126	24	2516	105	861	81	12507
2012	58	11994	207	838	14	2322	166	506	72	14316
2013	69	11136	161	1212	13	2111	162	442	82	13247
2014	78	12363	159	2162	7	2425	346	503	85	14788
2015	43	9468	220	955	11	2790	254	542	54	12258
2016	48	8906	186	1252	13	1753	135	564	61	10659
2017	52	10846	209	976	15	1097	73	255	67	11943

For the Feather River, there was a break in the survey effort, with an initial survey in 1987 by the CDFW, and later in 2002-03 by the CDWR. Since 2008, the CDWR has resumed surveys annually through 2017. Methods are consistent with the Sacramento River surveys, with an annual census conducted in June, double observers, and mobile GIS used to map colony locations in the field (Appendix A, *Bank Swallow Survey Methods for the Sacramento and Feather Rivers, California, Version 1.0, January 2017*). Surveys are conducted primarily by jetboat, however, the downstream extent of the lower Feather River (RM 1 - 12) is shallow and requires surveys by kayak or canoe. During the survey period, 140 colonies were recorded on the Feather River. The mean number of colonies observed each year are 14 (SE=1.9). Mean burrow numbers per year was 3,036. Surveys indicate declining trends on the Feather River, with a maximum count of 6,592 burrows in 1987, and subsequent surveys decreasing to 2,425 burrows in 2014.

Meander Belt Assessment

We determined the 100-year meander belt extent using digitized channel alignments from 1896 to 1991 (DWR 1995). Early alignments (1896-1937) were derived from Army Corps of Engineers Survey Maps, U.S. Geological Survey 15-minute Quadrangles, and CDWR Division of Engineering historical maps. Later alignments were derived from U.S. Army Corps of Engineers aerial atlases, U.S. Department of Agriculture Aerial Photography and U.S. Geological Survey topographic maps.

Surficial Geology Assessment

We also evaluated surficial geology at sites where revetment was removed or degraded using the Sacramento Geologic Units GIS database and the Feather River Geology Mapping Atlas (CDWR 1995, CDWR 2013, CDWR 2004). We used the gSSURGO (NRCS) soil database to assess soil formation.

Results

Through review of the aerial photos and databases, we identified 14 sites on the Sacramento River and four sites on the Feather River where revetment was placed on natural banks and removed by one of the three modes of failure described above. In one case, revetment was removed by a private landowner; in six instances the river channel cut off and moved away from its historical alignment thus exposing new natural bank and orphaning the revetment on the floodplain, and in 12 other cases, revetment was eroded and removed by river flood flows. On the Sacramento River seven sites involved revetment installed as part of the Chico Landing to Red Bluff Project; two sites were installed by the U.S. Army Corps of Engineers as part of the Sacramento River Bank Protection Project, and four sites were installed by private landowners. On the Feather River, all sites identified were installed by private landowners. Table 3.3 summarizes the watershed, location (river mile), rock type, and length of the revetment failure. Figure 3.1 provides a planning view and on-site photograph of a failure of private rock revetment where Bank Swallows recolonized at RM 185.9 on the Sacramento River.

Table 3.3. River, mile-marker location, revetment-type, year of revetment failure, and Bank Swallow recolonization information for 18 sites where rock revetment failed on the Sacramento River and Feather River.

River	River Mile	Bank	Failure Method	Length (m)	Type of Rock Revetement	Year Failure Occurred	BANS Return	Interval (years)	Colony Size	Surficial Geology	BANS Soil Suitability	To Levee Centerline (m)
Sacramento	237	L	Orphaned	550	Private Landowner	1997	1999	2	11	Alluvium - Qmb; Qhms	0.85359	no levee
Sacramento	237	R	Orphaned	1038	Chico Landing to Redbluff	1983	1986	2	180	Alluvium Qmb	0.85359	no levee
Sacramento	234.3	R	Orphaned	8500	Chico Landing to Redbluff	1981	1986	5	370	Alluvium Qmb	0.76641	699
Sacramento	233.4	L	Blowout	350	Chico Landing to Redbluff	1997	1999	2	180	Alluvium - Qhms	0.76742	no levee
Sacramento	233	R	Blowout	179	Private Landowner	1997	1999	2	930	Alluvium - Qmb; Qhms	0.655101	no levee
Sacramento	231.7	L	Blowout	100	Private Landowner	2002	2004	2	320	Alluvium Qmb	0.529536	no levee
Sacramento	227	L	Blowout	230	Chico Landing to Redbluff	2000	2001	1	300	Alluvium - Qhms	0.76641	335
Sacramento	226	R	Orphaned	2223	Chico Landing to Redbluff	1998	1999	1	580	Alluvium Qmb	0.85359	346
Sacramento	208	L	Blowout	300	Chico Landing to Redbluff	1997	2003	6	100	Alluvium - Qmb; Qhms	0.70953	660
Sacramento	198.8	L	Removed	150	Private Landowner	2007	2007	0	1130	Alluvium - Qmb; Qhms	0.776443	2081
Sacramento	196.5	R	Blowout	250	Chico Landing to Redbluff	1983	*na*	*na*	*na*	Alluvium - Qhm; Qmb	0.688568	no levee
Sacramento	185.9	R	Blowout	130	Private Landowner	2000?	2003	3	210	Alluvium - Qmb; Qhm	0.688568	no levee
Sacramento	174	R	Orphaned	1100	US Army Corps of Engineers	1997	1999	2	160	Alluvium - Qmb; Qm; Qhm	0.808063	516
Sacramento	154	R	Blowout	100	US Army Corps of Engineers	2000?	2005	4	100	Alluvium Qmb	0.45056	95
Feather	52.2	L	Blowout	20	Private Landowner	2006	2011	5	*na*	Alluvium Qmb	0.742919	64
Feather	46.1	L	Blowout	unk	Private Landowner	1986	2009	*unk*	110	Alluvium Qmb	0.776443	1143
Feather	43.5	L	Blowout	88	Private Landowner	1999	2008	*unk*	825	Alluvium Qmb	0.631644	2017
Feather	34.3	L	Blowout	60	Private Landowner	1997	*na*	*na*	*na*	Alluvium Qmb	0.631644	850

Figure 3.1. (Top) Plan view of private landowner-installed rock revetment failure at River Mile 186 with Bank Swallow colony on the cut bank behind the failure, Butte County, Sacramento River. (Bottom) Burrows on the bank which has eroded behind the alignment of failed revetment.

Revetment failure sites had a large range in size, with the smallest site being 20 m of revetment which eroded on the Feather River, and the largest site consisting of 2,223 m of revetment that was orphaned at RM 226 on the Sacramento River. The mean length of bank exposed when the revetment eroded and blew out at the sites was 163 m (SE =29, n=12).

Twelve of the identified sites were above the state-federal levee system on both the Sacramento and Feather rivers. At sites where either state-federal or private levees were present, a mean distance of 800 m (S.E.=209, n=11) existed between the rock revetment and the levee prism.

All sites where revetment failed were located within the 100-year historical meander belt. Surficial geology included alluvium (noted as Qmb, Qhms, Qhm, and Qm on surficial geology maps) and point bar meander scrolls. Soils included Columbia fine sandy loam, river wash, Molinos complex (sandy loam), silt loam, Gianella fine sandy loam, sand and gravel, and Moonbend silt loam.

Bank Swallows colonized 16 of the 18 locations where revetment once occupied the river bank but failed due to one of the three means described above. In the two cases where swallows did not colonize, the river did not form cut banks after the loss of revetment on the banks. Bank Swallows colonized revetment failure sites anywhere from within the same season of the failure to six years later. At two sites, revetment failed several years before surveys began, and while we can confirm these sites were colonized by the species, they were excluded from the response analyses due to the gap in surveys during the initial years after failure. The mean interval between failure and colonization was 2.6 years (S.E. = 0.5, n=16). Mean colony size was greatest in the initial years after revetment failure and decreased over time as is typical with the species and its ephemeral habitat (Appendix G, *Regression of Burrows by Year Since Revetment Failed*).

We compared both the mean annual burrow counts and the total number of burrows counted at each site over the study period against the length of bank exposed at each site where revetment eroded and blew out (n=12). We did not find a strong relationship between length of failure and mean or cumulative number of burrows.

Discussion

Bank Swallow habitat along the Sacramento and Feather rivers is naturally constrained by the distribution and extent of suitable soils that are cut into by lateral channel migration. Rock revetment placed to stabilize banks and prevent erosion has further constrained the availability of this limited habitat resource. It is notable that at all sites where revetment has failed or is no longer serving its design purpose and a cut bank has formed, Bank Swallows have colonized the site within several nesting seasons. This suggests that Bank Swallows may be limited by habitat availability. Placement of additional revetment on banks could further reduce habitat and impact the species ability to recover from declines that have been observed.

This study provides empirical evidence that Bank Swallows will nest in banks that have had revetment removed and lateral channel migration re-established such that steep cut banks are able to reform. While Garrison (1991) described in detail how artificial habitat performed poorly and required significant management, we suggest that restoration of river channel banks is a viable conservation measure for the species that is self-sustaining once established. The results of this study demonstrate that nesting habitat can be restored, and that Bank Swallows will respond in relatively short time frames (i.e. preceding nesting season). Girvetz (2010) demonstrates how this empirically supported conservation action, if undertaken at appropriate scales, has population-level effects and allows the species to avoid regional extirpation. Given the continental significance of the habitats within the Sacramento Valley of California (Chapter 1), these conservation actions could provide meaningful species response to the North American population.

Rock revetment is an important tool in flood control management allowing the protection of critical infrastructure. Sites where revetment failed within this study were on average 800 m from flood control levees. Along the Sacramento and Feather rivers rock revetment has been placed on river channels to halt lateral channel migration. Hydrological and ecological impacts include increased velocities, changes in bed and bank form at the bank stabilization site as well as upstream and downstream, and simplification of species' habitats (Buer et al. 1989). Placing rock revetment on wetted channel banks redirects hydrological impacts creating increased downstream velocities, erosion, and at times channel cutoff. As discussed above, these practices incrementally impact Bank Swallow habitat at multiple spatial and temporal scales (Chapter 1).

At five sites, the Sacramento River channel moved significant distances from rock revetment placed on its banks, allowing Bank Swallows to take advantage of new, un-rocked channel banks. This demonstrates that rock revetment can be placed off channel without impacting Bank Swallow habitat. A potential solution that could address flood control concerns and avoid impacts to Bank Swallows is to (1) relocate flood infrastructure out of the meander belt, and (2) place rock revetment off-channel, adjacent to levee prisms or other infrastructure, while preserving the river channels ability to move within the meander belt. This concept has been explored by Larsen et al. (2006a) who define the minimum width between the levees required to maintain geomorphic and resulting ecological function associated with lateral channel migration. This solution has the potential to reduce maintenance burdens on revetment projects, conserve habitats for river-associated species, and provide protections to critical flood control and other infrastructure.

This research exemplifies the need for state and federal natural resource agencies to develop specific objectives for the conservation ecosystem processes to benefit a variety of wildlife species' habitat, both terrestrial and aquatic (Golet et al. 2013). On the Sacramento and Feather rivers these processes include naturalization of regulated flow patterns to increase stream power (Larsen et al. 2006b), floodplain deposition for the development of riparian forests (Greco 2013), removal of riverine bank revetment (Fremier et al. 2014), and cut bank erosion (Chapter 2).

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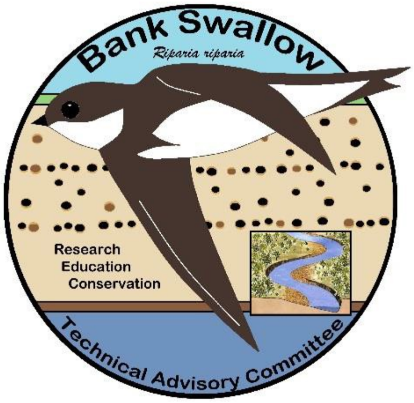
Appendices

Appendix A. Bank Swallow Survey Methods for the Sacramento and Feather Rivers, California, Version 1.0, January 2017

Bank Swallow Survey Methods for the Sacramento and Feather Rivers, California

Version 1.0, January 2017

Prepared by the Bank Swallow Technical Advisory Committee (BANS TAC) Research and Monitoring Subcommittee



Alphabetical listing of authors: Greg Golet, Adam Henderson, Jen Isola, Ryan Martin, Ron Melcer, Nat Seavy, Joe Silveira, Danika Tsao, and David Wright

History and Purpose

This document describes Standard Survey Methodology for annual burrow counts of Bank Swallow (*Riparia riparia*, or BANS) nesting colonies along the Sacramento River and Feather River, California. The California Department of Fish and Wildlife (CDFW) initiated the Sacramento River Bank Swallow Project in 1986 when the first surveys were conducted. Annual surveys continue to present day with the U.S. Fish and Wildlife Service (USFWS), Sacramento National Wildlife Refuge Complex forming a cooperative effort in 1998, and the California Department of Water Resources (DWR) Northern Region Office (NRO), Oroville Field Division (OFD), and staff from CDFW Region 2 joining in 2008.

Survey methods have evolved. For example, during the first two years, colonies occurring on opposite banks were identified as a single colony by River Mile (from the confluence of the Sacramento and San Joaquin rivers). Colonies are located by River Mile (RM) and bank, left (L) or right (R), oriented by the downstream direction of travel. Various U.S. Army Corp of Engineers (ACE) and DWR maps have been used to keep pace with channel migration of the Sacramento River. Yet every river atlas used for the survey required various degrees of interpretation regarding RM location of the actual colony on a bank of the channel because it no longer occurred as photographed on the atlas map. GPS technologies have been used since 1999 to increase survey accuracy. On-board GIS was first used on the survey in 2008 to increase both accuracy and efficiency in data recording. These developments are compatible with previous efforts. This document is the product of the Bank Swallow Technical Advisory Committee (BANS-TAC), 2013.

The methods described in this document are not intended to replace hands on training or experience. The BANS-TAC highly recommends that new surveyors be trained by experienced surveyors and participate in a minimum of one bank swallow nesting colony survey with an experienced team.

Planning and Logistics

Annual survey coordination starts at the beginning of each year in February (Attachment A-1). Survey leads and crews are identified and planning efforts commence. Survey leads are responsible for securing a boat, pilot, boat shuttle, survey crew, data collector, and survey equipment for their given survey area, as well as for overseeing equipment condition and safety (Attachment A-2). Survey leads must execute the annual coordination schedule (Attachment A-1).

Surveys are conducted and data collected using CDFW methods as described in this document. Survey crews consist of one boat operator, two burrow counters, and one mapping specialist/data collector. The boat operator should be familiar with the river and be skilled at operating slow maneuvers in swift currents. Burrow counters should be trained in the methods described in this document and have the ability to identify colonies, bank swallows, burrows, colony activity, and count burrows. The mapping specialist/data collector should have a working knowledge of the equipment and technologies described in this document and be able to troubleshoot problems in the field. Redundant methods for data collection are highly encouraged.

Required survey equipment includes three tally counters (one for a spare), binoculars, digital camera, notebooks, maps (recent aerial photography with previous surveys mapped on them would be best), two GPS units, and batteries. Recent surveys strive to use one of two preferable mapping methods: either a laptop running ArcGIS software, or a mapping-grade GPS unit that is configured with a data dictionary that will accept the necessary data fields (i.e. Trimble GeoExplorer). Survey crews should have a redundant system of paper maps, notebooks and recreation-grade GPS ready in case the GIS or GPS system goes down. See Attachment A-2.

The second week in June is the target survey window. This time period is in the middle of the breeding season and is consistent with surveys done since 1999.

Typically, the Sacramento River survey is completed in four sections: Reach 1 = Keswick to Red Bluff, Reach 2 = Red Bluff to Ord Ferry, Reach 3 = Ord Ferry to Colusa, and Reach 4 = Colusa to Verona. Each section takes a full day to survey. Sections may be surveyed on concurrent days if multiple surveys crews are available. Alternate survey days should be arranged to allow for any unforeseen problems.

The Feather River survey is typically completed in three days due to two navigational barriers, Sunset Pumps located at RM 38.5, and Shanghai Falls at RM 24.5. Using these barriers as landmarks the river is divided into three survey sections with the upper reach from RM 59 to RM 38.5 surveyed on day 1, the middle reach from RM 38.5 to RM 24.5 on day two, and the lower reach from RM 24.5 to the mouth near Verona (RM 0) on day three.

In order to complete these surveys in a timely manner, it is important to have a shuttle set up so the boat trailer is transported down to the take out spot while the boat is on the water.

Survey Methodology

Colony Location

Whenever possible, river surveys should be conducted starting from the upstream end of the survey area, moving downstream. Moving downstream makes surveys more efficient. Both banks of the river should be surveyed during the same trip, with at least one surveyor constantly looking for burrows on each bank while traveling downstream. While looking for burrows and colonies, the boat speed should not be excessive, but fast enough to stay on plane. Once burrows are located, the upriver extent should be noted and the boat operator should float down river at low speed while the survey team determines activity (see Determination of Activity, below). After the team has determined that all burrows have been seen within the colony reach, the downriver extent is determined and the reach of bank is considered a colony. Survey teams should document the location of both active and inactive colonies Note: surveys conducted between 1999 and 2014 counted burrows for only active colonies, but. beginning in 2015 burrows are counted on both active and inactive colonies. The boat operator will need to make adjustments to speed and distance to the bank based on the request of the counters.

Colony Identification

Colonies are typically clusters of burrows in bare or nearly bare, near-vertical banks; usually with more than 30 holes (but can have as few as 2 and more than 3,000), often somewhat horizontally arrayed along favorable strata. Burrows may be evenly dispersed throughout the length of the colony or may be more sporadic with different densities of burrow numbers within the colony length. Burrows within 0.10 miles of each other are considered part of the same colony.

A "typical" BANS burrow entrance is wider than tall, roughly 3 inches wide by 2 inches tall, but there is great variation in this. Figure 1 is a representative photo of a BANS colony.

Figure 1. BANS colony illustrating the variation in burrow shape.

The birds can get into considerably smaller holes, and sometimes the opening of the burrow is eroded or collapsed so that it becomes larger, rounded, or even taller than wide. BANS burrows are oftentimes dug into by raccoons such that they have a greatly enlarged opening. Claw marks are typically evident when this has happened. Occasionally Northern Rough-winged swallows (*Stelgidopteryx serripennis*, or NRWS) may nest within BANS colonies. Typically, Northern rough-winged swallow nest in burrows excavated by other bank nesting species including the Bank Swallow and Belted Kingfisher (*Ceryle alcyon).* Therefore, their nesting burrows may vary in size, but they typically nest singly or in small groups (Djong 1996). Also, the NRWS is similar in appearance to the BANS, but is slightly larger and lacks the distinctive brown breast band of the BANS.

Determination of Activity

A colony may only be classified as active if bank swallows are deemed to be present. Presence of bank swallows may include a swarm of birds around the burrows, birds popping in and out of holes, or young peering out. Even if only one bird is observed entering or exiting a burrow then the colony may be classified as active. If bank swallows are not immediately apparent, then the condition of the burrows should be assessed; if burrows appear to be fresh then extra time should be spent trying to confirm bank swallow presence. Clapping hands loudly near the colony may elicit bank swallows to exit their burrows, confirming presence and activity.

Active colonies will have active burrows that are clean and well-maintained, and may have white wash or guano at the entrance. Burrows appear inky black, because they are deeply dug, and in general they have a smooth, uniform appearance. They may have claw marks associated with them, either faint tiny swallow marks at the burrow entrance, or deeper marks of predators that attempted to dig out the burrows to prey on young and/or eggs.

Inactive burrows often appear rough or craggy and lack scrape marks and white wash. They may appear grayish because they are shallow, incompletely dug or collapsed. Spider webs may crisscross inactive burrows and should not to be confused with root fringes which may occur at the edges of active burrows.

In 1989, Garrison et al. noted "Burrows counted had dark entrances (> 2 cm deep) when viewed from a distance of 5-25 meters. We counted all burrows in active sections of banks and did not count old burrows from inactive sections. Bank Swallows flying into burrows were used to determine activity, and we observed colonies for 15-60 minutes to assess whether or not a colony or section of colony was active." ... "inactive burrows from previous years were often filled with spider webs, vegetation, or collapsed soil."

Both active and inactive colony locations should be mapped, with all burrows that appear to be from the current year counted (beginning in 2015, see Counting section, below) and habitat physical characteristics documented.

Counting

Binoculars are not to be used except in special circumstances when the boat cannot be piloted close enough to the colony for counts to be made with the naked eye.

<u>For active colonies:</u> Two people (the counters) use a standard handheld tally counter to count each active burrow within the active colony (see above for classification of active burrows and active colonies). Large colonies may require the counter to tally groups of 5 or 10 burrows per tally click and multiply the resulting tally accordingly. Pointing to burrows with an extended hand or finger may aid counter in keeping their place. During the count, the crew should remain quiet because any distraction may cause the counters to lose their place and require them to begin the count again. The boat should move slowly upstream, as per counter instruction, to be sure all active burrows are included in the count. Once the count is completed, the counters determine if they are within 10% of each other. Tallies that are significantly off (over 10%) are not documented, and the tally counters are zeroed and colony is recounted. Once a satisfactory tally is made, both tallies are entered into the database or field notes by the mapping specialist.

For inactive colonies: Burrow counts are done in the same manner as with active colonies. That is, only “active” burrows are counted. The only exception is that there is not a requirement for counts of the two observers to be within 10%. This requirement was removed to save time during the surveys.

Beginning in 2013 an estimate of the number of bank swallows observed at each colony is recorded. This includes all visible BANS either foraging or perched near the colony site. This estimate is recorded in the “number of birds” field and can be used as a general “activity index” for each colony.

Mapping

Each colony should be mapped from the downstream to upstream end by the mapping specialist. The lead counter determines the beginning and end of each colony, instructing the mapping specialist where to start and end each colony. Mapping should be performed using either the mobile GIS or mapping-grade GPS method. If it is not possible to use these methods then a recreational-grade GPS unit may be used with paper datasheets, although this method yields less accurate locational data and has other disadvantages. Each method is described below. Data collection (see Data Collection Section, below) is performed concurrently as the counters are tallying burrows and colony boundaries are being mapped.

Mobile GIS

Equipment includes a laptop computer with sufficient battery power to last the entire field day, ArcGIS (or equivalent) software, and a GPS unit that can be connected to and communicate with laptop and software. The GIS project should include the latest high resolution aerial photography of the study area in georeferenced raster format, river mile markers in vector format, current State and Federal ownership in vector format, and previous BANS survey records in vector format. Each colony should be mapped by heads up digitizing the colony from recent aerial photos on a laptop computer running ArcGIS (or equivalent software), using the GPS to locate the position of the boat.

The advantages of using this method include higher accuracy, digital data collection, creation of the GIS file in the field, and easy access to previous BANS data and other GIS features which increases flexibility. The disadvantages of this method are that required hardware and software can be expensive and bulky in the field and requires the mapping specialist have a working knowledge of the hardware and GIS software.

Mapping-Grade GPS

Equipment includes a mapping-grade GPS (such as a Trimble GeoExplorer or equivalent) with sufficient battery power to last the entire field day and a paper map or atlas of aerial photography and river miles. Mapping-grade GPS units provide two major advantages over recreational grade GPS units for BANS surveys: GPS data can be post processed using differential correction to improve accuracy and data dictionaries can be both preloaded in the unit and exported directly into GIS files. The mapping-grade GPS should be preloaded with a data dictionary which includes the data types described in this document and vector files of river miles, recent channel alignment, State and Federal ownership, and previous BANS surveys. Each colony should be mapped by acquiring a GPS position at the upstream and downstream end points of the colony as close to the bank as possible.

In the office, the GPS points are differentially corrected and exported into a GIS point file. Using recent high resolution rectified aerial photography or accurate channel lines as base maps, the colony lines are developed in the GIS between the endpoints using heads up digitizing or spatial joins. The data collected in the GPS form are then attributed to the newly created colony lines.

The advantages of using this method include high accuracy, portable and easy to use hardware, digital data collection, creation of a GPS file that can be exported to GIS in the office, and some access to previous BANS data and other GIS features. The Trimble GPS interface is more intuitive to most users than GIS software. The disadvantages of this method are that required hardware and software can be expensive, data requires more manipulation in post processing, lower ability to leverage other digital data in the field, and requires the mapping specialist have a working knowledge of the GPS unit.

Recreation-Grade GPS

Equipment includes a recreation-grade GPS unit (Garmin, Magellan, Delorme or equivalent) with sufficient battery power to last the entire field day, a paper map or atlas of aerial photography and river miles, and several paper data sheets. If possible, the recreation-grade GPS should be preloaded with vector files of river miles, recent channel alignment, and previous BANS surveys. Each colony should be mapped by acquiring a GPS position at the upstream and downstream end points of the colony as close to the bank as possible.

In the office, the GPS points are downloaded and exported into a GIS point file. Using recent high resolution rectified aerial photography or accurate channel lines as base maps, the colony lines are developed in the GIS between the endpoints using heads up digitizing or spatial joins. The data collected on the paper form are keyed into the database and then attributed to the newly created colony lines.

The advantages of using this method include portable, easy to use, and inexpensive hardware, GPS waypoints that can be imported to GIS in the office, and some limited access to previous BANS data and other GIS features. The recreation-grade GPS interface is more intuitive to most users than mapping-grade GPS and GIS software. The disadvantages of this method are lower accuracy, data requires more post processing including keying in data from paper form into GIS database, and requires the mapping specialist have a working knowledge of the GPS unit.

Regardless of the method used, data should be processed and QA/QCed as soon as possible after the survey date. A back up method should be available to surveyors in case of hardware or software failure in the field.

Data Collection

In addition to spatial colony location, field data to be recorded in the GIS database (maintained by DWR), GPS form, or paper field data sheets that are used during the survey include the following:

Survey Reach – the "name" of the survey section. The survey is broken down into seven sections: Sac Reach 1 = Sacramento River from Keswick to Red Bluff, Sac Reach 2 = Sacramento River from Red Bluff to Ord Bend, Sac Reach 3 = Sacramento River from Ord Bend to Colusa, Sac Reach 4 = Sacramento River from Colusa to Verona, Feather Reach 1 = Feather River from RM 59 to 38.5, Feather Reach 2 = Feather River from RM 38.5 to 24.5, and Feather Reach 3 = Feather River from

RM

24.5 to 0 (the mouth at Verona).

Approximate River Mile--this is recorded for the center of the colony, rounded to the nearest tenth and can be determined from the GIS or paper maps. River miles are general locations that are taken from the 1991 United States Army Corp of Engineers Aerial Atlas.

Colony Number – this is similar to, and based upon, the Approximate River Mile, but is basically a “name” for the colony that is consistently used from year to year, even if the Approximate River Mile differs slightly based upon the interpretation of the surveyors. This field will allow quick reference with colonies mapped in the past and is considered the unique colony identifier. These data are improved in the office, post- survey.

Active Colony- Yes or no. Whether or not BANS were witnessed by surveyors flying in or out of burrows in the colony while surveying the colony.

River Bank- Left or Right bank. River right is the bank on the right when moving or looking downstream.

Number of BANS – estimate of the number of bank swallows actually observed at the colony (new in 2013). This is an approximation of BANS observed at the colony during survey and may not represent actual number of birds in the colony.

Burrow Estimate 1 – estimate of the number of active burrows observed at the colony, collected by observer #1.

Burrow Estimate 2 – estimate of the number of active burrows observed at the colony, collected by observer #2.

Burrow Average – the average taken from Burrow Estimate 1 and Burrow Estimate 2 at the colony, calculated post-survey

Elevation Above Water- Approximation, to the half meter, of how high above the current waterline the first band of burrows in the colony are on the bank.

Elevation Above Slope Break- Approximation, to the half meter, of how high above the slope break the first band of burrows in the colony are on the bank. On very steep vertical banks, this maybe the same as the elevation above water.

Total Bank Height- Approximation, within a range of 2 meters, of how high the top of bank is above the waterline. Categorized as 0-2m, 2-4m, 4-6m, 6-8m, 8-10m, and >10m.

Vegetation at Bank- riparian forest (>6 meters), riparian shrub scrub (<6 meters), grassland/herbaceous, orchard (tree or herb), disturbed. This is the dominant vegetation directly above the colony at the bank edge.

Vegetation Over Bank- riparian forest (>6 meters), riparian shrub scrub (<6 meters), grassland/herbaceous, orchard (tree or herb), disturbed. This is the dominant vegetation overbank which is viewable from the boat, and is often different than the vegetation at the bank. This should characterize the dominant vegetation beyond the colony, where the river may erode into in the future or where foraging may occur.

Ownership - If the ownership is known, record whether it is private or public, who the landowner or managing agency is. These data can be improved in the office.

Location Name – If colony is located on property owned by a public agency, record the name of the management unit. These data can be improved in the office. Observation Date and Time – these are recorded automatically if using ArcGIS or GPS software.

Flow (Q) and Gauge- The average daily flow can be retrieved from the CDEC website. These data can be added in the office. This is important because Elevation Above Water, Elevation Above Slope Break, and Total Bank Height estimates are based on the waterline (stage) and may need to be adjusted if flows are significantly different during survey periods and years.

Photo Number- Digital photos are an important dataset. Multiple photographs should be taken of each colony. The photo numbers should be recorded for each colony in the database and linked in the GIS.

Notes- Any noteworthy data or observations not recorded in the other data fields should be recorded in the *notes* field.

Data Analysis and Storage

Within two weeks of survey completion, the data collectors will meet for a QA/QC session. Datasets for each survey section will be provided in an .xls or GIS format. Excel data will be transformed into a GIS format. The group will go through each record to check for errors and to verify that fields such as Ownership, Location Name, Colony Number, and Approximate River Mile are accurate and consistent with previous years' datasets. Fields that need to be calculated/filled post-survey, such as Burrow Average, Flow, Gauge, and Survey Reach, will be completed. All data will be merged into a single feature class or shapefile. Metadata will be updated. A "distributable version" of the dataset will be created, which will exclude sensitive data (Ownership, Location Name, Notes) and data that may be misinterpreted by external users (Burrow Estimate 1, Burrow Estimate 2, Number of BANS).

Each survey will have two final products: a GIS spatial data set, and a summary report. A GIS geodatabase or shapefile will be created with complete metadata. The shapefile will include a series of lines that represent each colony mapped. All the data described above is easily incorporated in the GIS database, which is spatially linked to each colony as part of the GIS shapefile or geodatabase. Photos should be included and distributed with the GIS file and may be hyperlinked to each colony in the database. Using the data generated from the GIS, a summary report will be created that puts the current survey in the context of population trends. The summary report is completed and distributed by appropriate CDFW staff.

A copy of the final full GIS dataset, a set of maps in PDF format, and a summary report will be stored with the California Department of Water Resources Northern Region Office, the U.S.

Fish and Wildlife Service at the Sacramento National Wildlife Refuge Complex, and on the Bank Swallow Portal (accessible only to members of the Bank Swallow Technical Advisory Committee) at http://www.sacramentoriver.org/bans. A copy of the "distributable format" GIS dataset will be provided to the California Department of Fish and Wildlife's California Natural Diversity Database (CNDDB) and to their Biogeographic Information & Observation System (BIOS).

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Attachment A-1. Annual Schedule of Bank Swallow Survey Coordination

Task 1. USFWS Lead will select survey date and send out Draft Survey Coordination Spreadsheet – see Attachment A.

- Who: USFWS Lead is Joe Silveira (current as of 2016)
- Due Date: End of February
- Subtask 1. Leads review and update table with information
    - Due Date: End of March

- Subtask 2. USFWS Lead will finalize draft
  - Due Date: End of April

Task 2. Pre-survey Coordination

Conference Call or in person meeting to formalize survey schedule Due Date: End of May

- Subtask 1. Final Logistics Plan by June 1

Task 3. Complete surveys following BANS-TAC Survey Methods

Task 4. Post survey QA/QC Meeting

- Who: Leads and GIS staff
- Due Date: within 2 weeks of survey completion
- Subtasks
  - Adjust River Miles as needed
  - Fill in property ownership in database
  - Correct any data entry/transcription errors
  - DFW Lead for Reach 4 – provide data to QA/QC group to digitize lines and incorporate data into database
  - Update Metadata
  - Create a distributable version of the database
    - Remove Property Ownership
    - Only include burrow average (not both counter totals)

Task 5. Distribute and Archive Annual Survey Data

- Who: Survey Leads and/or GIS staff
- Due Date: Beginning of August
- Subtasks
  - Produce a standardized summary table and map of data

        - Distribute/share data with the BANS-TAC
        - Upload data to the BANS Portal
        - Send data to CNDDB and BIOS
        - Provide CDFW Lead (currently David Wright) with summary

Attachment A-2. Pre-survey Checklist

- Verify qualifications of boat pilot and survey crew
- Verify condition of boat and safety equipment meets standards
- Arrange for boat shuttle
- File float plan
- Equipment:
    - Three tally counters (one for each surveyor, and one spare)
    - Binoculars
    - Digital camera
    - Notebooks
    - Maps (recent aerial imagery with previous surveys overlaid is best)
        - Make sure digital versions are loaded onto laptop
        - Bring paper copies as backup in case of software malfunction
    - Two GPS units
    - Batteries
    - Digital data collection device. Acceptable devices include:
        - Laptop running ArcGIS software
        - Mapping-grade GPS unit configured with data dictionary to accept necessary fields (i.e. Trimble GeoExplorer)

    - Approved personal floatation devices for each boat occupant
- Cell phone in waterproof case

- Give pre-float safety talk

Appendix B. MaxEnt Input Model Input Development

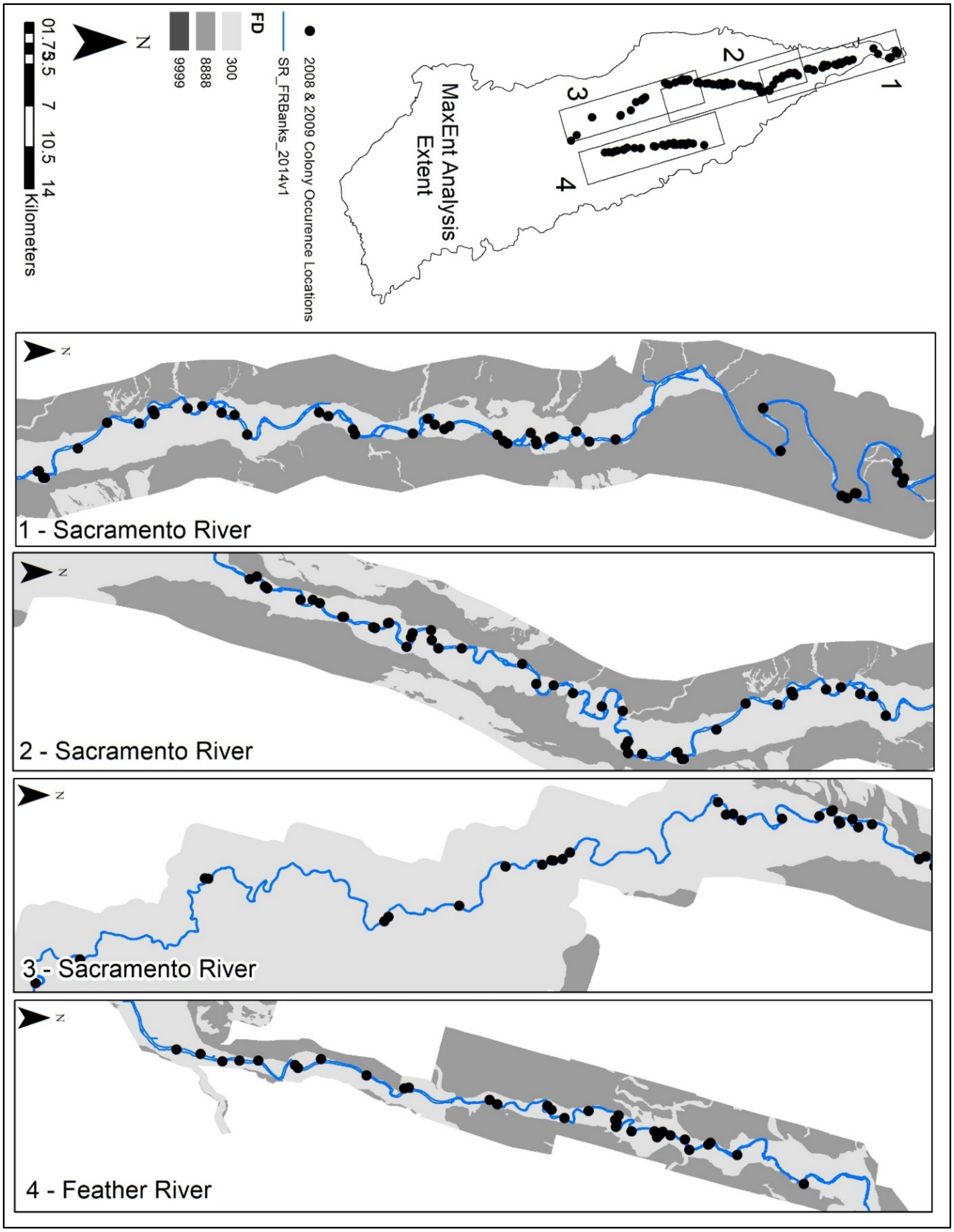


Figure B-1. Bank Swallow Occurrence Locations

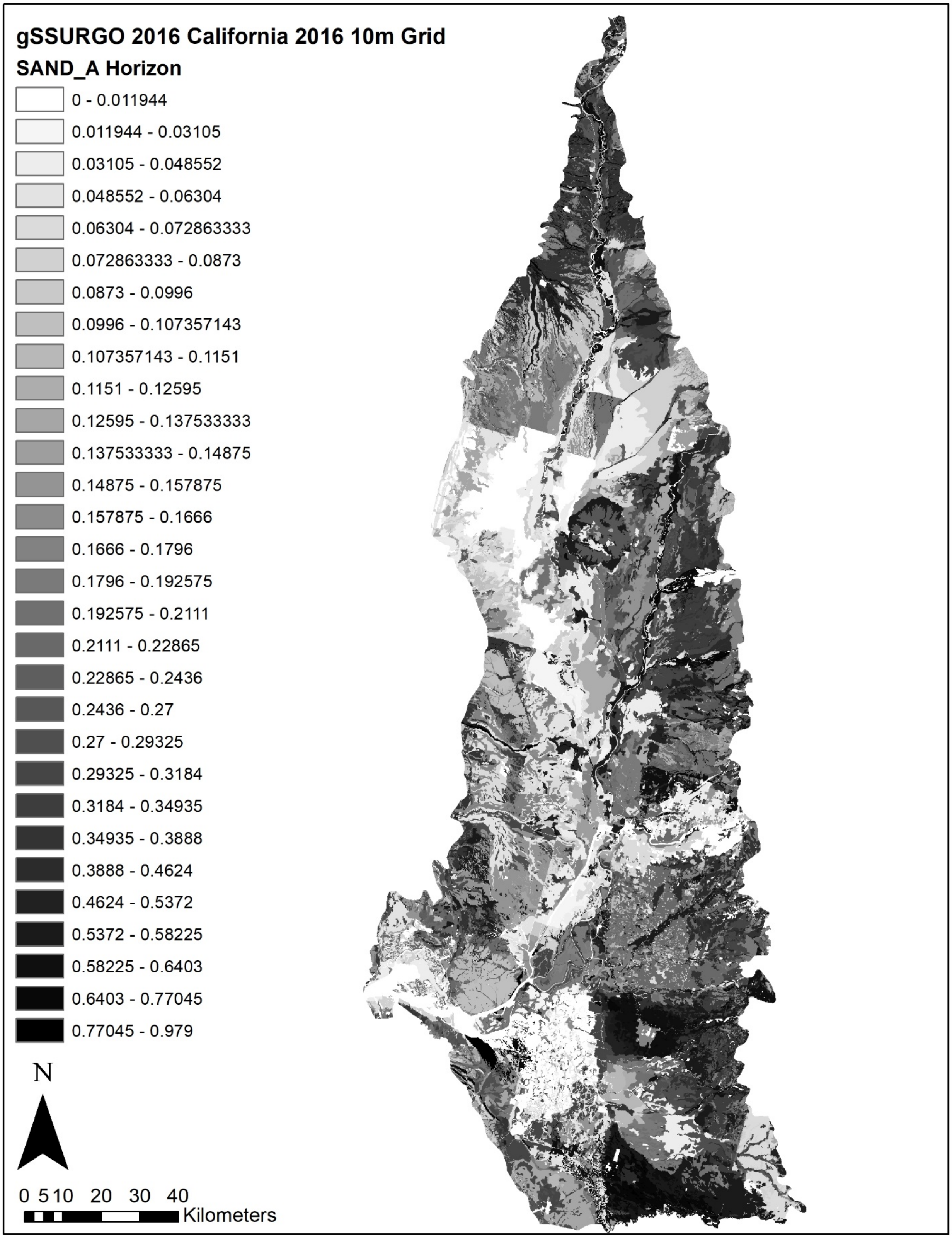


Figure B-2. Map of percent sand in soil horizon A used in MaxEnt analysis

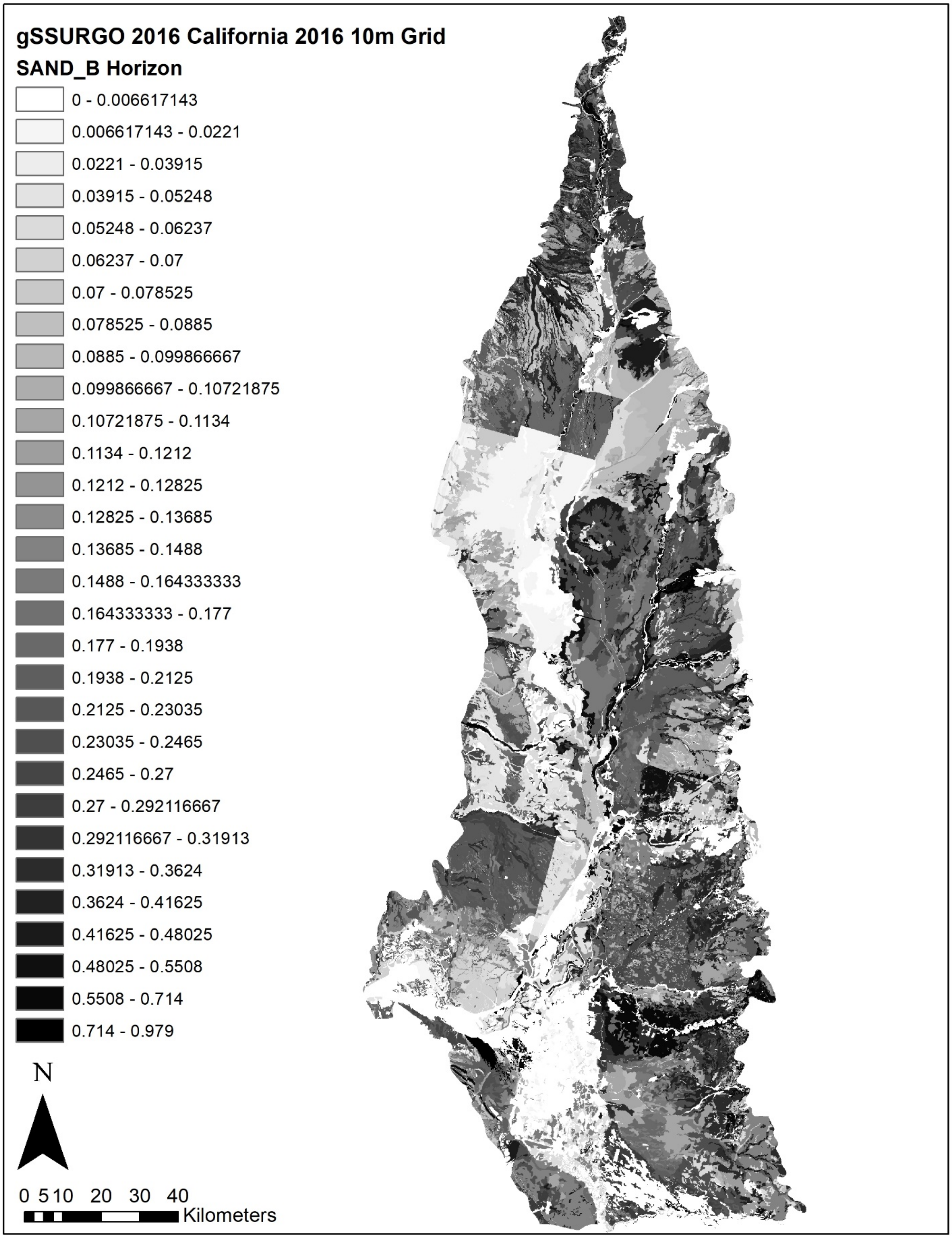


Figure B-3. Map of percent sand in soil horizon B used in MaxEnt analysis

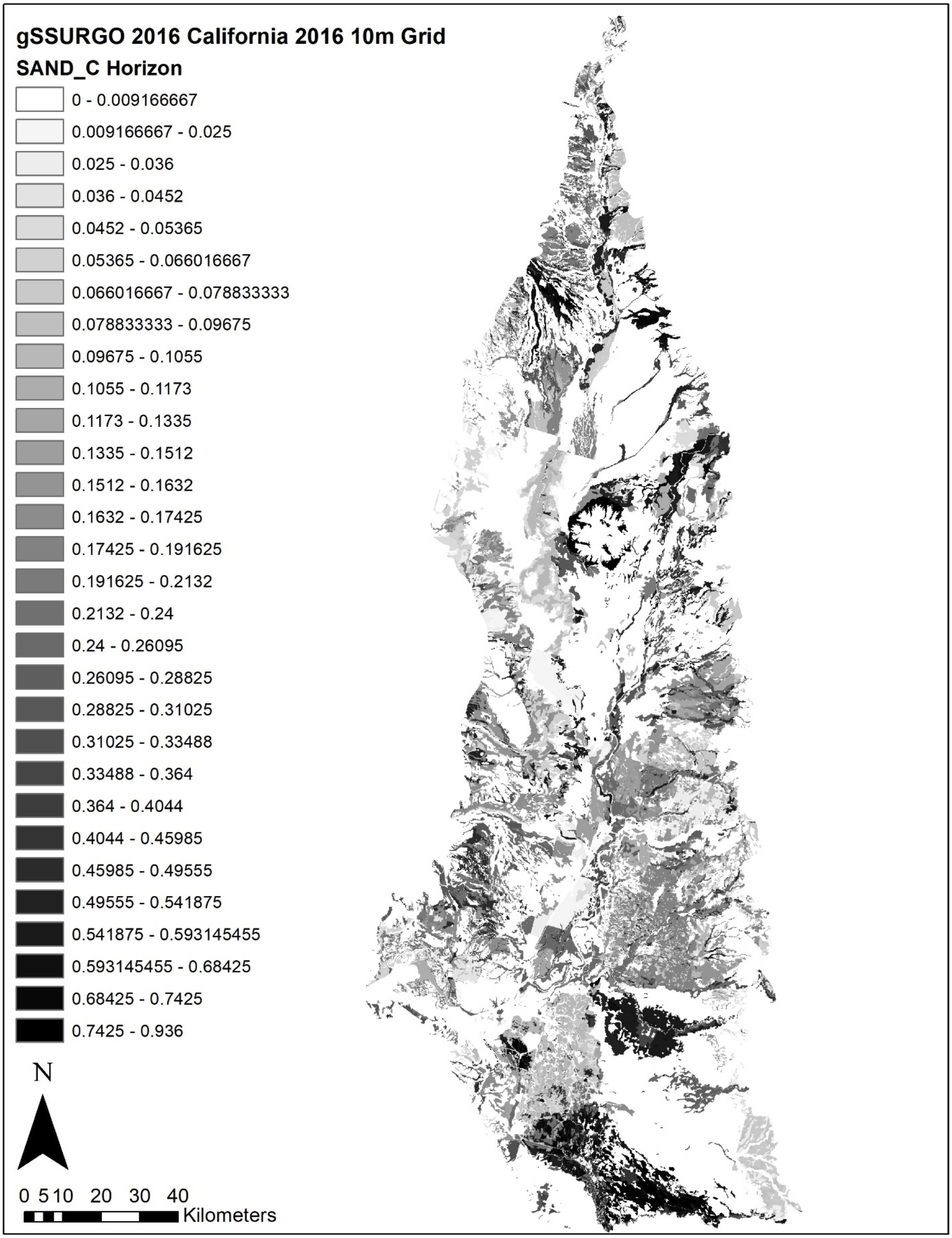


Figure B-4. Map of percent sand in soil horizon C used in MaxEnt analysis

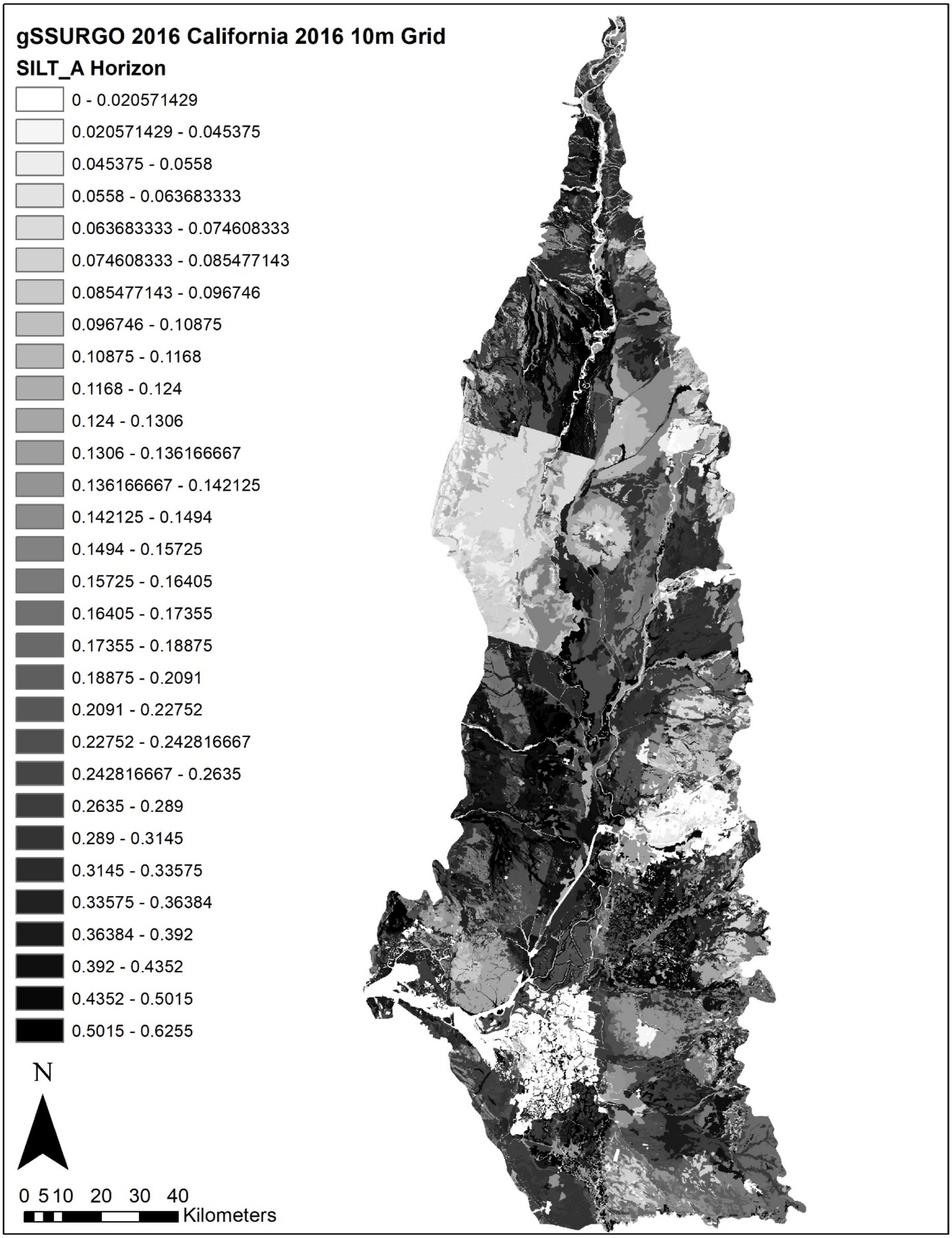


Figure B-5. Map of percent silt in soil horizon A used in MaxEnt analysis

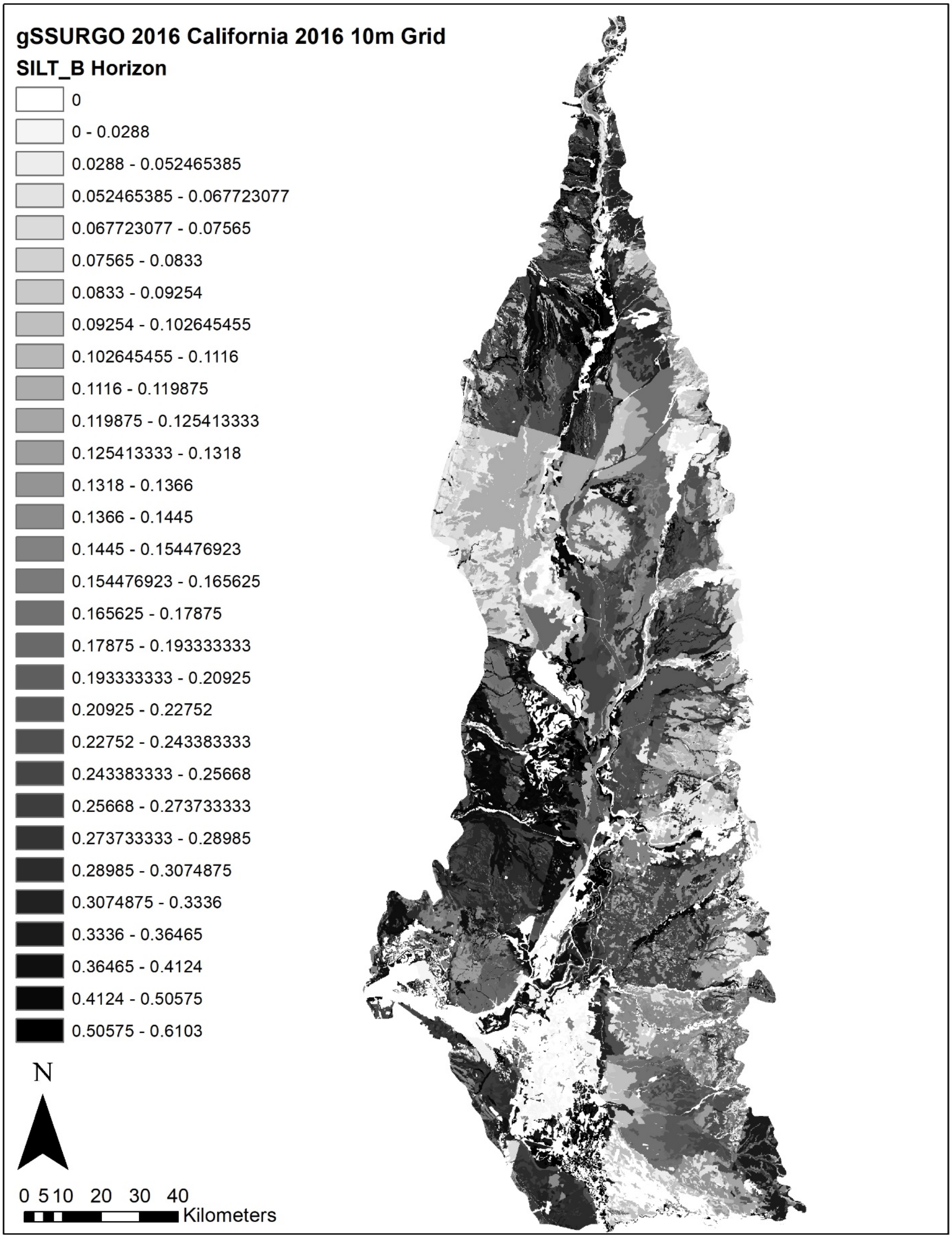


Figure B-6. Map of percent silt in soil horizon B used in MaxEnt analysis

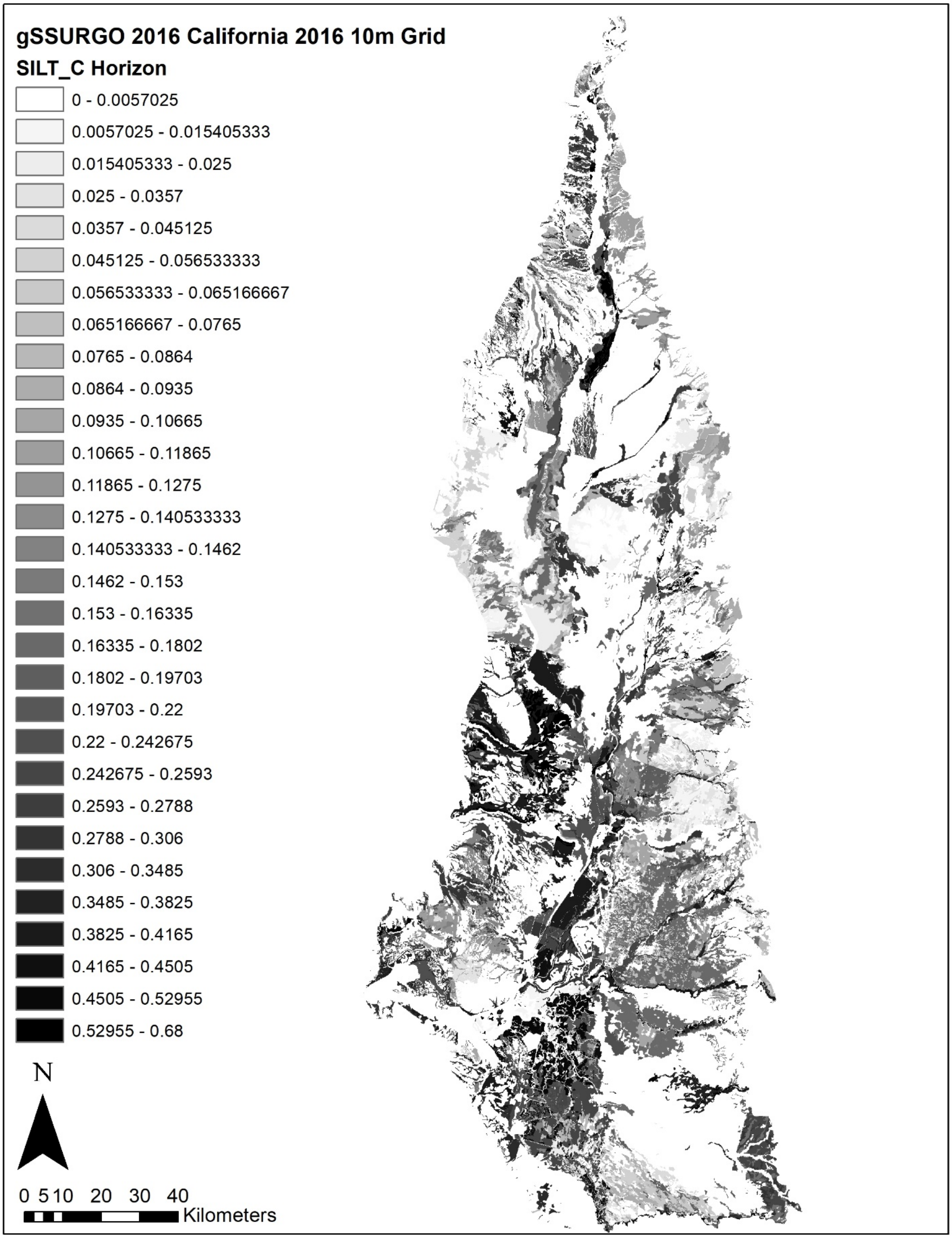


Figure B-7. Map of percent silt in soil horizon C used in MaxEnt analysis

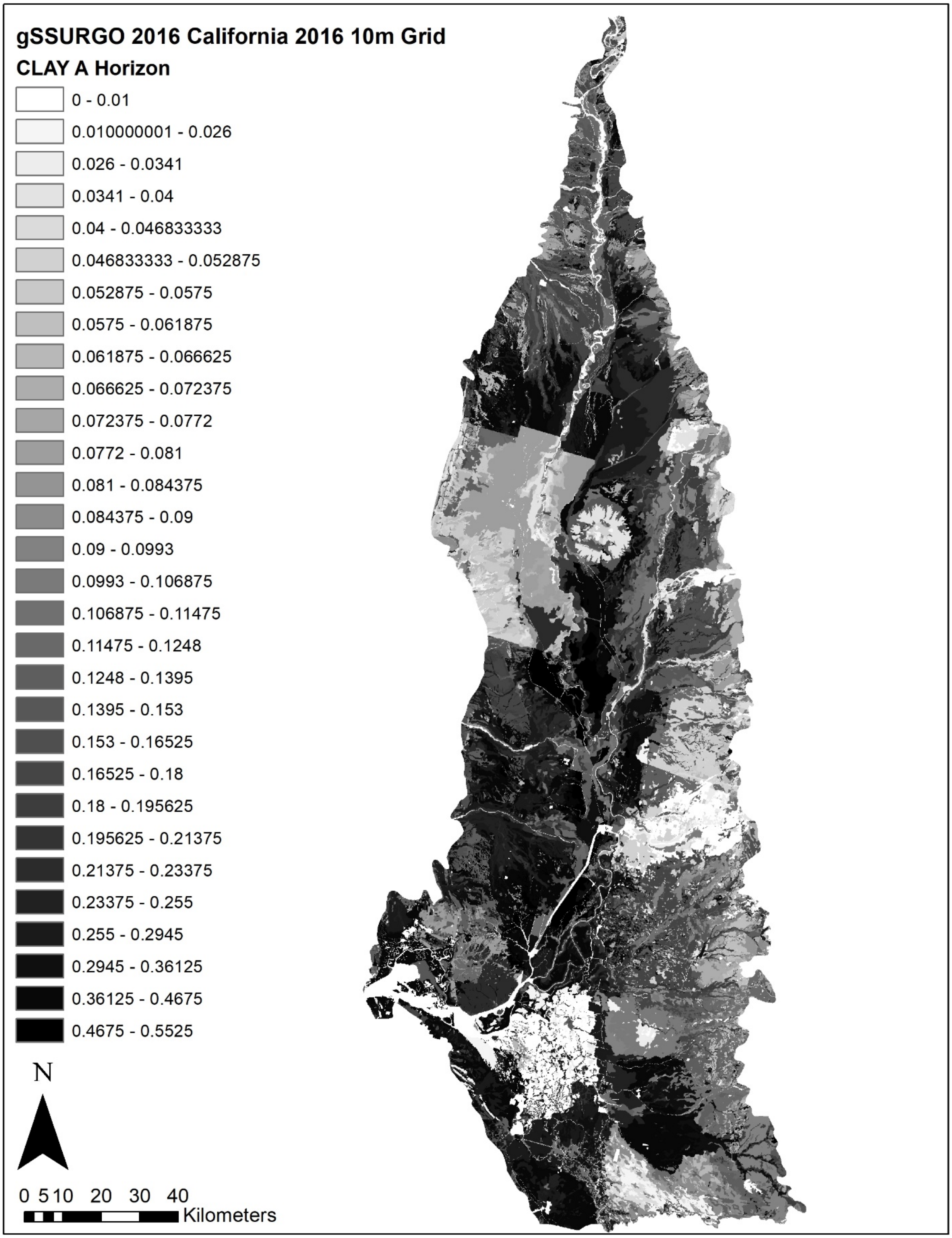


Figure B-8. Map of percent clay in soil horizon A used in MaxEnt analysis

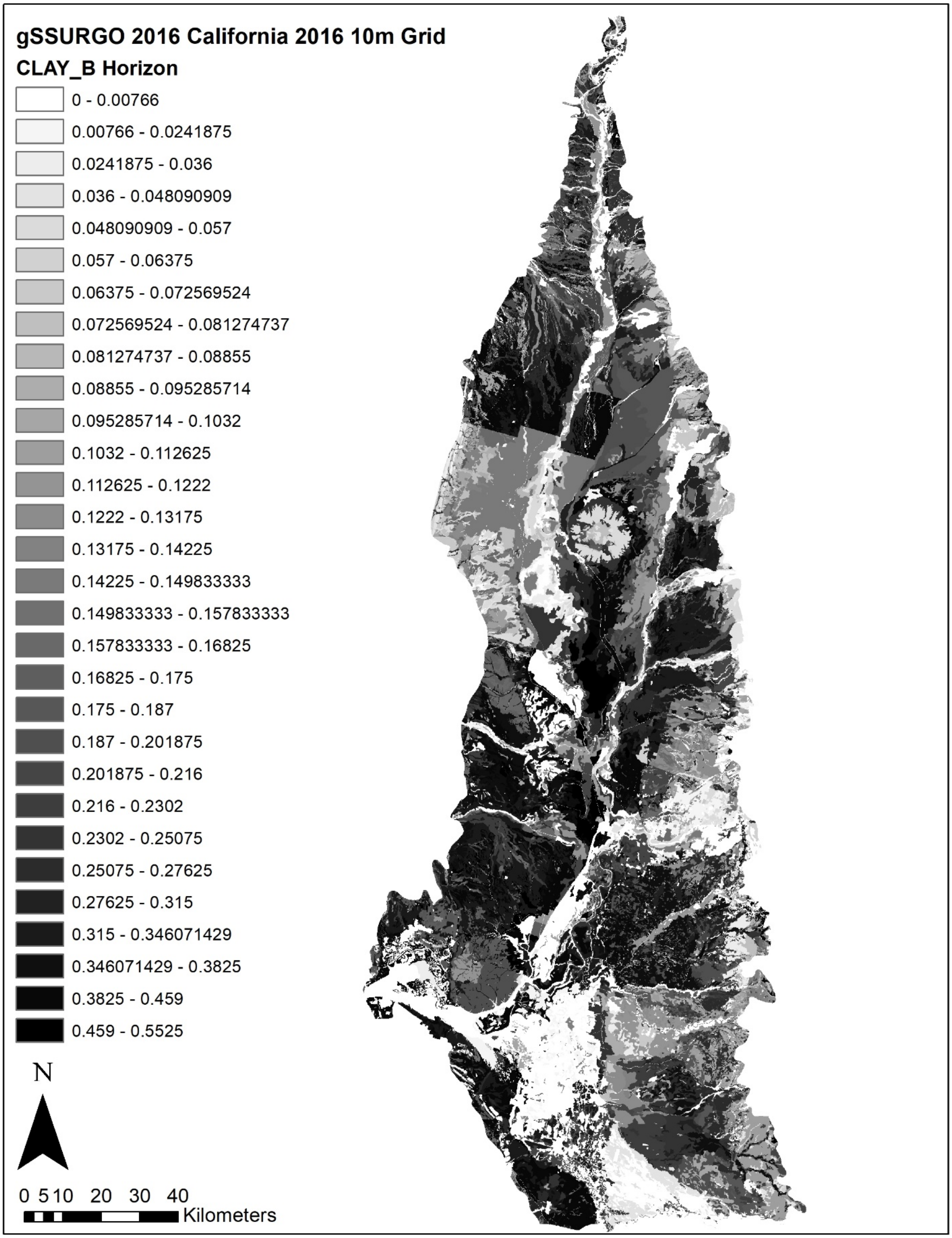


Figure B-9. Map of percent clay in soil horizon B used in MaxEnt analysis

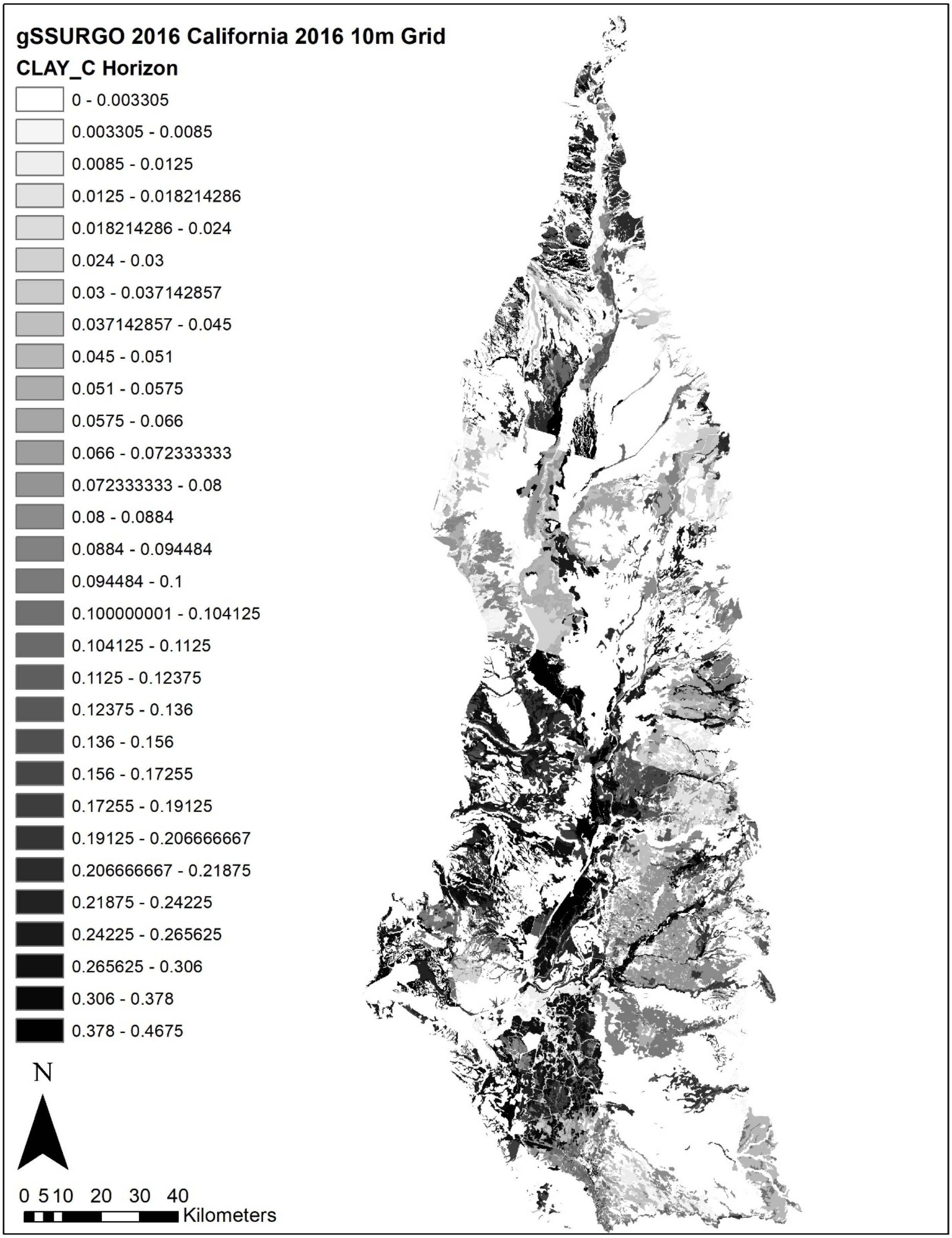
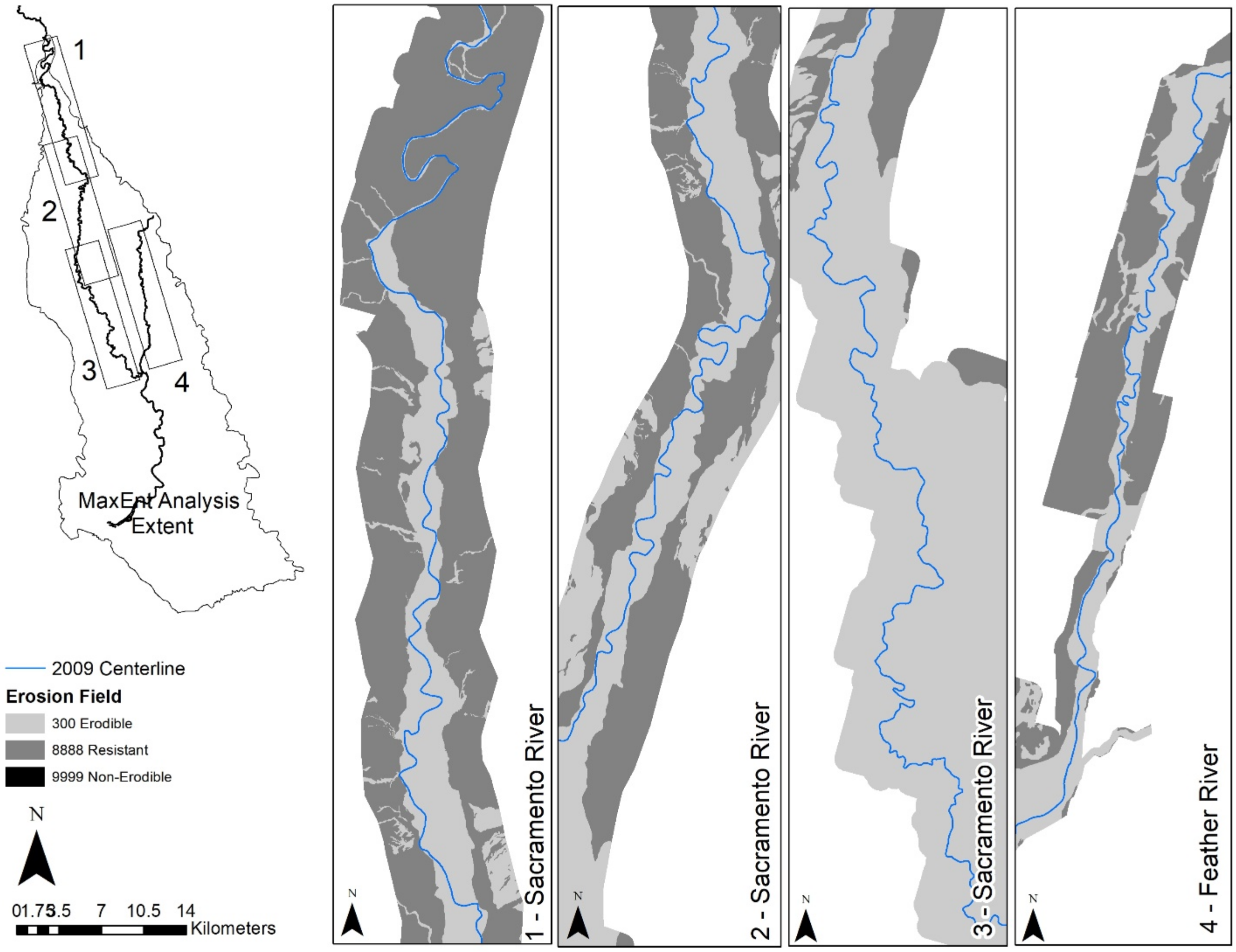


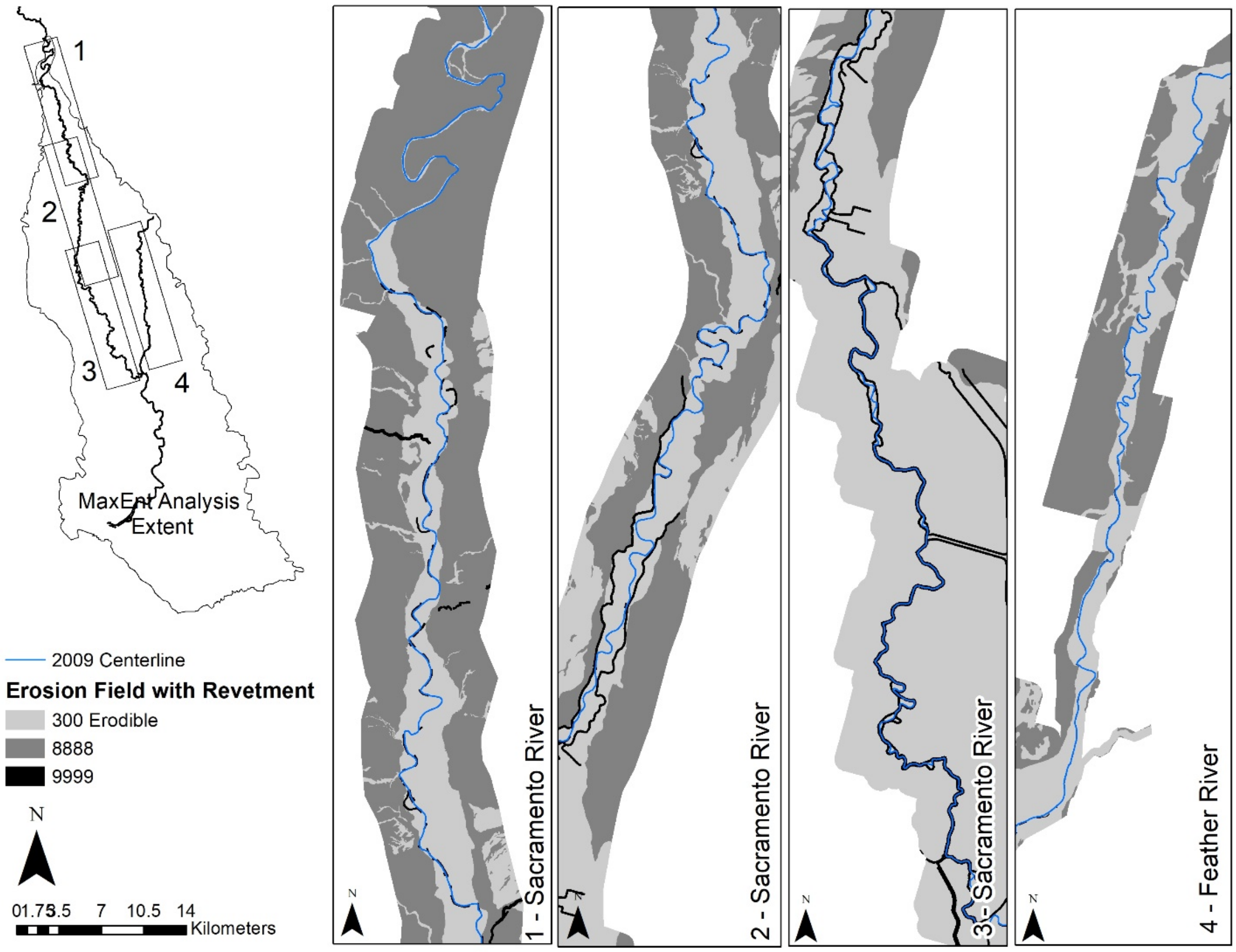
Figure B-10. Map of percent clay in soil horizon C used in MaxEnt analysis

Appendix C. IRIC Inputs: Erosion Fields and Centerlines

Appendix C-1. IRIC Input: Erosion field and centerline – EO no Revetment.



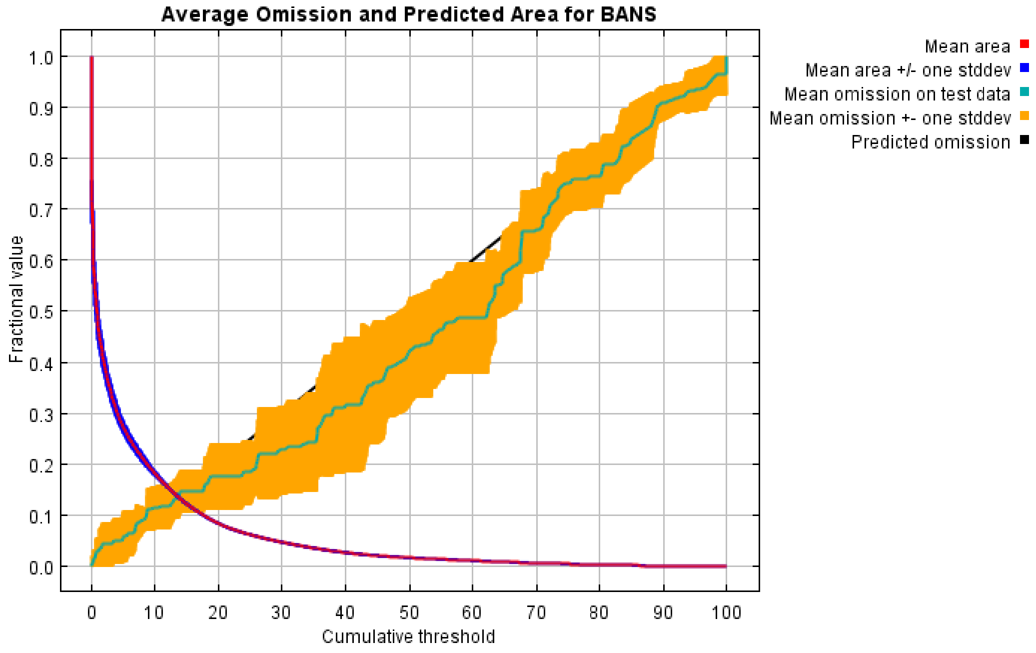
Appendix C-2. IRIC Input: Erosion field and centerline – EO with Revetment



Appendix D. MaxEnt 5-fold Cross Validation Model Fit and Accuracy Diagnostics

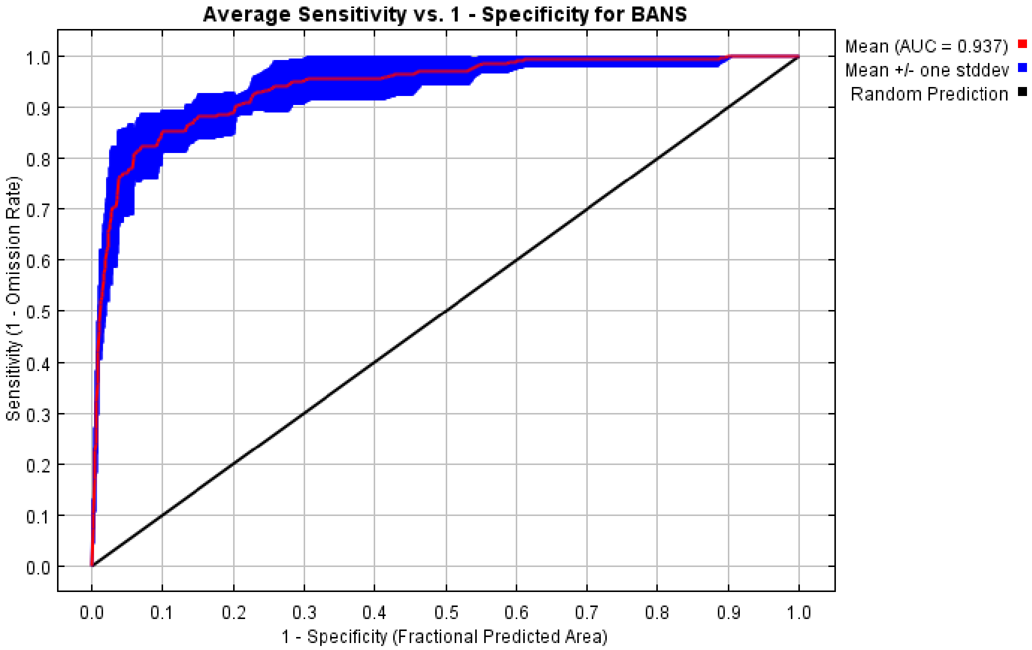
Appendix D-1. Analysis of omission/commission

The following figure is the test omission rate and predicted area as a function of the cumulative threshold, averaged over the modeled runs.



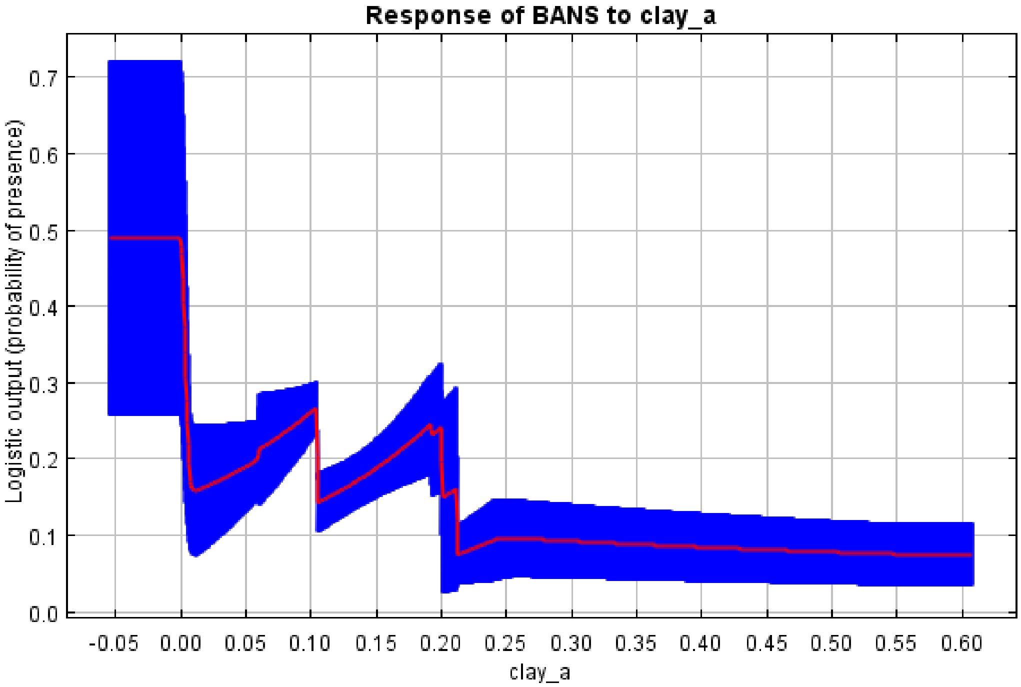
Appendix D-2. Receiver Operating Characteristic (ROC) Curve

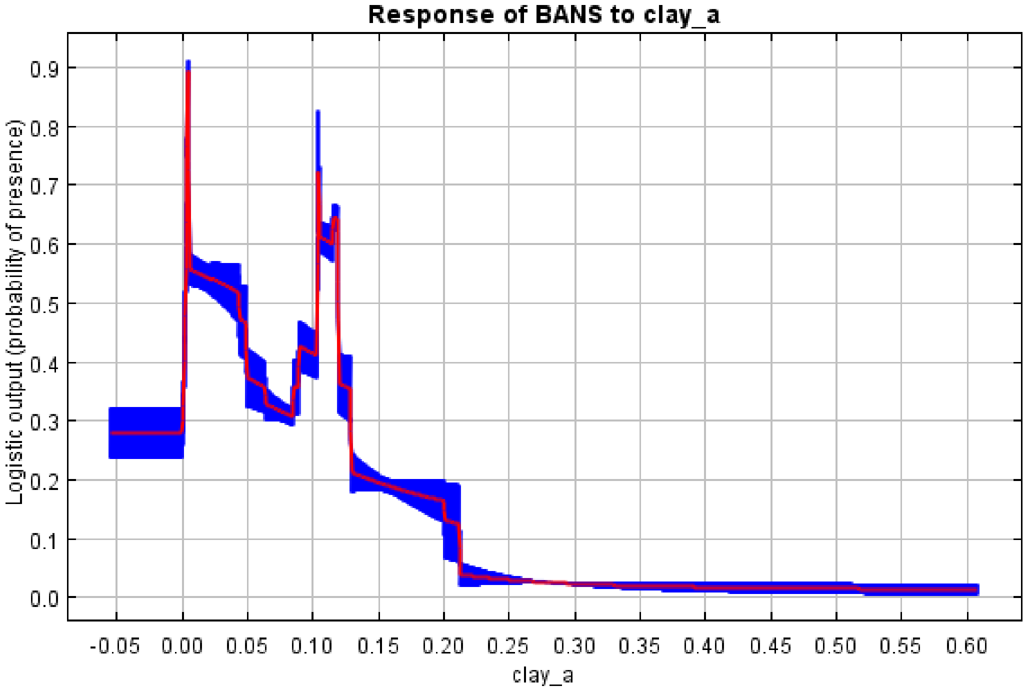
The mean test Area Under the Curve (AUC) for the model runs is 0.937 with a standard deviation of 0.015.

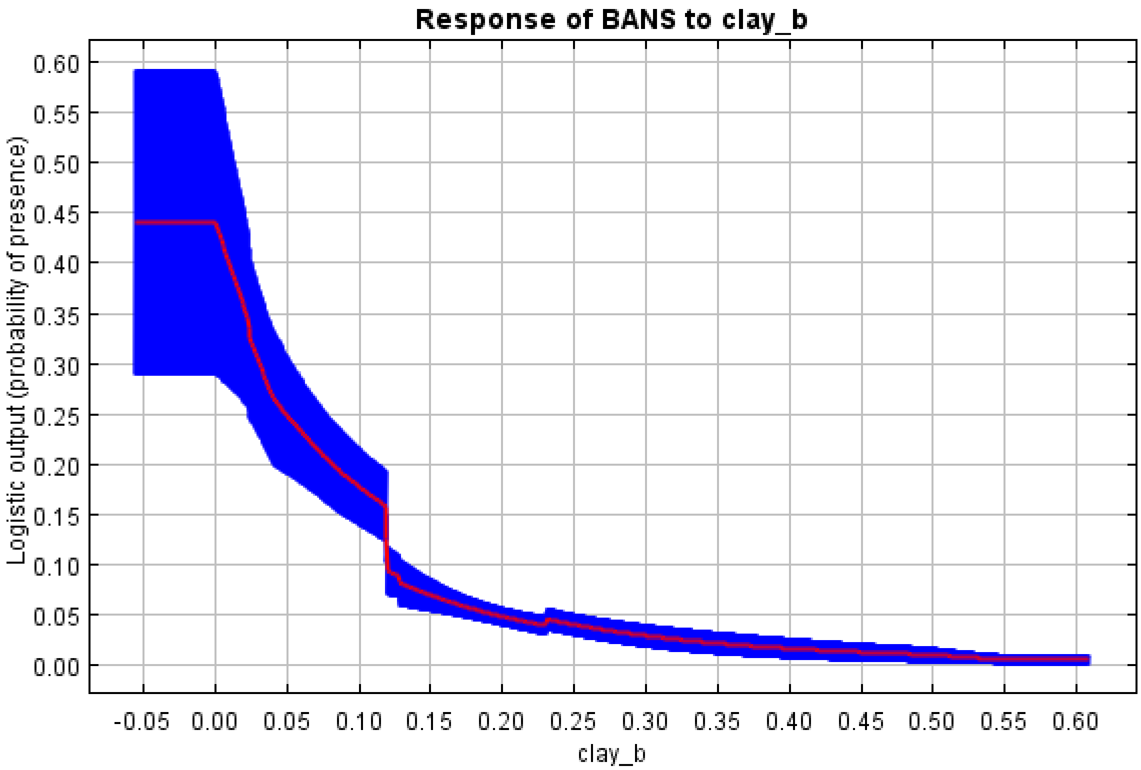


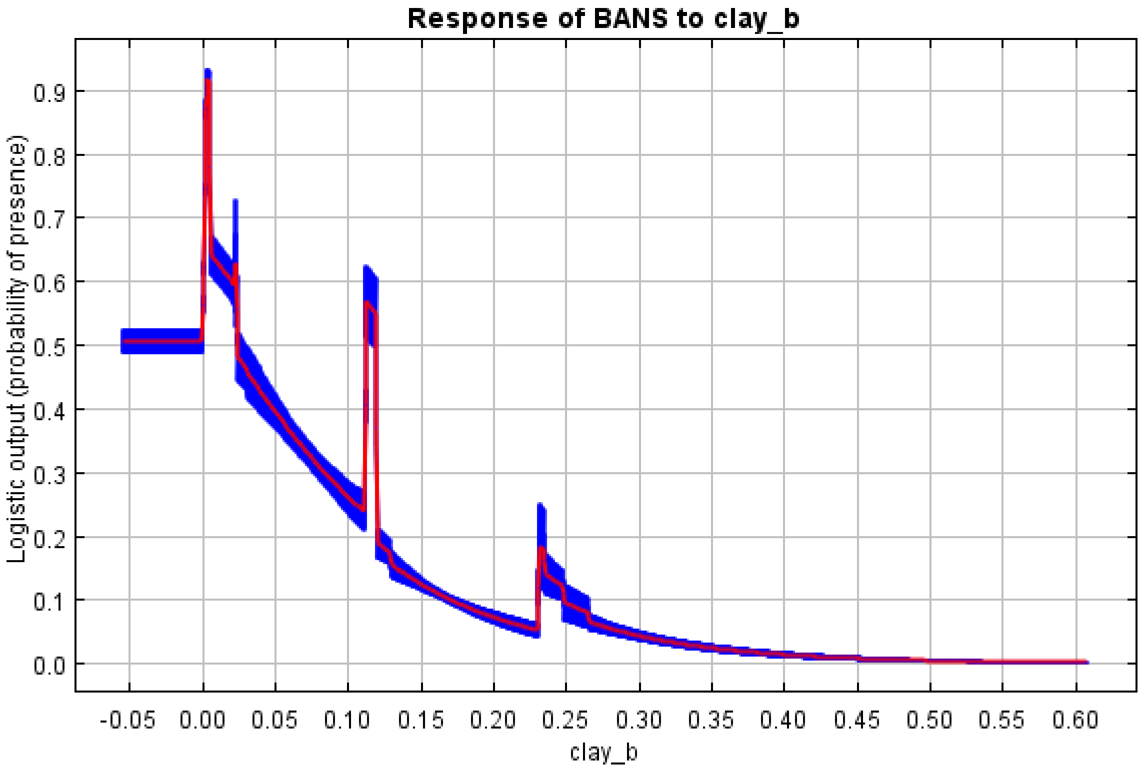
Appendix D-3. MaxEnt Variable Response Curves

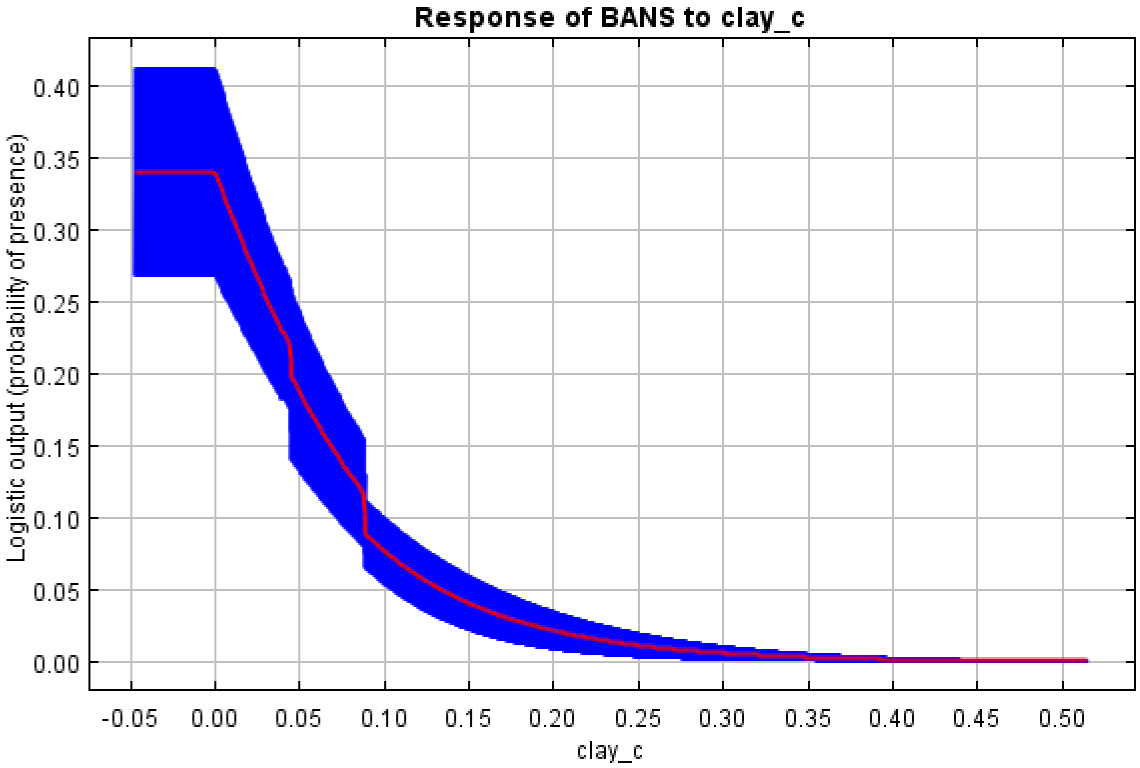
Curves represent how the logistic prediction varies as each predictor variable changes, while all other covariates are held constant.

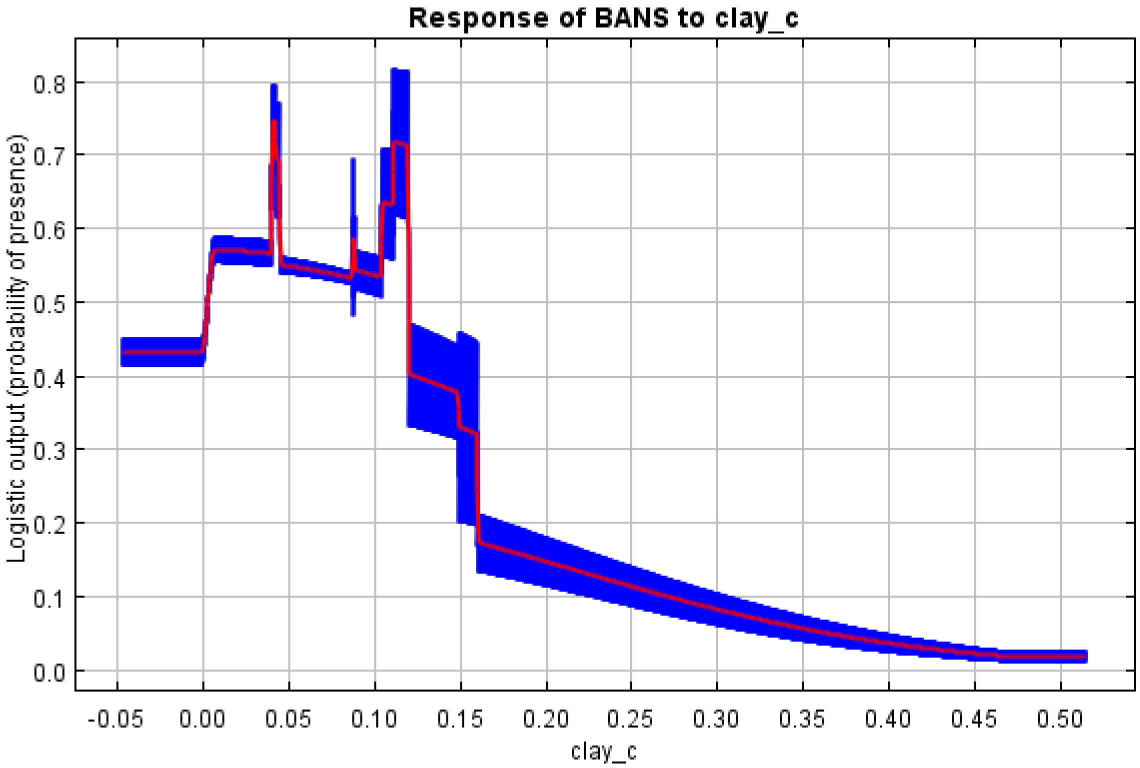


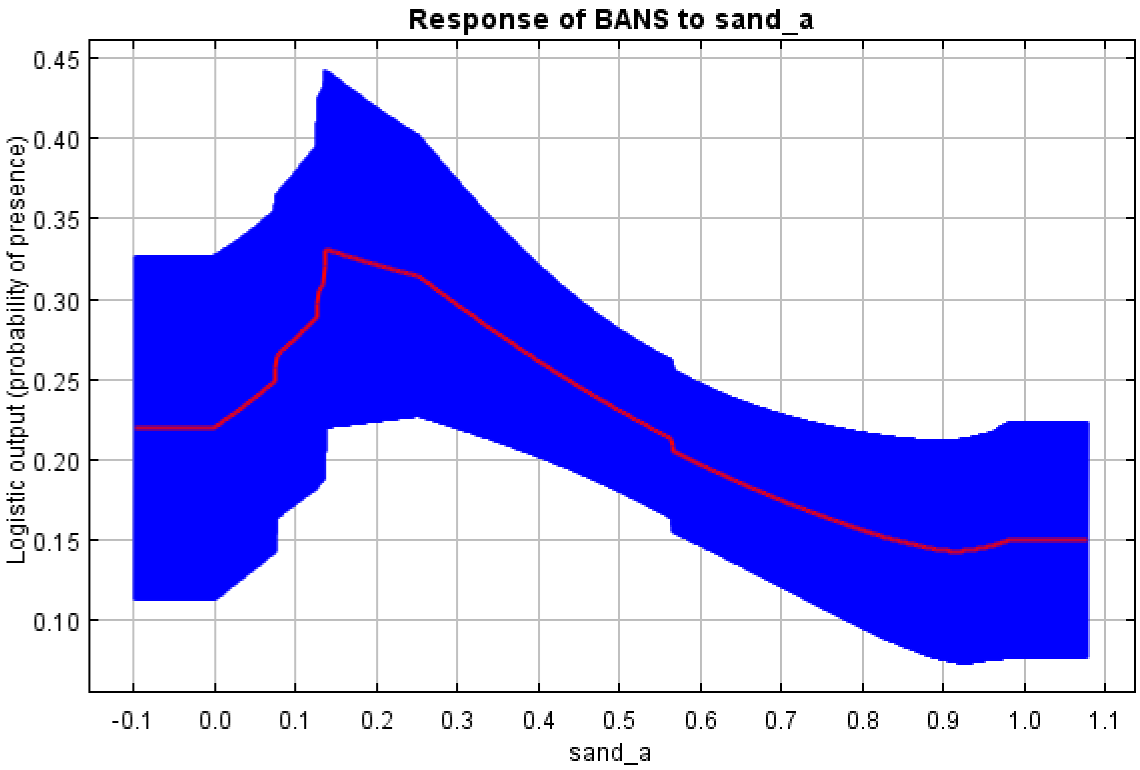


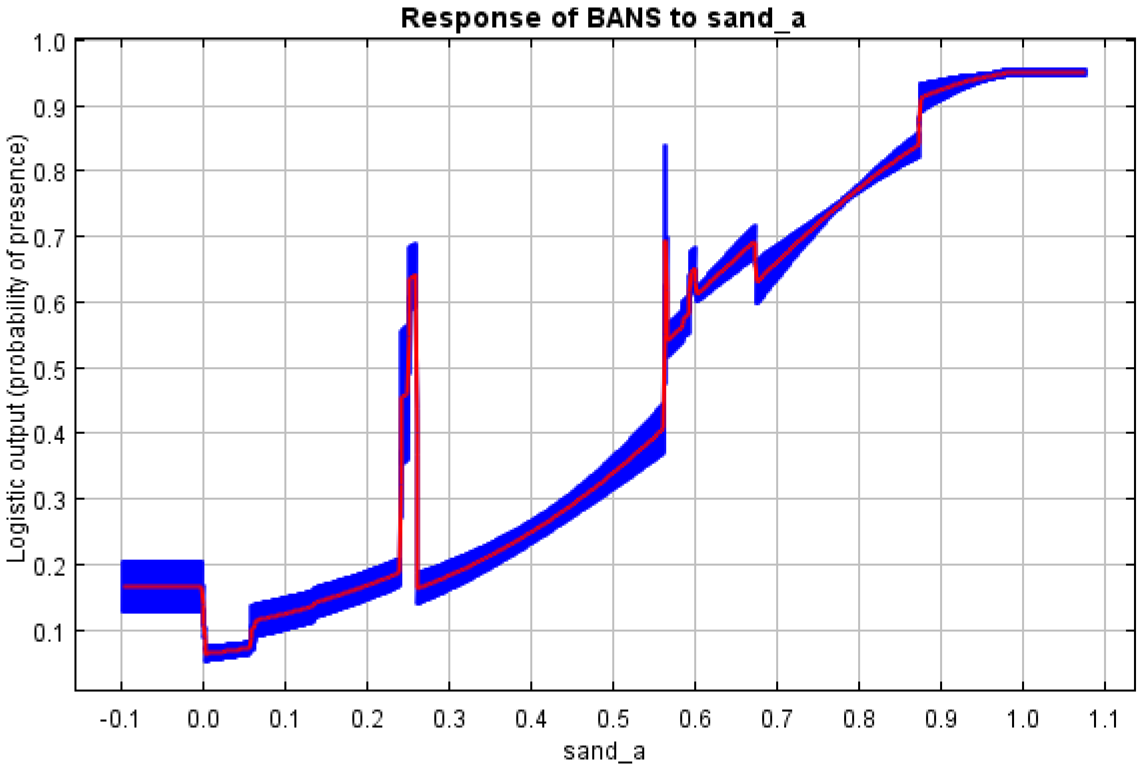

Response of BANS to clay_b
Logistic output (probability of presence)
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
clay_b

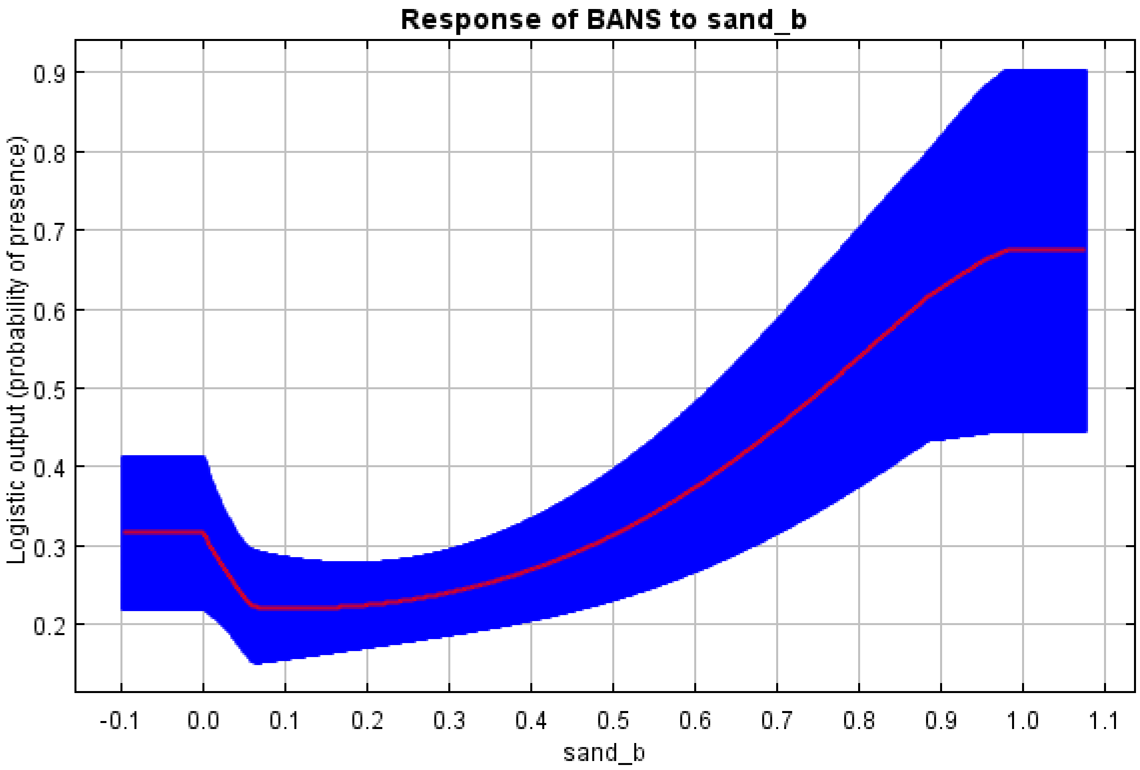

Response of BANS to clay_b
Logistic output (probability of presence)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
clay_b

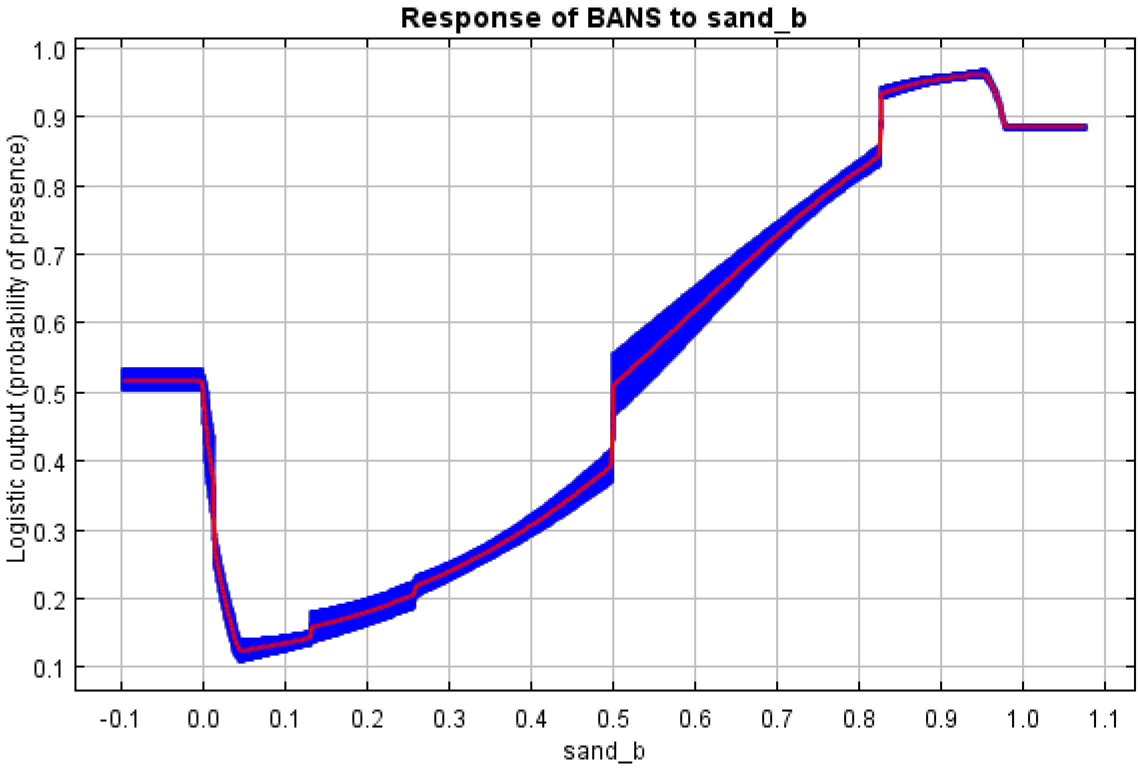

Response of BANS to clay_c
Logistic output (probability of presence)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
clay_c

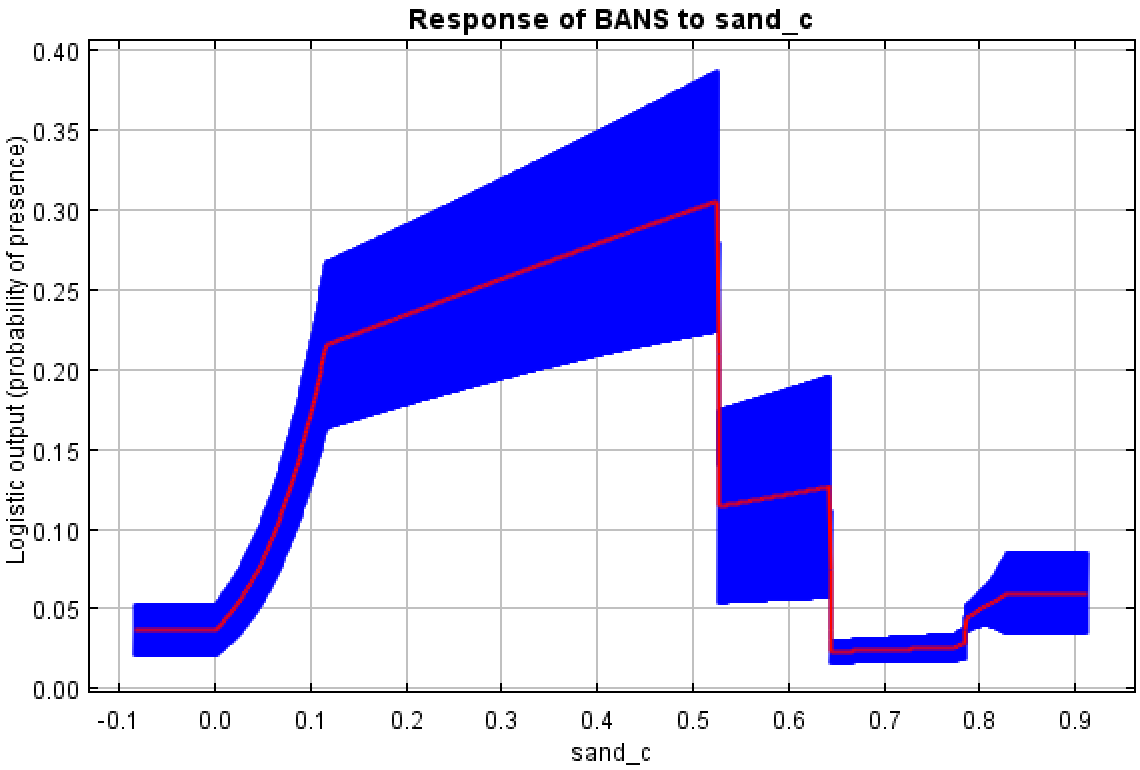

Response of BANS to clay_c
Logistic output (probability of presence)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
clay_c


Response of BANS to sand_a
Logistic output (probability of presence)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
sand_a

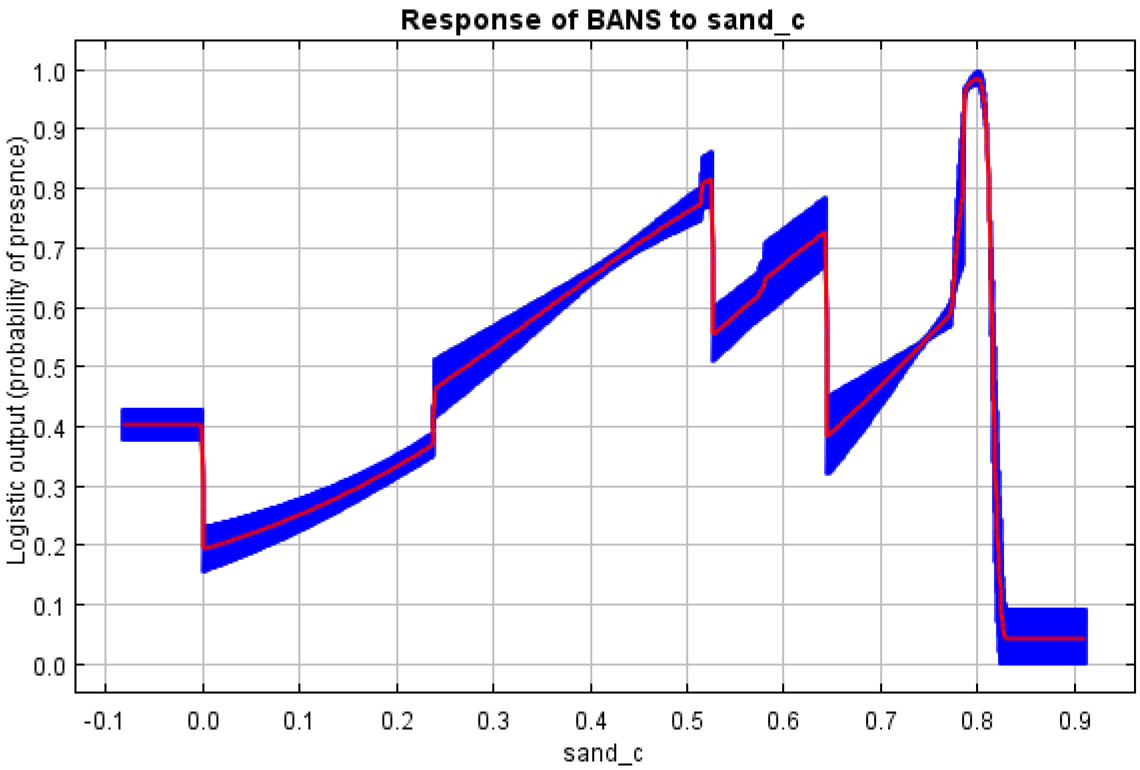

Response of BANS to sand_a
Logistic output (probability of presence)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
sand_a


Response of BANS to sand_b
Logistic output (probability of presence)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
sand_b

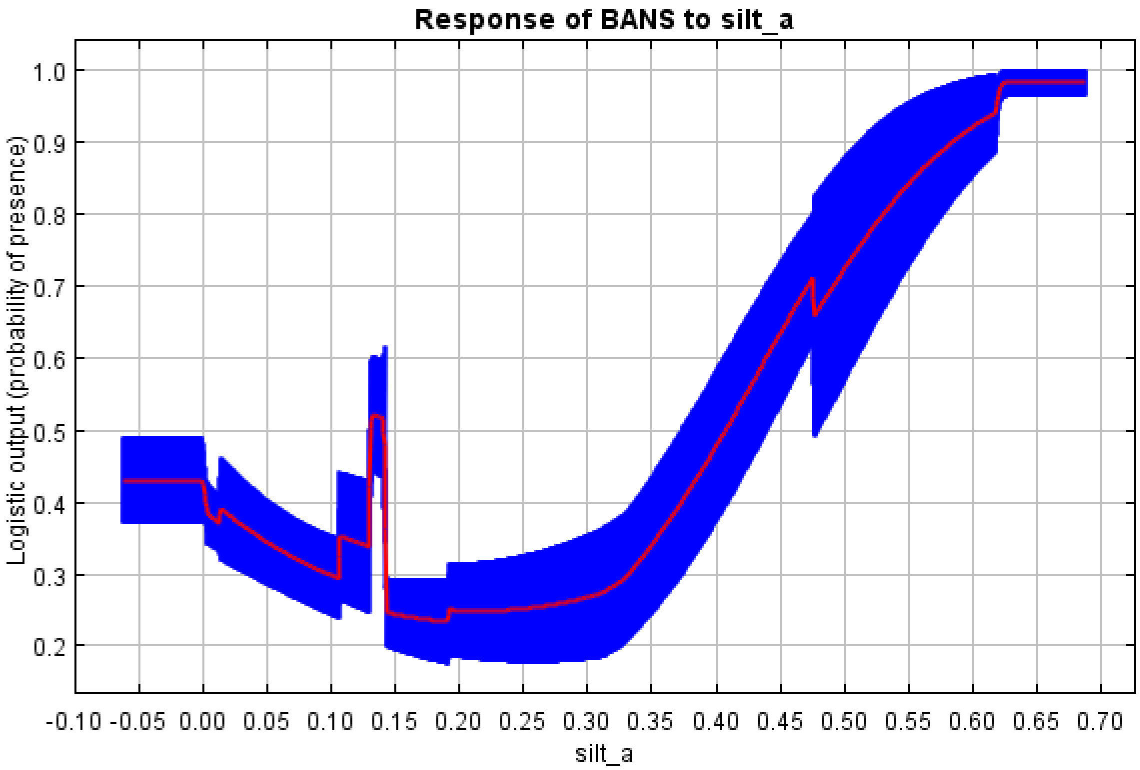

Response of BANS to sand_b
Logistic output (probability of presence)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
sand_b

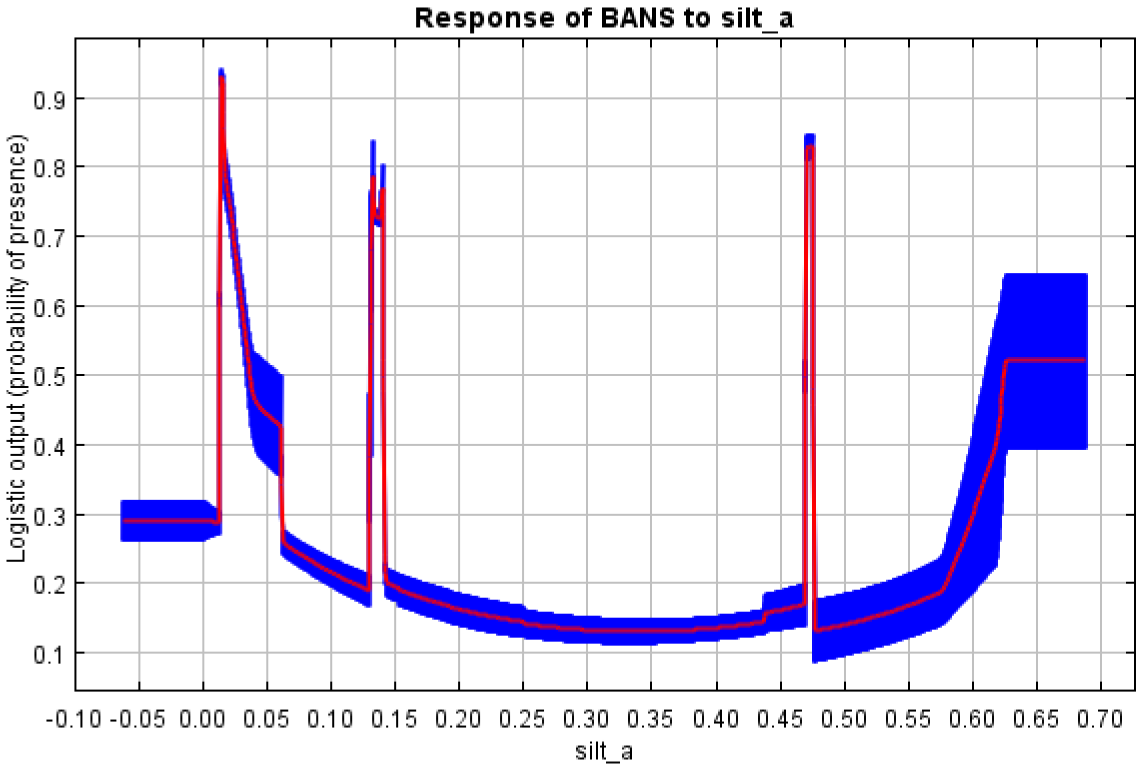


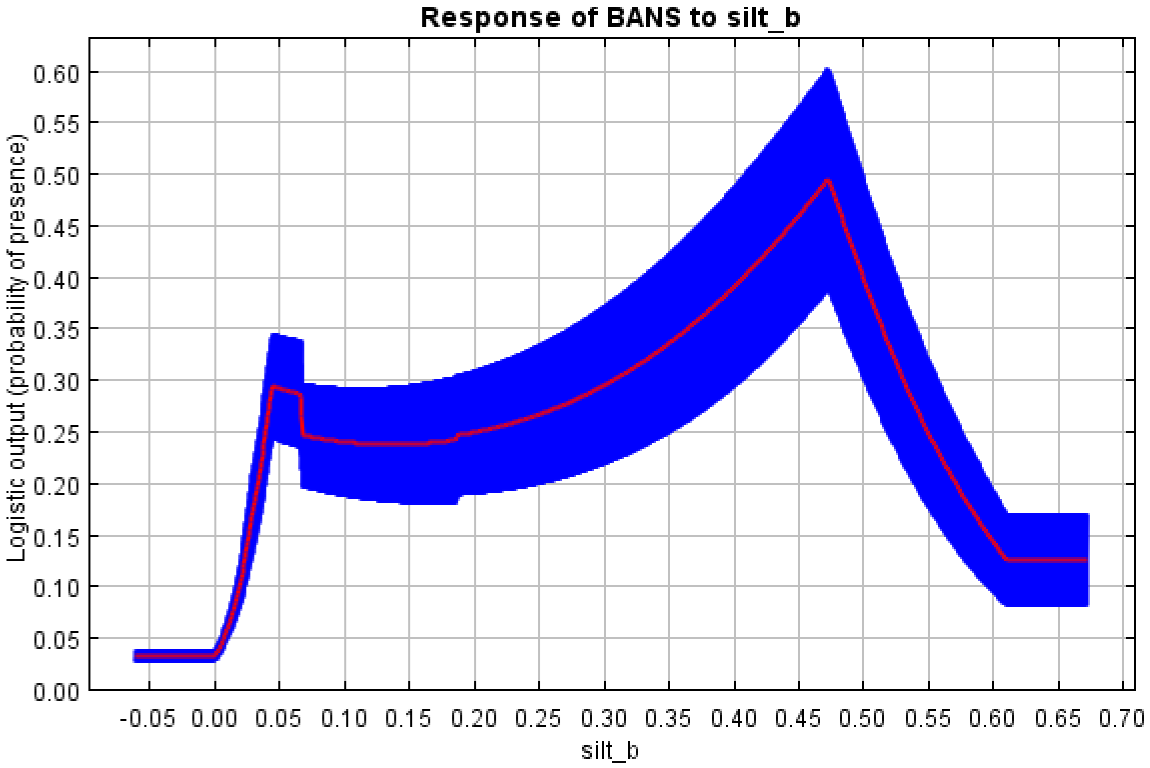
Response of BANS to sand_c



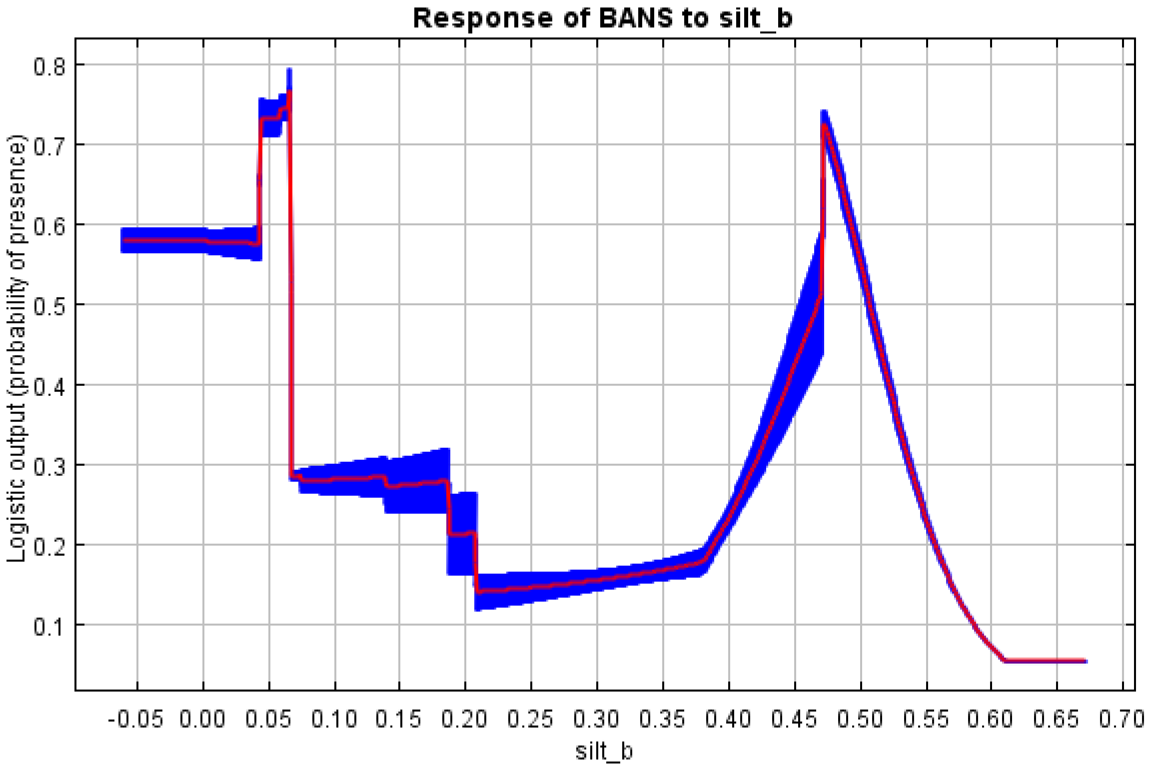
Response of BANS to sand_c


Response of BANS to silt_a
Logistic output (probability of presence)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
silt_a

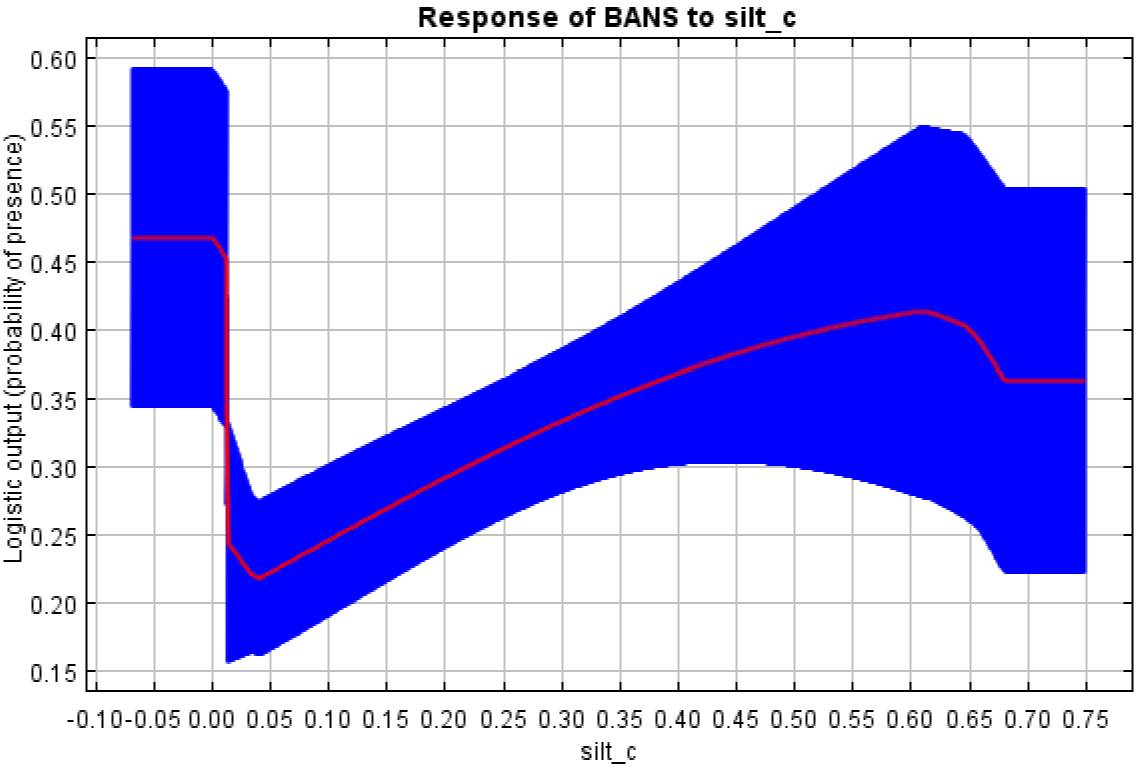

Response of BANS to silt_a
Logistic output (probability of presence)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
silt_a

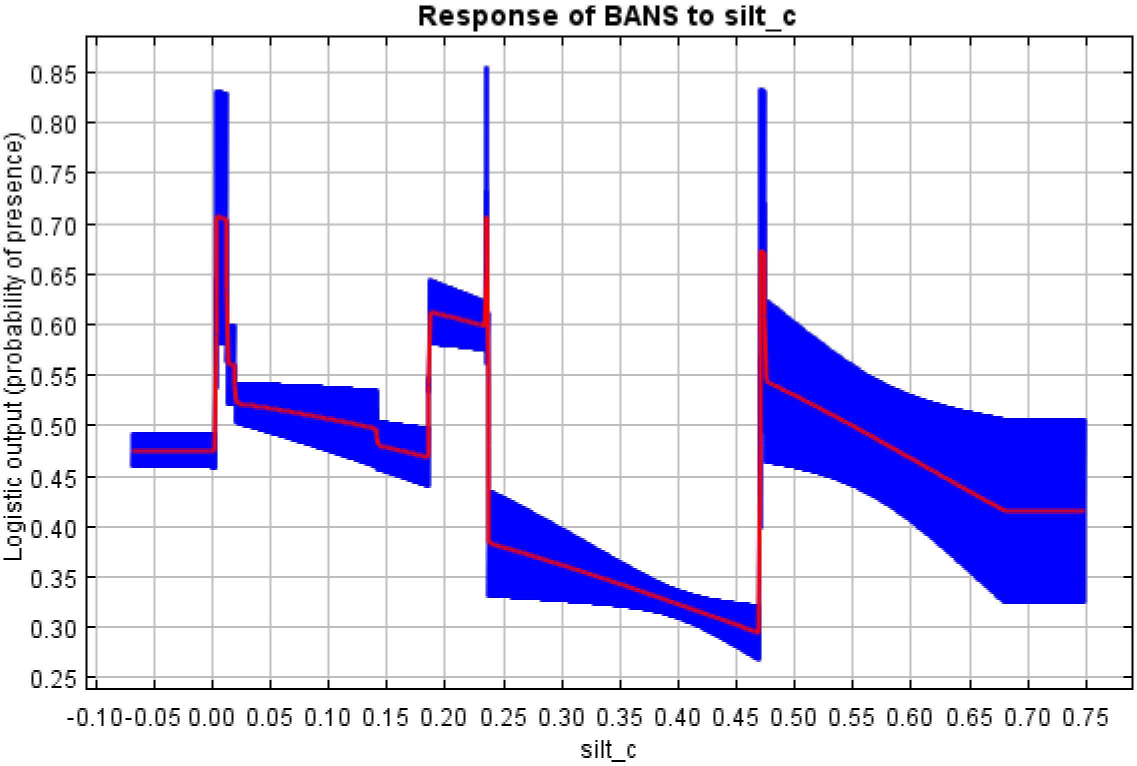


Response of BANS to silt_b
Logistic output (probability of presence)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
silt_b



Response of BANS to silt_b
Logistic output (probability of presence)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
silt_b


Response of BANS to silt_c
Logistic output (probability of presence)
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
-0.10 -0.05 0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75
silt_c


Response of BANS to silt_c
Logistic output (probability of presence)
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
-0.10 -0.05 0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75
silt_c

Appendix D-4. MaxEnt tabular diagnostic outputs.

Species	#Training samples	Regularized training gain	Unregularized training gain	Iterations	Training AUC	#Test samples	Test gain	Test AUC	AUC Standard Deviation	#Background points	Entropy	Prevalence (average of logistic output over background sites)
BANS_0	108.000	2.113	2.766	1000.000	0.975	28.000	2.478	0.945	0.033	10005.000	7.141	0.060
BANS_1	109.000	2.163	2.800	1000.000	0.968	27.000	2.089	0.946	0.014	10004.000	7.072	0.056
BANS_2	109.000	2.140	2.827	1000.000	0.973	27.000	2.195	0.953	0.013	10004.000	7.120	0.059
BANS_3	109.000	2.191	2.888	1000.000	0.974	27.000	1.886	0.910	0.031	10005.000	7.073	0.056
BANS_4	109.000	2.135	2.873	1000.000	0.974	27.000	2.316	0.932	0.028	10006.000	7.110	0.058
BANS (MEAN)		2.148	2.831	1000.000	0.973	27.200	2.193	0.937	0.024	10004.800	7.103	0.058
BANS (SE)		0.013	0.023	0.000	0.001	0.200	0.100	0.008	0.004	0.374	0.014	0.001

Species	clay_a contribution	clay_b contribution	clay_c contribution	sand_a contribution	sand_b contribution	sand_c contribution	silt_a contribution	silt_b contribution	silt_c contribution
BANS_0	6.540	33.195	7.151	24.289	5.520	8.847	8.831	3.894	1.734
BANS_1	4.077	27.124	3.333	32.737	4.071	12.100	11.761	1.780	3.017
BANS_2	8.427	29.877	4.644	28.975	3.039	10.900	7.623	3.647	2.868
BANS_3	7.922	30.008	3.139	31.219	3.693	8.178	10.678	3.979	1.184
BANS_4	5.941	30.926	6.132	26.636	4.579	12.352	9.032	2.400	2.002
BANS (MEAN)	6.581	30.226	4.880	28.771	4.180	10.475	9.585	3.140	2.161
BANS (SE)	0.771	0.977	0.781	1.523	0.419	0.845	0.730	0.443	0.346

Species	clay_a permutation importance	clay_b permutation importance	clay_c permutation importance	sand_a permutation importance	sand_b permutation importance	sand_c permutation importance	silt_a permutation importance	silt_b permutation importance	silt_c permutation importance
BANS_0	6.880	31.299	15.907	3.320	11.956	11.047	6.539	8.400	4.651
BANS_1	7.035	29.150	10.885	1.811	11.582	21.104	6.841	5.861	5.732
BANS_2	7.723	32.749	6.454	2.980	11.068	16.260	9.620	7.829	5.317
BANS_3	5.740	34.809	9.985	1.935	13.480	10.331	9.567	12.234	1.919
BANS_4	6.794	20.870	13.945	2.787	18.393	17.224	5.851	8.007	6.130
BANS (MEAN)	6.835	29.775	11.435	2.566	13.296	15.193	7.684	8.466	4.750
BANS (SE)	0.319	2.410	1.636	0.296	1.336	2.013	0.796	1.039	0.749

Species	Training gain without clay_a	Training gain without clay_b	Training gain without clay_c	Training gain without sand_a	Training gain without sand_b	Training gain without sand_c	Training gain without silt_a	Training gain without silt_b	Training gain without silt_c
BANS_0	2.023	1.961	2.056	2.048	1.945	1.928	1.998	2.000	2.039
BANS_1	2.106	2.035	2.113	2.112	2.017	1.981	2.087	2.096	2.090
BANS_2	2.071	2.025	2.111	2.049	2.012	1.968	2.062	2.034	2.035
BANS_3	2.146	2.106	2.150	2.145	2.058	2.019	2.053	2.062	2.180
BANS_4	2.051	2.029	2.074	2.082	1.957	1.948	2.040	2.060	2.068
BANS (MEAN)	2.079	2.031	2.101	2.087	1.998	1.969	2.048	2.050	2.082
BANS (SE)	0.022	0.023	0.016	0.019	0.021	0.016	0.015	0.016	0.026

Species	Training gain with only clay_a	Training gain with only clay_b	Training gain with only clay_c	Training gain with only sand_a	Training gain with only sand_b	Training gain with only sand_c	Training gain with only silt_a	Training gain with only silt_b	Training gain with only silt_c
BANS_0	0.762	0.897	0.206	0.792	0.675	0.205	0.789	0.471	0.065
BANS_1	0.765	0.868	0.196	0.985	0.756	0.396	0.922	0.470	0.098
BANS_2	0.741	0.856	0.244	0.856	0.656	0.296	0.786	0.510	0.091
BANS_3	0.814	0.919	0.197	0.945	0.729	0.254	0.983	0.442	0.026
BANS_4	0.701	0.805	0.253	0.846	0.624	0.362	0.786	0.430	0.066
BANS (MEAN)	0.757	0.869	0.219	0.885	0.688	0.302	0.853	0.465	0.069
BANS (SE)	0.018	0.019	0.012	0.035	0.024	0.035	0.042	0.014	0.013

Species	Test gain without clay_a	Test gain without clay_b	Test gain without clay_c	Test gain without sand_a	Test gain without sand_b	Test gain without sand_c	Test gain without silt_a	Test gain without silt_b	Test gain without silt_c
BANS_0	2.468	2.463	2.432	2.365	2.245	2.062	2.377	2.363	2.225
BANS_1	1.981	1.993	1.978	2.004	1.934	1.941	1.898	1.906	2.055
BANS_2	2.101	2.150	2.116	2.223	1.928	1.989	2.043	2.059	2.262
BANS_3	1.782	1.758	1.877	1.847	1.652	1.501	2.148	2.131	1.799
BANS_4	2.307	2.314	2.404	2.246	2.235	2.169	2.196	2.249	2.276
BANS (MEAN)	2.128	2.135	2.161	2.137	1.999	1.932	2.132	2.141	2.123
BANS (SE)	0.120	0.123	0.111	0.093	0.111	0.114	0.080	0.078	0.090

Species	Test gain with only clay_a	Test gain with only clay_b	Test gain with only clay_c	Test gain with only sand_a	Test gain with only sand_b	Test gain with only sand_c	Test gain with only silt_a	Test gain with only silt_b	Test gain with only silt_c
BANS_0	0.807	1.009	0.303	1.468	0.832	0.829	1.533	0.639	0.087
BANS_1	0.926	1.129	0.318	0.745	0.471	0.066	1.009	0.644	0.066
BANS_2	0.973	1.149	0.178	1.067	0.835	0.406	1.545	0.465	0.039
BANS_3	0.809	0.960	0.370	0.842	0.628	0.705	0.932	0.738	0.132
BANS_4	1.159	1.346	0.147	1.324	1.037	0.193	1.654	0.773	0.182
BANS (MEAN)	0.934	1.118	0.263	1.089	0.761	0.440	1.335	0.652	0.101
BANS (SE)	0.065	0.067	0.043	0.138	0.097	0.146	0.151	0.054	0.025

Species	AUC without clay_a	AUC without clay_b	AUC without clay_c	AUC without sand_a	AUC without sand_b	AUC without sand_c	AUC without silt_a	AUC without silt_b	AUC without silt_c
BANS_0	0.941	0.943	0.940	0.942	0.934	0.933	0.941	0.941	0.938
BANS_1	0.939	0.949	0.938	0.938	0.935	0.946	0.928	0.927	0.942
BANS_2	0.949	0.947	0.945	0.954	0.933	0.945	0.946	0.938	0.952
BANS_3	0.892	0.880	0.907	0.903	0.879	0.882	0.942	0.940	0.905
BANS_4	0.941	0.931	0.948	0.937	0.926	0.926	0.935	0.938	0.935
BANS (MEAN)	0.933	0.930	0.936	0.935	0.922	0.926	0.938	0.937	0.934
BANS (SE)	0.010	0.013	0.007	0.009	0.011	0.012	0.003	0.003	0.008

Species	AUC with only clay_a	AUC with only clay_b	AUC with only clay_c	AUC with only sand_a	AUC with only sand_b	AUC with only sand_c	AUC with only silt_a	AUC with only silt_b	AUC with only silt_c
BANS_0	0.826	0.848	0.708	0.918	0.820	0.717	0.866	0.786	0.600
BANS_1	0.827	0.879	0.678	0.744	0.713	0.619	0.739	0.815	0.545
BANS_2	0.868	0.886	0.608	0.844	0.865	0.706	0.887	0.773	0.579
BANS_3	0.821	0.846	0.733	0.790	0.792	0.737	0.789	0.822	0.725
BANS_4	0.855	0.881	0.633	0.810	0.772	0.676	0.877	0.832	0.656
BANS (MEAN)	0.839	0.868	0.672	0.821	0.792	0.691	0.831	0.806	0.621
BANS (SE)	0.009	0.009	0.023	0.029	0.025	0.020	0.029	0.011	0.032

Species	Fixed cumulative value 1 cumulative threshold	Fixed cumulative value 1 logistic threshold	Fixed cumulative value 1 area	Fixed cumulative value 1 training omission	Fixed cumulative value 1 test omission	Fixed cumulative value 1 binomial probability
BANS_0	1.000	0.013	0.430	0.009	0.036	0.000
BANS_1	1.000	0.010	0.490	0.000	0.000	0.000
BANS_2	1.000	0.009	0.512	0.000	0.000	0.000
BANS_3	1.000	0.009	0.488	0.000	0.074	0.000
BANS_4	1.000	0.009	0.482	0.000	0.037	0.000
BANS (MEAN)	1.000	0.010	0.480	0.002	0.029	0.000
BANS (SE)	0.000	0.001	0.013	0.002	0.014	0.000

Species	Fixed cumulative value 5 cumulative threshold	Fixed cumulative value 5 logistic threshold	Fixed cumulative value 5 area	Fixed cumulative value 5 training omission	Fixed cumulative value 5 test omission	Fixed cumulative value 5 binomial probability
BANS_0	5.000	0.051	0.255	0.009	0.071	0.000
BANS_1	5.000	0.038	0.273	0.018	0.000	0.000
BANS_2	5.000	0.041	0.290	0.018	0.000	0.000
BANS_3	5.000	0.049	0.271	0.018	0.111	0.000
BANS_4	5.000	0.047	0.276	0.009	0.111	0.000
BANS (MEAN)	5.000	0.045	0.273	0.015	0.059	0.000
BANS (SE)	0.000	0.002	0.006	0.002	0.025	0.000

Species	Fixed cumulative value 10 cumulative threshold	Fixed cumulative value 10 logistic threshold	Fixed cumulative value 10 area	Fixed cumulative value 10 training omission	Fixed cumulative value 10 test omission	Fixed cumulative value 10 binomial probability
BANS_0	10.000	0.102	0.176	0.009	0.071	0.000
BANS_1	10.000	0.090	0.144	0.092	0.111	0.000
BANS_2	10.000	0.066	0.185	0.046	0.074	0.000
BANS_3	10.000	0.073	0.180	0.046	0.185	0.000
BANS_4	10.000	0.077	0.170	0.046	0.148	0.000
BANS (MEAN)	10.000	0.082	0.171	0.048	0.118	0.000
BANS (SE)	0.000	0.006	0.007	0.013	0.022	0.000

Species	Minimum training presence cumulative threshold	Minimum training presence logistic threshold	Minimum training presence area	Minimum training presence training omission	Minimum training presence test omission	Minimum training presence binomial probability
BANS_0	0.916	0.011	0.440	0.000	0.036	0.000
BANS_1	4.068	0.032	0.303	0.000	0.000	0.000
BANS_2	3.551	0.029	0.341	0.000	0.000	0.000
BANS_3	3.859	0.033	0.308	0.000	0.111	0.000
BANS_4	3.115	0.026	0.339	0.000	0.074	0.000
BANS (MEAN)	3.102	0.026	0.346	0.000	0.044	0.000
BANS (SE)	0.570	0.004	0.025	0.000	0.022	0.000

Species	10 percentile training presence cumulative threshold	10 percentile training presence logistic threshold	10 percentile training presence area	10 percentile training presence training omission	10 percentile training presence test omission	10 percentile training presence binomial probability
BANS_0	32.388	0.346	0.043	0.093	0.107	0.000
BANS_1	17.601	0.138	0.099	0.092	0.148	0.000
BANS_2	31.545	0.353	0.044	0.092	0.185	0.000
BANS_3	26.137	0.260	0.058	0.092	0.259	0.000
BANS_4	23.561	0.242	0.069	0.083	0.148	0.000
BANS (MEAN)	26.246	0.268	0.063	0.090	0.170	0.000
BANS (SE)	2.718	0.039	0.010	0.002	0.026	0.000

Species	Equal training sensitivity and specificity cumulative threshold	Equal training sensitivity and specificity logistic threshold	Equal training sensitivity and specificity area	Equal training sensitivity and specificity training omission	Equal training sensitivity and specificity test omission	Equal training sensitivity and specificity binomial probability
BANS_0	20.279	0.217	0.083	0.083	0.071	0.000
BANS_1	17.601	0.138	0.099	0.101	0.222	0.000
BANS_2	22.259	0.219	0.073	0.073	0.185	0.000
BANS_3	20.160	0.175	0.083	0.083	0.259	0.000
BANS_4	21.943	0.209	0.076	0.073	0.148	0.000
BANS (MEAN)	20.448	0.192	0.083	0.083	0.177	0.000
BANS (SE)	0.829	0.016	0.005	0.005	0.032	0.000

Species	Maximum training sensitivity plus specificity cumulative threshold	Maximum training sensitivity plus specificity logistic threshold	Maximum training sensitivity plus specificity area	Maximum training sensitivity plus specificity training omission	Maximum training sensitivity plus specificity test omission	Maximum training sensitivity plus specificity binomial probability
BANS_0	32.388	0.346	0.043	0.093	0.107	0.000
BANS_1	25.826	0.284	0.058	0.110	0.222	0.000
BANS_2	20.846	0.187	0.080	0.055	0.185	0.000
BANS_3	34.244	0.354	0.035	0.110	0.333	0.000
BANS_4	20.295	0.171	0.085	0.064	0.148	0.000
BANS (MEAN)	26.719	0.268	0.060	0.086	0.199	0.000
BANS (SE)	2.875	0.038	0.010	0.011	0.039	0.000

Species	Equal test sensitivity and specificity cumulative threshold	Equal test sensitivity and specificity logistic threshold	Equal test sensitivity and specificity area	Equal test sensitivity and specificity training omission	Equal test sensitivity and specificity test omission	Equal test sensitivity and specificity binomial probability
BANS_0	22.911	0.260	0.072	0.083	0.071	0.000
BANS_1	13.939	0.098	0.132	0.092	0.148	0.000
BANS_2	12.932	0.092	0.143	0.055	0.148	0.000
BANS_3	9.649	0.070	0.185	0.046	0.185	0.000
BANS_4	12.816	0.097	0.148	0.046	0.148	0.000
BANS (MEAN)	14.449	0.123	0.136	0.064	0.140	0.000
BANS (SE)	2.235	0.034	0.018	0.010	0.019	0.000

Species	Maximum test sensitivity plus specificity cumulative threshold	Maximum test sensitivity plus specificity logistic threshold	Maximum test sensitivity plus specificity area	Maximum test sensitivity plus specificity training omission	Maximum test sensitivity plus specificity test omission	Maximum test sensitivity plus specificity binomial probability
BANS_0	42.791	0.503	0.027	0.185	0.107	0.000
BANS_1	13.939	0.098	0.132	0.092	0.111	0.000
BANS_2	35.396	0.399	0.037	0.128	0.185	0.000
BANS_3	18.326	0.139	0.094	0.073	0.185	0.000
BANS_4	23.561	0.242	0.069	0.083	0.148	0.000
BANS (MEAN)	26.803	0.276	0.072	0.112	0.147	0.000
BANS (SE)	5.373	0.077	0.019	0.020	0.017	0.000

Species	Balance training omission, predicted area and threshold value cumulative threshold	Balance training omission, predicted area and threshold value logistic threshold	Balance training omission, predicted area and threshold value area	Balance training omission, predicted area and threshold value training omission	Balance training omission, predicted area and threshold value test omission	Balance training omission, predicted area and threshold value binomial probability
BANS_0	4.513	0.048	0.267	0.009	0.071	0.000
BANS_1	4.068	0.032	0.303	0.000	0.000	0.000
BANS_2	3.551	0.029	0.341	0.000	0.000	0.000
BANS_3	3.859	0.033	0.308	0.000	0.111	0.000
BANS_4	3.115	0.026	0.339	0.000	0.074	0.000
BANS (MEAN)	3.821	0.034	0.312	0.002	0.051	0.000
BANS (SE)	0.236	0.004	0.014	0.002	0.022	0.000

Species	Equate entropy of thresholded and original distributions cumulative threshold	Equate entropy of thresholded and original distributions logistic threshold	Equate entropy of thresholded and original distributions area	Equate entropy of thresholded and original distributions training omission	Equate entropy of thresholded and original distributions test omission	Equate entropy of thresholded and original distributions binomial probability
BANS_0	14.635	0.112	0.125	0.056	0.071	0.000
BANS_1	15.386	0.114	0.118	0.092	0.148	0.000
BANS_2	14.770	0.114	0.124	0.055	0.185	0.000
BANS_3	15.456	0.114	0.117	0.064	0.185	0.000
BANS_4	15.354	0.112	0.122	0.055	0.148	0.000
BANS (MEAN)	15.120	0.113	0.121	0.064	0.148	0.000
BANS (SE)	0.173	0.000	0.002	0.007	0.021	0.000

Appendix E. IRIC & MaxEnt Results

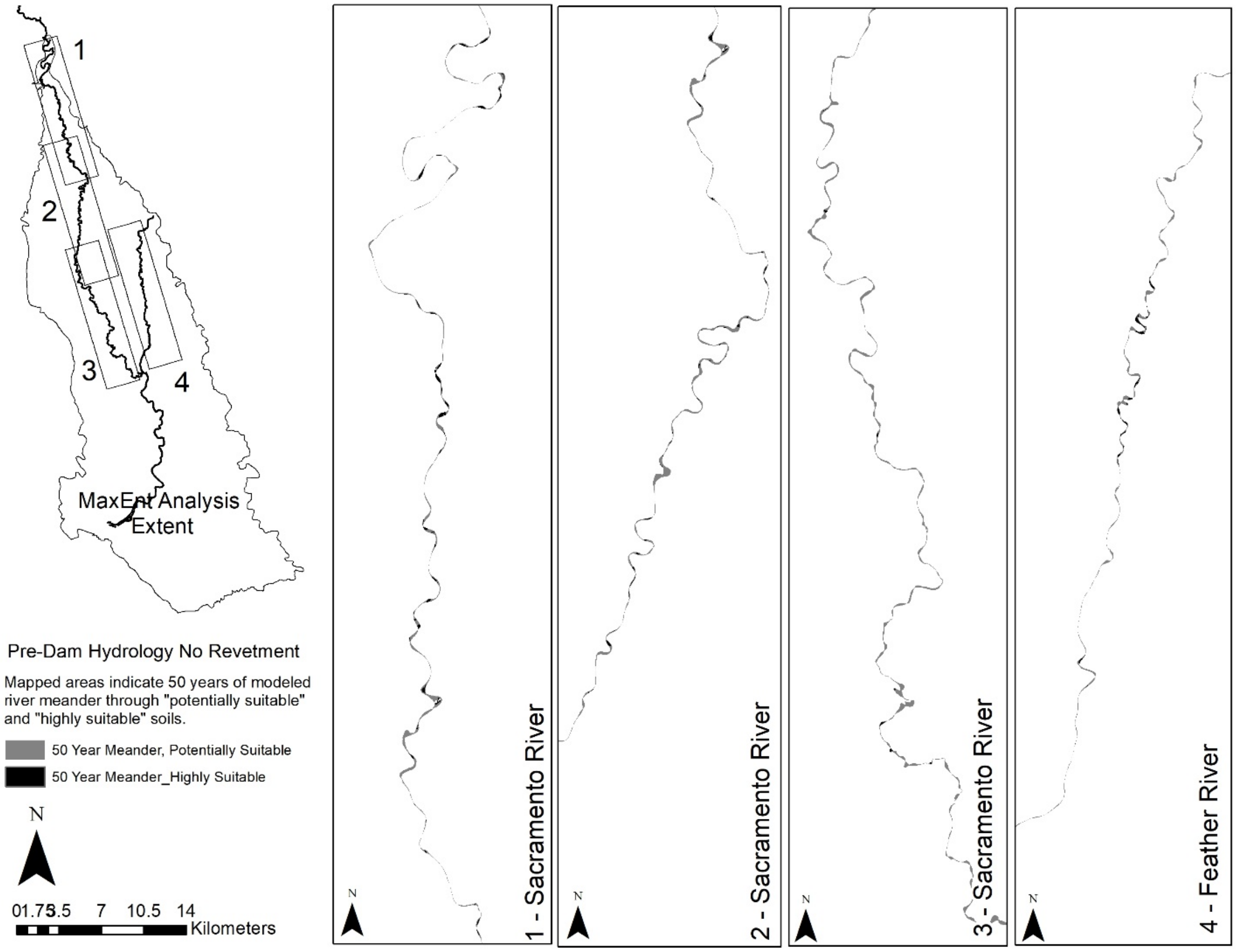


Figure E-1. Combined outputs from IRIC and MaxEnt for Sacramento and Feather River 50-year scenario Pre-Dam Hydrology with No Revetment.

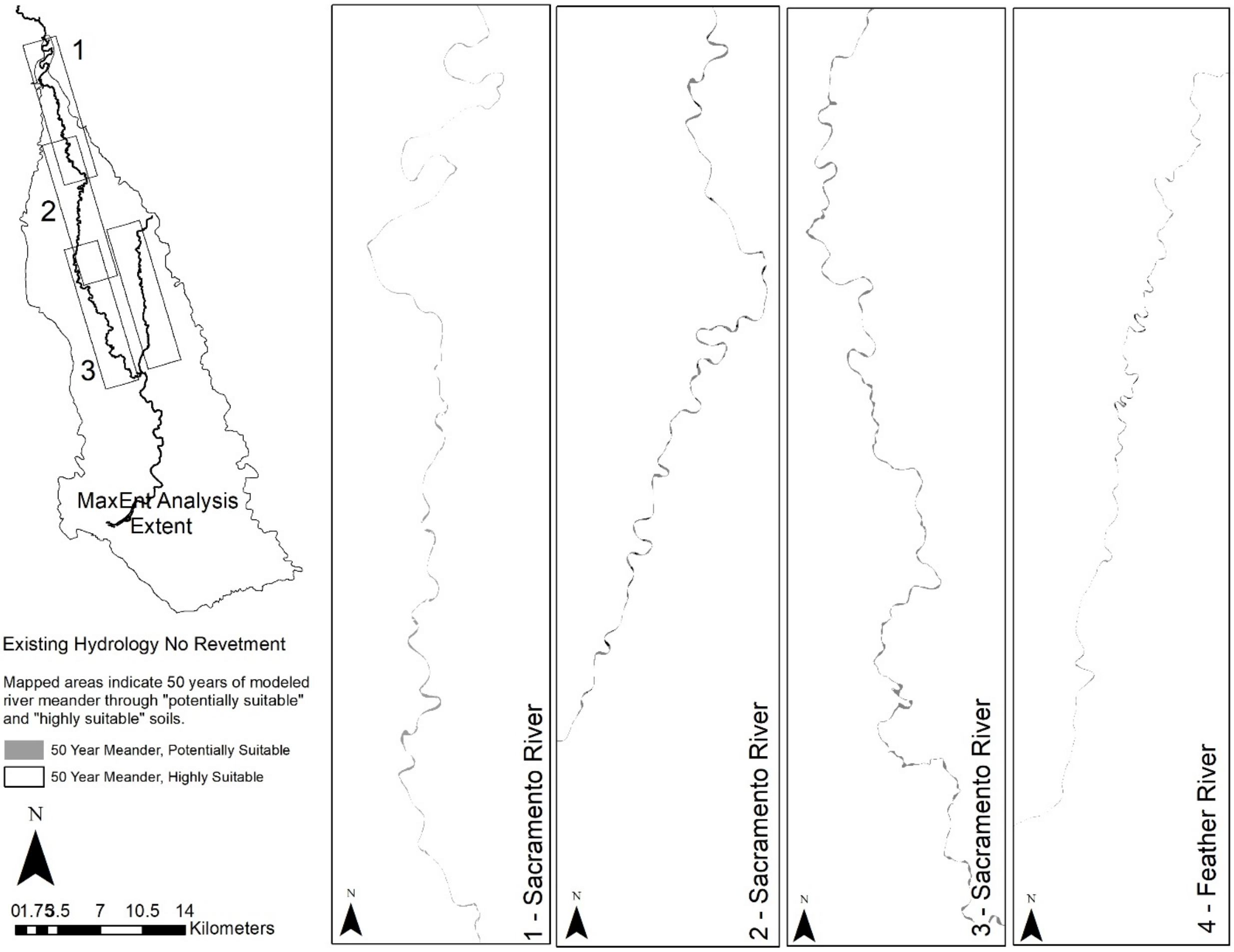


Figure E-2. Combined outputs from IRIC and MaxEnt for Sacramento and Feather River 50-year scenario Existing Hydrology with No Revetment.

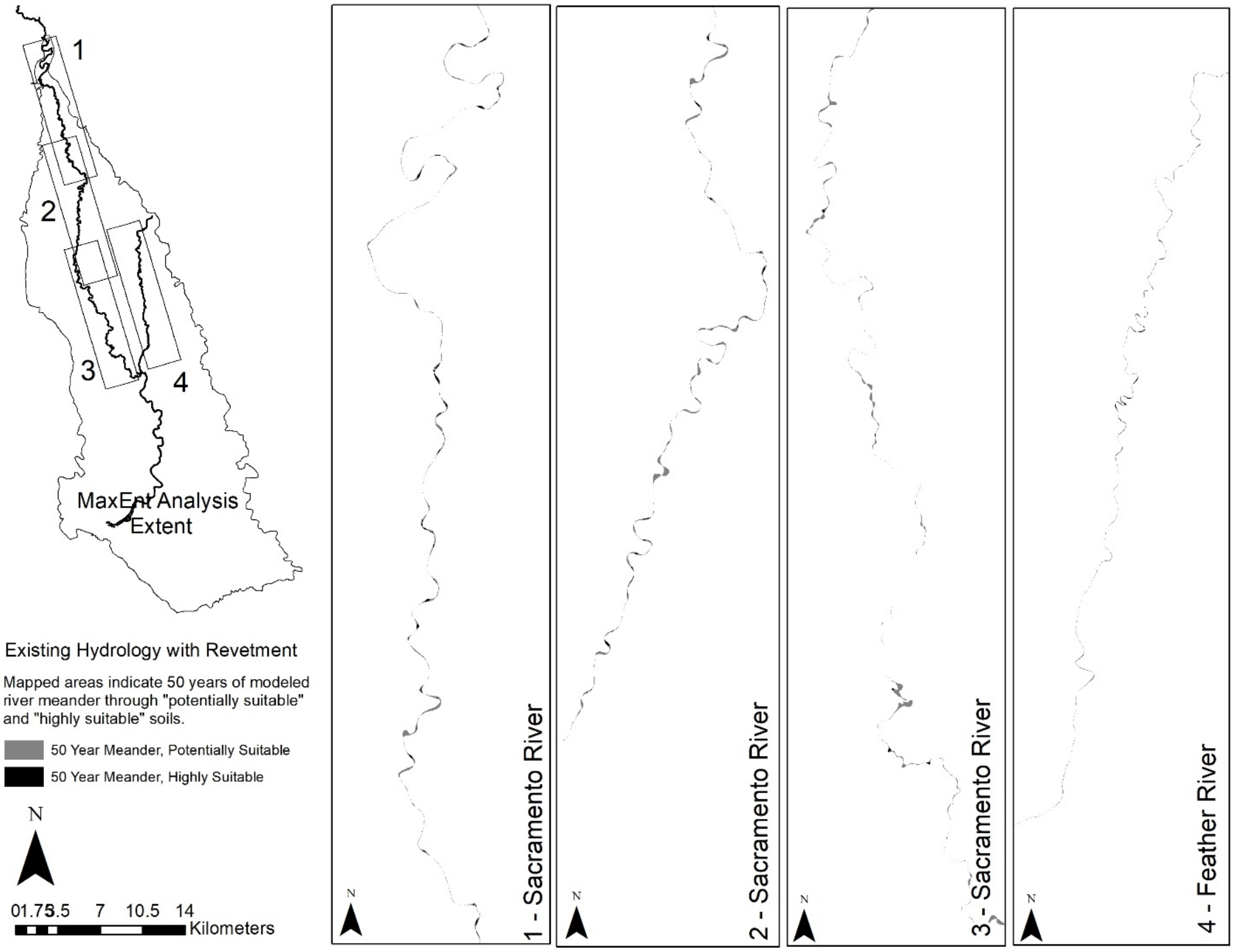


Figure E-3. Combined outputs from IRIC and MaxEnt for Sacramento and Feather River 50-year scenario Existing Hydrology with Revetment.

Appendix F. Summary of California Protected Areas Database (CPAD) holdings with potential for bank restoration through rock revetment removal.

Management Unit Name	Responsible Agency	Access Type	County	Designation	Year Establis hed	Park Unit Size (ha)	Extent of Bank Swallow Soils (ha)
Mouth of Cottonwood Creek Wildlife Area	California Department of Fish and Wildlife	Open Access	Shasta	State Conservation Area	1982	411.43	0.00
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	Restricted Access	Tehama	National Wildlife Refuge	1989	1665.43	8.27
Levee Park	Colusa, City of	Open Access	Colusa	Local Park	0	1.10	0.07
Sacramento River Wildlife Area	California Department of Fish and Wildlife	Open Access	Colusa	State Conservation Area	1978	401.20	2.17
Unnamed Site - California Reclamation District 2140	California Reclamation District 2140	No Public Access	Glenn	Local Other or Unknown	0	411.22	3.66
Sacramento River Wildlife Area	California Department of Fish and Wildlife	Open Access	Tehama	State Conservation Area	1978	53.69	3.01
Sacramento River Wildlife Area	California Department of Fish and Wildlife	Open Access	Butte	State Conservation Area	1978	241.89	0.02
Colusa-Sacramento River State Recreation Area	California Department of Parks and Recreation	Open Access	Colusa	State Recreation Area	1955	147.40	0.66
BLM	United States Bureau of Land Management	Open Access	Shasta	National Public Lands	1899	55852.63	0.00
BLM	United States Bureau of Land Management	Open Access	Tehama	National Public Lands	1899	19184.90	0.78
Hartley Island	The Nature Conservancy	No Public Access	Glenn	Private Conservation	0	129.96	1.16
Sacramento River	The Nature Conservancy	No Public Access	Colusa	Private Conservation	0	50.63	3.85
Sacramento River	The Nature Conservancy	No Public Access	Glenn	Private Conservation	0	140.55	0.52
Butte Sink Wildlife Management Area	United States Fish and Wildlife Service	Restricted Access	Butte	Conservation Area	1980	265.14	6.90
Red Bluff Recreation Area	United States Forest Service	Open Access	Tehama	Recreation Management Area	0	375.33	0.13
Tehama River County Park	Tehama, County of	Open Access	Tehama	Local Park	0	5.53	0.76
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	Restricted Access	Glenn	National Wildlife Refuge	1989	608.86	1.44
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	No Public Access	Glenn	National Wildlife Refuge	1989	4239.35	2.42
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	Restricted Access	Glenn	National Wildlife Refuge	1989	88.25	0.82
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	Open Access	Tehama	National Wildlife Refuge	1989	111.68	1.75
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	Open Access	Butte	National Wildlife Refuge	1989	11.36	0.00
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	Restricted Access	Tehama	National Wildlife Refuge	1989	35.06	0.16
Bidwell-Sacramento River State Park	California Department of Parks and Recreation	Open Access	Butte	State Park	1979	108.37	2.47
Woodson Bridge State Recreation Area	California Department of Parks and Recreation	Open Access	Tehama	State Recreation Area	1959	140.84	9.01
Merrill's Landing Wildlife Area	California Department of Fish and Wildlife	Open Access	Tehama	State Conservation Area	1980	111.18	0.08
Sacramento River Wildlife Area	California Department of Fish and Wildlife	Open Access	Glenn	State Conservation Area	1978	829.07	12.22
Fremont Weir Wildlife Area	Central Valley Flood Protection Board	Open Access	Yolo	State Conservation Area	1981	579.04	2.56
Fremont Weir Wildlife Area	Central Valley Flood Protection Board	Open Access	Sutter	State Conservation Area	1981	12.86	1.31
Butte Sink Wildlife Management Area	United States Fish and Wildlife Service	Restricted Access	Butte	Conservation Area	1980	486.73	1.09
Sutter Bypass Wildlife Area	Central Valley Flood Protection Board	Open Access	Sutter	State Conservation Area	1968	1067.56	0.07
California State Lands Commission	California State Lands Commission	Open Access	Tehama	State Resource Management Ar	0	1371.53	0.03
Sacramento River	The Nature Conservancy	No Public Access	Glenn	Private Conservation	0	140.55	0.02
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	Restricted Access	Glenn	National Wildlife Refuge	1989	608.86	0.02
Tehama River County Park	Tehama, County of	Open Access	Tehama	Local Park	0	5.53	0.01
Woodson Bridge State Recreation Area	California Department of Parks and Recreation	Open Access	Tehama	State Recreation Area	1959	140.84	0.01
Sacramento River National Wildlife Refuge	United States Fish and Wildlife Service	Restricted Access	Glenn	National Wildlife Refuge	1989	608.86	0.00
Sacramento River Wildlife Area	California Department of Fish and Wildlife	Open Access	Glenn	State Conservation Area	1978	829.07	0.00

Appendix G. Regression of Burrows by Year Since Revetment Failed

Regression Analysis: Burrow Average versus Normalized Year

Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	1	52559	52559	8.95	0.008
Normalized Year	1	52559	52559	8.95	0.008
Error	17	99831	5872		
Total	18	152390			

Model Summary

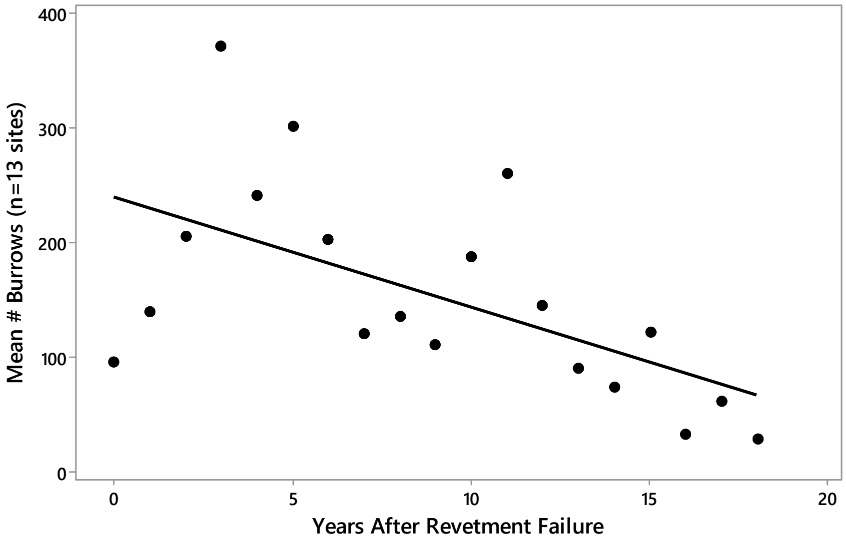
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
76.6315	34.49%	30.64%	14.50%

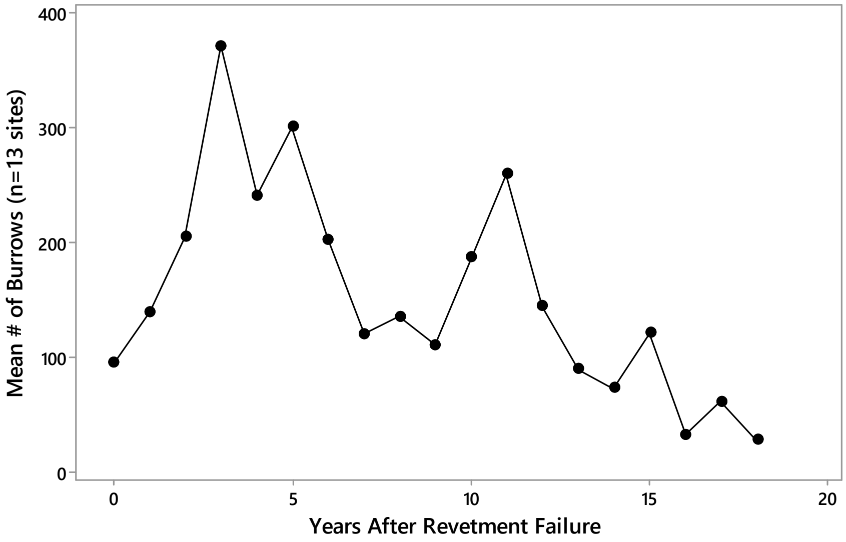
Coefficients

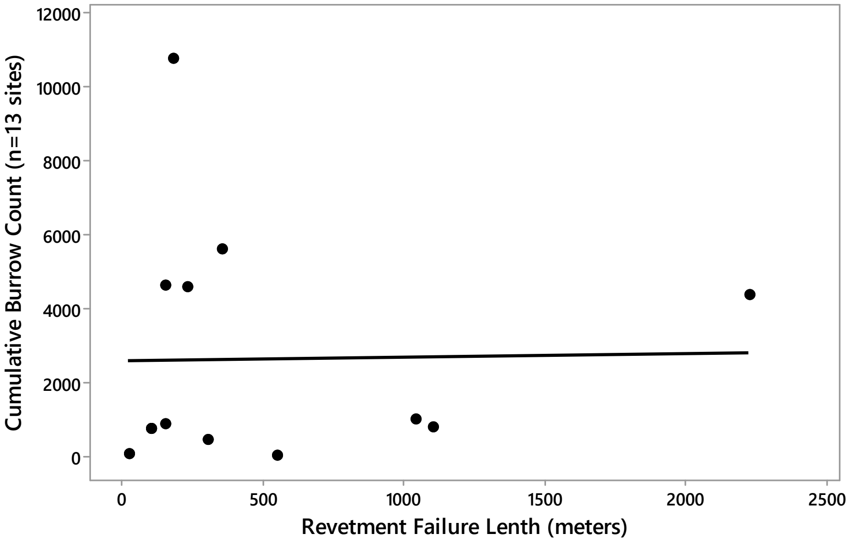
Term	**Coef**	**SE Coef**	**T-Value**	**P-Value**	**VIF**
Constant	239.6	33.8	7.09	0.000	
Normalized Year	-9.60	3.21	-2.99	0.008	1.00

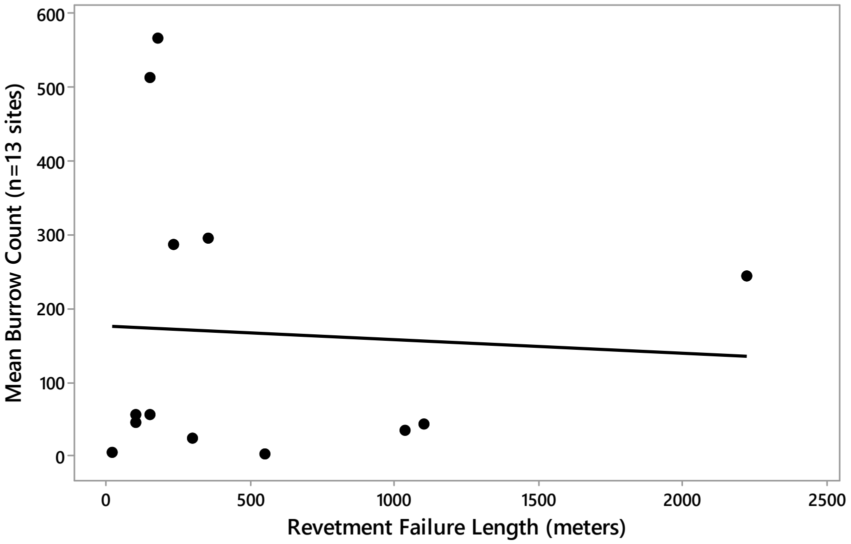
Regression Equation

Burrow Average = 239.6 - 9.60 Normalized Year


Mean # Burrows (n=13 sites)
Years After Revetment Failure
0
100
200
300
400
0
5
10
15
20


Mean # of Burrows (n=13 sites)
Years After Revetment Failure
0
100
200
300
400
0
5
10
15
20


Cumulative Burrow Count (n=13 sites)
12000
10000
8000
6000
4000
2000
0
0
500
1000
1500
2000
2500
Revetment Failure Lenth (meters)


Mean Burrow Count (n=13 sites)
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500
Revetment Failure Length (meters)