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The Delta as Changing Landscapes

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ABSTRACT

What happens at one place in a landscape influences and is influenced by what happens in other places. Consequently, management and restoration that focus on individual places may fail to recognize and incorporate interactions across entire landscapes. The science of landscape ecology, which emphasizes the interplay of landscape structure, function, and change at multiple scales, offers a perspective that can integrate the spatial relationships of ecological processes and the functional interconnections of land and water in the Delta.

Although the Delta is one of the most studied estuaries in the world, applications of landscape science have been limited. We describe why it is important to incorporate landscape science into management and restoration, emphasizing how Delta landscapes have changed over the past centuries. The land–water linkages of the past have been broken, waterways have been over-connected, and hard boundaries have replaced the gradual and dynamic transitions among landscape patches. The contemporary landscape also has new, novel assemblages of species and stressors that were not there in the past. This historical perspective indicates how knowledge of past landscape functions can contribute to the restoration and management of contemporary landscapes. We illustrate these points with case studies of inundation dynamics and riparian woodlands, and use a third example to describe a landscape approach to restoration.

We propose that science that encompasses the multiple, interacting components of functional landscapes in the Delta will foster resilient and enduring restoration and management outcomes that benefit both people and wildlife. We suggest several ways of moving landscape science to the forefront of management and restoration in the Delta.

KEY WORDS

McCormack–Williamson Tract, historical ecology, inundation, landscape, , restoration, riparian woodland, scale, waterscape

INTRODUCTION

The Delta tells many stories. There are stories told by indigenous people for thousands of years; stories of families that have farmed the Delta for generations; stories of the shifting balance between native and introduced species; stories of floods and droughts; and stories of astounding engineering accomplishments. Here we consider stories of Delta landscapes: what they are, how they have changed, and how the science of landscapes can enrich management and restoration of the Delta and its resources.

Scientists who study landscapes—landscape ecologists—are concerned with how spatial heterogeneity affects ecological systems. The composition, configuration, and arrangement of patches in a landscape mosaic influence the movement and distribution of water, sediment, nutrients, organisms, people, and much else over the landscape as a whole (Turner 1989; Wiens et al. 1993; Fahrig 2007). Landscape heterogeneity affects the persistence of populations (Fraterrigo et al. 2009), species interactions (Polis et al. 2004), and ecosystem function (Lovett et al. 2005)—in short, just about everything that happens in the environment.

Viewing the Delta through the lens of landscapes is important for several reasons. First, landscapes are where people and the Delta intersect, where people raise crops and families, and experience the environment and nature. Thinking about “the Delta as an evolving place” (Delta Reform Act of 2009; California Water Code §85054) requires thinking about where people are in a landscape and what they are doing there.

Second, landscapes in the Delta include the water, the transitions across wetlands and levees, and the multiple uses of the lands behind the levees. A landscape perspective expands the focus from the fish, flows, and water that dominate science and drive debates to consider how the lands and waters interact in the Delta.

Third, landscapes provide a feasible middle ground. somewhere between the individual places where restoration or management are undertaken and the overwhelming complexity of the entire Delta. The focus of planning and management, for example, can expand from protecting or restoring individual habitat areas for native species to a more comprehensive approach that encompasses multiple species and functioning ecosystems (Opdam et al. 2002; NAS 2016).

Fourth, by considering entire landscapes rather than individual places, the broad-scale patterns and processes that determine how Delta ecosystems function emerge. An integrated landscape perspective can provide the foundation, for example, for managing or restoring ecological connectivity, habitat diversity, landscape adaptability, and resilience to change—all critically important factors in a Delta faced with climate change and sea-level rise (Cloern et al. 2011; Dettinger et al., submitted).

These points speak to the value of going beyond site-specific plans and actions to manage larger functional and interconnected landscapes, as called for in the Delta Plan (DSC 2013). Here, we explore how current thinking in landscape ecology can foster the development of a stronger, more cohesive approach to restoration and management in the Delta. We emphasize studies that have documented past landscapes in the Delta and how they have changed (Whipple et al 2012; SFEI–ASC 2014), not to establish historical targets for landscape management or restoration (see Wiens and Hobbs 2015), but because these studies show how changes to the landscape have led to the loss of desired functions and suggest opportunities to regain some of that functionality.

PERSPECTIVES ON LANDSCAPES

Landscapes can be viewed in multiple ways (Figure 1). A soil scientist or geographer may see the landscape as a mosaic of soil types or topographies. An engineer may see the same landscape as an interwoven network of roadways and levees. To a land-use planner or farmer, the landscape is a patchwork of ownerships, land uses, and agricultural crops. A wildlife biologist may focus on the distribution of habitats for a species of interest. A conservationist may view the landscape in terms of protected areas or occurrences of invasive species.

To a landscape ecologist, these perspectives are all characterized by their spatial heterogeneity—they are mosaics of relatively discrete “patches” such as the agricultural fields or riparian woodlands of Figure 1. Patches are delimited by boundaries of varying width and resistance to movement (permeability) and may be linked together in various ways (connectivity). This patch-boundary-connectivity-mosaic conceptualization of landscapes fits nicely with tools such as remote sensing, geographic information

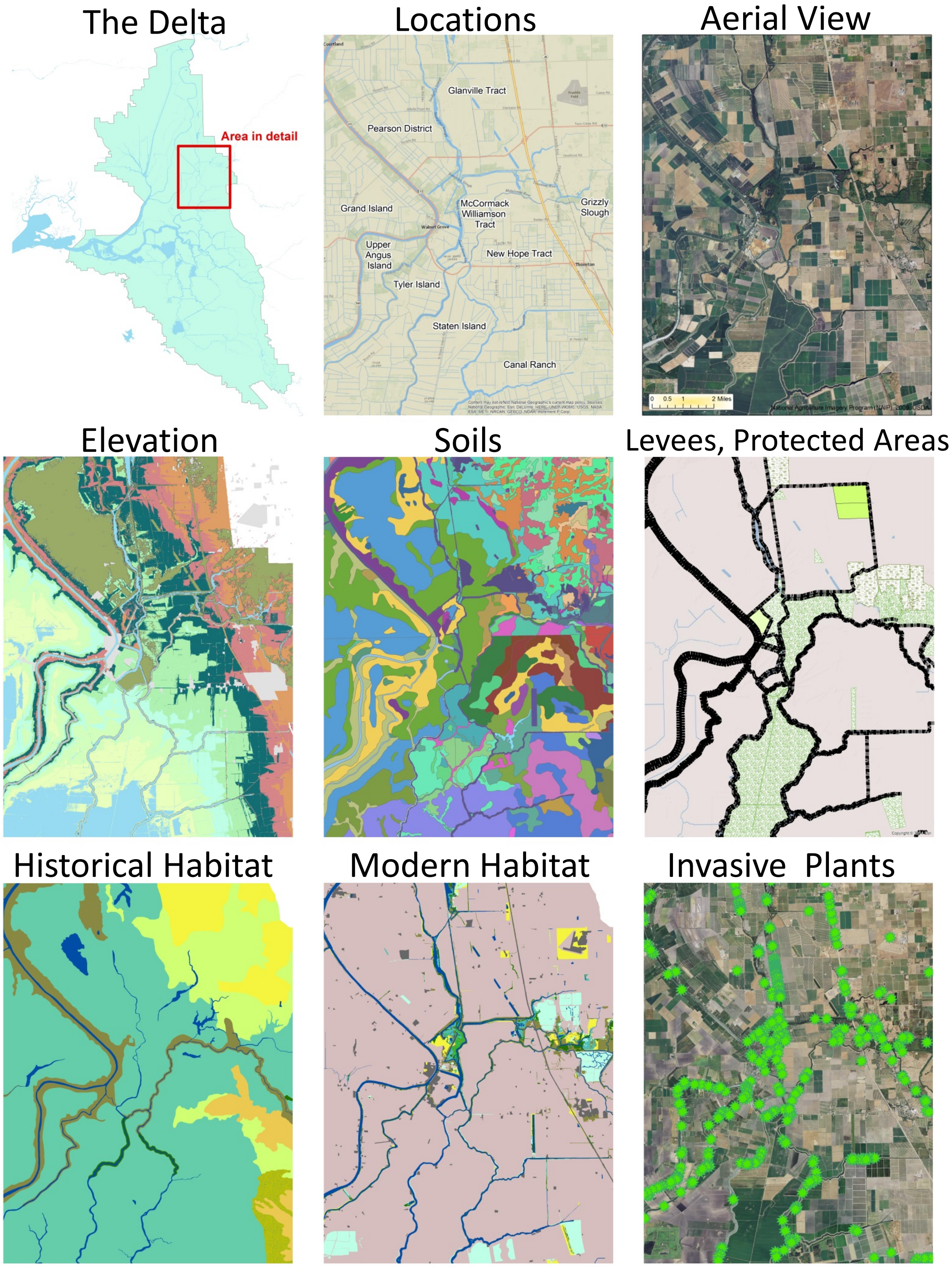

Figure 1 The landscape surrounding the McCormack–Williamson Tract, as viewed from a variety of perspectives. The details of each map are unimportant; the important point is that different perspectives lead to quite different perceptions of how the same landscape is structured.

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systems, geospatial modeling, spatial statistics, percolation theory, and even fractal geometry. It has spawned a variety of landscape metrics and has nurtured much of the growth of landscape ecology as a science (Forman 1995; Wiens 1999).

Landscapes defined by spatial patterns in hydrology, land uses, vegetation, human infrastructure, or geology express how humans using different criteria perceive landscapes. The species that are often the focus of management, however, respond to the spatial heterogeneity of an area in different ways, based on different landscape features (Wiens et al. 1993; Mac Nally 2005; Fahrig et al. 2011). A barrier to a frog or salamander may be a corridor to a small mammal; a strip of riparian woodland that is too narrow to support a hawk may be just right for a songbird. When the objectives of management deal with species, how the species and we humans view the landscape must both be considered.

STRUCTURE, FUNCTION, AND CHANGE

These perspectives emphasize the spatial structure of landscapes. Landscape-level processes, such as movements of materials, nutrients, or organisms or the spread of disturbances are shaped by this landscape structure. For example, fish movements are influenced by the configuration of water channels, the spatial arrangement of feeding and spawning habitats, or the occurrence of predators (Bennett and Burau 2015). Movements of terrestrial species among habitats can be blocked by infrastructure or land uses that sever migration corridors or fragment habitat. Concentrations of contaminants such as selenium depend on where in a landscape selenium is deposited or released and how it is moved from place to place, affecting its uptake and accumulation in food webs (Luoma et al. 2008).

Landscape structure and processes are spatial properties of an area. But there is also a temporal dimension: landscapes change. The contemporary landscape of leveed islands, farms, and urban communities bears little resemblance to the historical mosaic of wetlands and riparian woodlands (Whipple et al. 2012). Biological communities and ecosystems have been dramatically altered, particularly by the spread of invasive, non-native species (Moyle 2013). In addition, land uses have changed in response to regional and global economics. As Delta ecosystems and landscapes have been engineered away from their natural states, their inherent resilience has been reduced, increasing their vulnerability to large disturbances (as suggested more generally by Walker and Salt 2006). This vulnerability will increase as the effects of accelerated sea-level rise and climate change emerge with full force in the Delta, bringing additional changes in the occurrences of species, agricultural practices, and the structure and composition of landscapes.

These three dimensions of landscapes—structure, function, and change—intersect (Figure 2). The spatial arrangement of landscape elements and the composition of a mosaic—its structure—affect how organisms are distributed and disperse. For example, the species composition of fish assemblages in the Delta may vary among sampling locations and seasons in ways related to the structural characteristics of the sampling sites (Nobriga et al. 2005). Landscape structure also determines how water, nutrients, and disturbances move through an

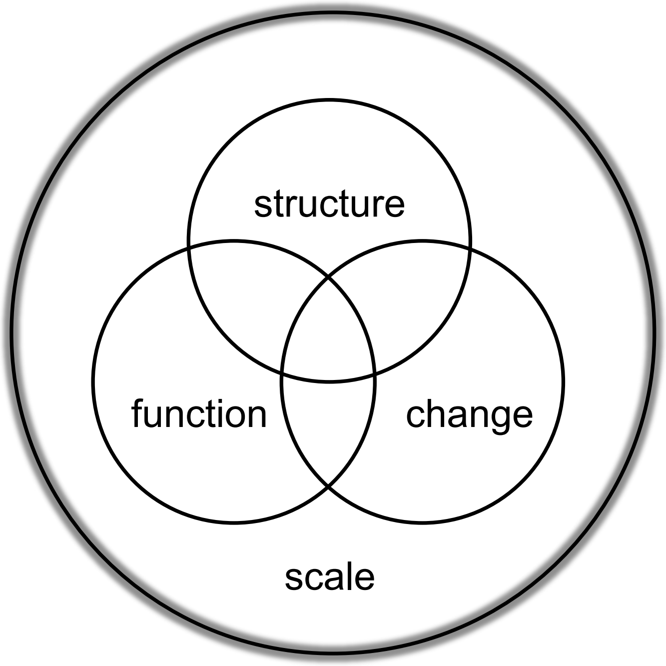

Figure 2 A Venn diagram showing the intersection of structure, function, and change that are the key elements of a scientific approach to the study and management of landscapes. The relationships among these elements change with changes in spatial or temporal scale.

area (Turner et al. 1989; Reiners and Driese 2004). These functions also affect structure. Movements of organisms alter patch composition, movements of nutrients affect water quality, floods reconfigure river channels, and droughts alter the vegetation or land uses in a landscape. This mélange of structure, function, and change in landscapes is why the Delta is such a complex and dynamic place, rife with “wicked problems” that challenge management or restoration (*Luoma et al. 2015*).

SCALE

The complexity of Delta ecosystems is exacerbated by scale. Components of the system operate at different scales in space and time. Delta Smelt (*Hypomesus transpacificus*) and Sacramento Splittail (*Pogonichthys macrolepidotus*) occupy only small parts of the Delta, whereas Chinook Salmon (*Oncorhynchus tshawytscha*) and sandhill cranes (*Grus canadensis*) cover large areas in migratory movements that extend well beyond the Delta. Each of these species responds to spatial and temporal variation in different features of the environment at different scales of resolution (Nobriga et al. 2005).

People do this, too. The composition of crops in an agricultural landscape is determined by farmers at a local scale, but their decisions are influenced by policies and economics at national and international scales. Management of natural resources is usually implemented at scales of hectares to a few square kilometers—scales that humans find familiar and manageable. Problems arise, however, when the scale(s) of management actions do not match the scale(s) of the species or processes they are intended to benefit.

Scale also affects the design of habitat restoration or monitoring. It might seem obvious, for example, that restoring even small areas of wetland should be worthwhile, since so much of the historic wetland has been lost and the cumulative effects of restoring many small areas may appear to be large. But if the scale of the restored patches is insufficient to meet the needs of the target species, or if the restored hydrology does not provide appropriate habitat or connectivity for fish feeding and movement, the restoration project may not have the desired results. Monitoring designs should capture the scales of the overall distribution of monitoring targets and the scale(s) on which they respond to environmental factors. These scales differ among species, making it difficult to design monitoring protocols that will be effective for multiple targets. A formal analysis of sampling design that takes landscape structure and scale into account could allow managers to determine the optimal density, distribution, and placement of sampling sites within the landscape mosaic. Unfortunately, such analyses are seldom undertaken, greatly compromising the efficiency and effectiveness of monitoring.

The upshot is that the appropriate scale (or scales) for measurement and analysis depends on what is being managed or restored, and for whom. Scale can be thought of as an umbrella that extends over landscape structure, function, and change (Figure 2). As scale changes, how people perceive landscapes and how the landscapes should be managed also change.

LANDSCAPE LINKAGES

A core principle of landscape ecology is that places in a landscape are linked together—what happens in one place affects what happens elsewhere, and the nature of the effects depends on the spatial configuration and composition of the landscape mosaic (Bennett 1999). These interconnections are determined in part by the permeability of boundaries—how they differentially hinder or facilitate movement of energy, materials, organisms, or disturbances among the patches in a landscape mosaic (Wiens et al. 1985; Hansen and di Castri 1992). Maintaining such movements in the face of ongoing fragmentation of habitats (which creates hard boundaries that impede movements) is the rationale for enhancing landscape connectivity, which has become a major focus of terrestrial landscape management and conservation (Crooks and Sanjayan 2006; Hilty et al. 2006; Lindenmayer and Fischer 2006).[1] There is a plethora of methods (e.g., graph theory, network theory, least-cost path analysis; Pinto and Keitt 2002; Cushman and Huettmann 2010) to describe and

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[1] The California Essential Habitat Connectivity Project (available at *https://www.wildlife.ca.gov/Conservation/Planning/Connectivity/CEHC*) develops a strategy to enhance the connectivity of habitats across the state; the framework was used as the basis for evaluating habitat connectivity in the Delta as part of the Bay Delta Conservation Plan (*http://baydeltaconservationplan.com/*).

quantify landscape connectivity. Most of these relate to landscape structure (e.g., the physical networks in a GIS image; Figure 1), but landscape ecologists also talk of functional connectivity, how organisms, materials, etc. actually move from place to place (Tischendorf and Fahrig 2000).

Land and water are largely disconnected in the contemporary Delta landscape. A highly engineered network of levees directs flows and (most of the time) prevents the water from intruding into places where it is not wanted (Figure 1). At the same time, however, the engineered waterways of the rivers and Delta transport materials more quickly than would have occurred in the dendritic network of the past (Figure 3). This excessive connectivity can compromise navigational cues used by migrating fish, facilitate the spread of non-native species, and cause phytoplankton to be moved through the system before their populations can become large enough to fuel the food web. The increased connectivity of aquatic systems in the Delta contrasts with the reduced connectivity among terrestrial habitats and between terrestrial and aquatic habitats that has resulted from landscape alteration and fragmentation.

The ecological partitioning of water and land in the Delta has been accompanied by a bureaucratic

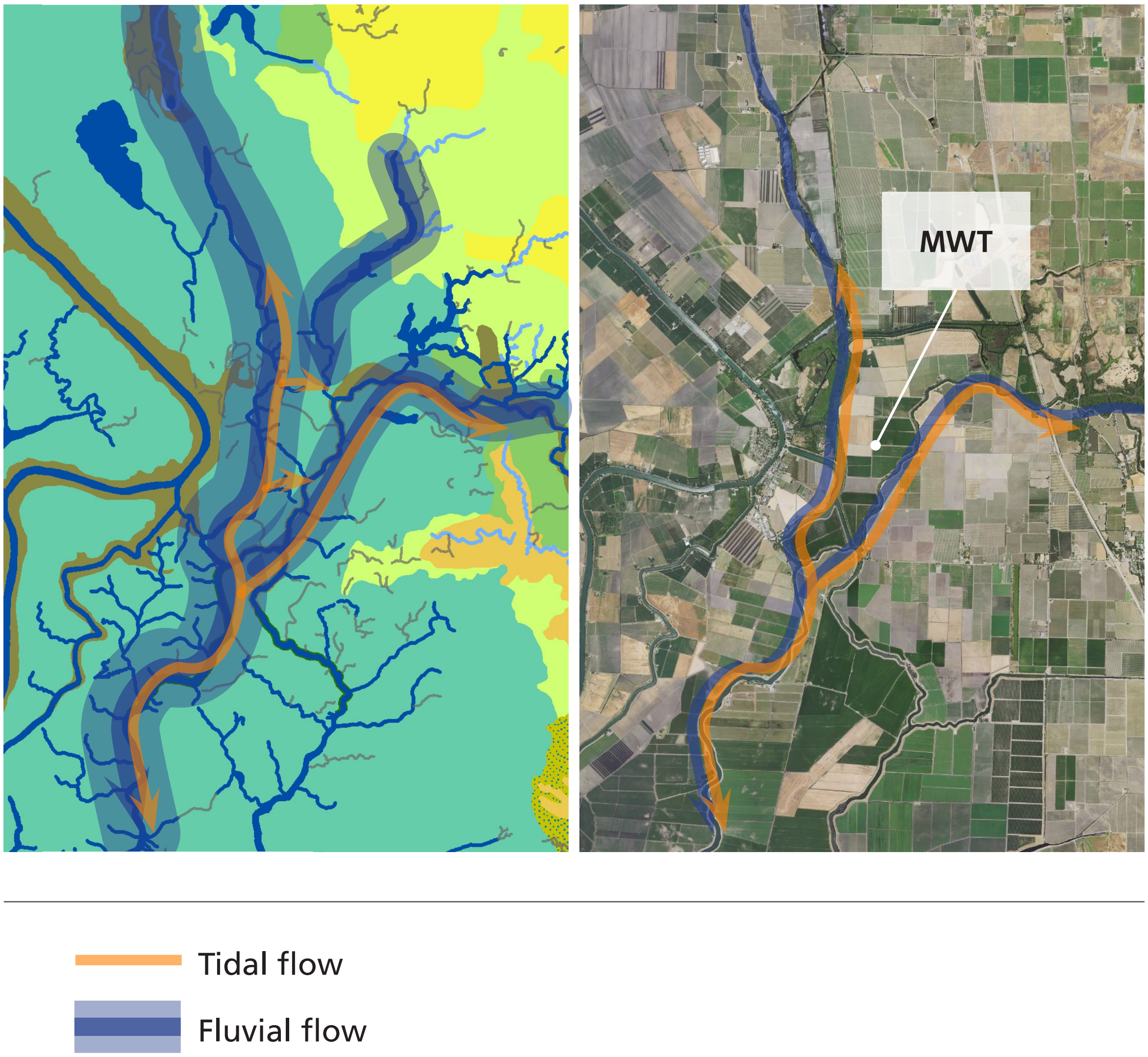

Figure 3 The McCormack–Williamson Tract in the early 1800s (left) and contemporary aerial photography (right). Modifications to the Delta over time have altered hydrological flows and the way land and water interact. Source: Beagle et al. (2013).

partitioning of management and regulatory responsibilities among various state and federal agencies. Some, such as the U.S. Bureau of Reclamation, the California Department of Water Resources, or the U.S Army Corps of Engineers, deal chiefly with the water (and the levees). Others, such as the Delta Protection Commission and the U.S. Department of Agriculture, focus on the lands behind the levees. Agencies charged with managing wildlife (the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, the California Department of Fish and Wildlife) consider either water or land (or both), depending on the species of interest. Overall, more than 230 agencies, institutions, and stakeholders are involved in water and environmental management in the Delta (*Luoma et al. 2015*), many dealing with different parts of the same landscapes.

The message of landscape ecology is that, while landscape structure can be easily partitioned into discrete classes, ecological processes such as nutrient flows, food webs, or the movements of many species are not so restricted. Because landscapes are linked and interconnected across the boundaries between water and land, management practices and policies must also be. Agency mandates need to facilitate the important ecological exchange processes, and decision-makers need to understand that decisions about one element in a landscape have implications for adjacent (or even distant) elements.

TAKING LANDSCAPE ECOLOGY INTO THE WATER

The previous sections make clear not only that Delta landscapes encompass both land and water, but also that the conceptual framework of landscape ecology—structure, function, change, and scale—applies to aquatic ecosystems—waterscapes—as well as to the land (Poff 1997; Wiens 2002; Leuven et al. 2002). There are obvious differences, however, Most of the functions and dynamics of terrestrial landscapes are determined by the structure of the land, which is relatively fixed over short time periods. Variations in the medium above the substrate (the air) are important, but they do not dominate the ecological systems. In water it is reversed. The substrate beneath the water may have many of the same structural features as terrestrial landscapes—patches, corridors, boundaries, etc. The important processes, however, take place in the water.

As in most riverine ecosystems (Postel and Richter 2003; Auerbach et al. 2012; Webb et al. 2015), hydrological flows dictate much of the ecology of the Delta. Delta Smelt and their predators respond differently to patches of high-turbidity water, migrating salmon seek out streams of cool water that provide connectivity, and the shifting boundary of the low-salinity zone (X2)[2] determines the distribution of pelagic organisms that are the foundation for aquatic food webs. Where channels intersect, complex and tidally changing flow dynamics affect how both actively migrating and passively drifting organisms distribute among the channels. Small changes in the physical structure of a channel can create fine-scale turbulence and eddies that provide feeding and resting opportunities for fish (Bennett and Burau 2015). At a broader scale, tidal surges, releases of cold water from upstream reservoirs, floods, droughts, and changing diversion patterns create highly variable temporal dynamics. These dynamics are what make management of the water and its occupants so difficult. Terrestrial landscape managers can change the structure of a mosaic and the changes will stick, at least for a while. Similar kinds of changes are much more difficult in the water. Managing landscapes in water is a slippery business. Modern fluid-dynamics models (e.g., Fong et al. 2009; Monismith et al. 2014) may allow one to build models of Delta channels and channel junctions and test how modifying the physical configuration would affect the waterscape. Provided one knew what kinds of fluid-dynamic features one wanted, the Delta could be restructured to provide those features. Moyle et al.'s (2010) proposal to reconfigure Delta channels to be more structurally complex so as to create spatial variation in water-residence time and local productivity reflects this kind of landscape thinking.

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[2] X2 is the distance, measured upstream from the Golden Gate Bridge, where salinity at the river's bottom is about 2 parts per thousand (ppt).

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SETTING THE STAGE: HISTORICAL LANDSCAPE CHANGE

Although we are constrained to manage landscapes (and waterscapes) in the Delta as they are now, history leaves its imprint on the present. Understanding past landscapes can provide a useful perspective on the interplay among structure, function, change, and scale.

According to the detailed historical ecology investigations carried out by the San Francisco Estuary Institute (Whipple et al. 2012; SFEI–ASC 2014), landscapes in the Delta before the major modifications of the 19th and 20th centuries had a finely reticulated structure of water, wetlands, and riparian and terrestrial vegetation, all functionally linked together and all subject to the time and space dynamics of tides and river flows. The aquatic ecosystem was a complex, fine-scale mosaic of patches that differed in depth, velocity, turbidity, salinity, and water-residence time. Tidal and freshwater wetlands and riparian woodlands linked the water to the land, promoting exchanges of nutrients and organic material that were the foundation of the aquatic food chain. Seasonal flooding reworked and redistributed sediments, activating foodwebs in enormous off-channel flood basins and creating and maintaining natural levees and complex river habitats. The seamless linkages among habitat types allowed unobstructed movement of organisms and materials, so there was a high degree of connectivity between adjacent habitats—organisms that depended on more than one habitat type had easy access to virtually any Delta habitat.

That is how the Delta used to be. But even then the landscapes and the ways they functioned were not the same everywhere in the Delta. At a broad scale, landscapes in different regions of the Delta were structured and functioned in different ways that reflected differences in the interplay among river hydrology, topography, and tides (see Figure 4; Whipple et al. 2012). The same was true of Suisun Marsh, where distinct subregions were defined by different geomorphologic and hydrologic processes (Manfree 2014).

These broad sub-regions of the Delta and Suisun Marsh were, in turn, mosaics of habitat patches. The modern Delta is also a mosaic of habitat patches, but the extensive marshes with their associated tidal channels have been almost entirely replaced by diked agricultural lands and the branching network of sloughs and channels has been straightened and simplified by levees lined with riprap rather than by wetland or riparian vegetation (SFEI–ASC 2014; Figure 1). Much of Suisun Marsh is similarly diked and is managed for waterfowl production by duck-hunting clubs (Moyle et al. 2014). Instead of the extensive and highly productive wetland transition zones between upland and water of historical landscapes, terrestrial and aquatic systems are now functionally partitioned. Instead of dendritic channels with variable water-residence times and complex productivity, channels are now mainly uniform and trapezoidal—they are designed to convey water efficiently, not to provide habitat for aquatic species. Instead of a terrestrial mosaic that provides habitat for many species, large areas are now dedicated to specific human uses. These dramatic changes in the structure and function of the Delta landscape place severe constraints on the Delta's ability to support many native species, which poses a formidable challenge to managers.

CASE STUDIES OF LANDSCAPE CHANGE OVER TIME IN THE DELTA

A premise of landscape ecology is that that what happens in one place is contingent on structure, function, and change in the broader landscape—and everything is affected by scale. The only constant seems to be that "it all depends," which may explain why the incorporation of a landscape perspective into management, conservation, and restoration in the Delta has been slow. To illustrate how a landscape perspective can help to provide a foundation for management in the Delta, we now consider three case studies. The first two draw from the historical landscape studies conducted by the San Francisco Estuary Institute (Whipple et al. 2012, SFEI–ASC 2014); the third provides a landscape perspective on an ongoing restoration effort (Beagle et al. 2013).

Inundation

Historically, inundation shaped the Delta landscapes. At the regional scale, the Delta was a meeting area of two great rivers coming from the north and south,

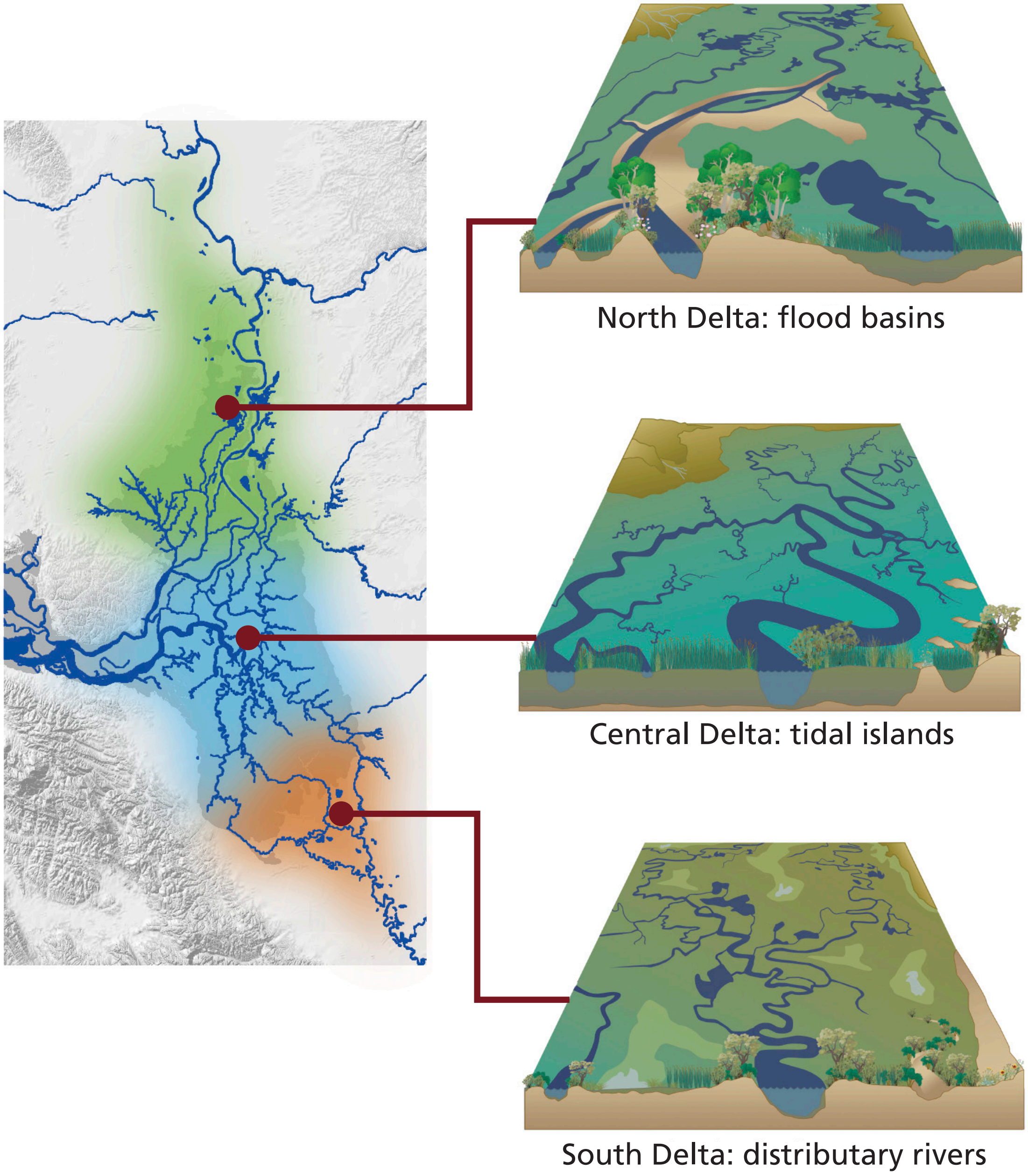


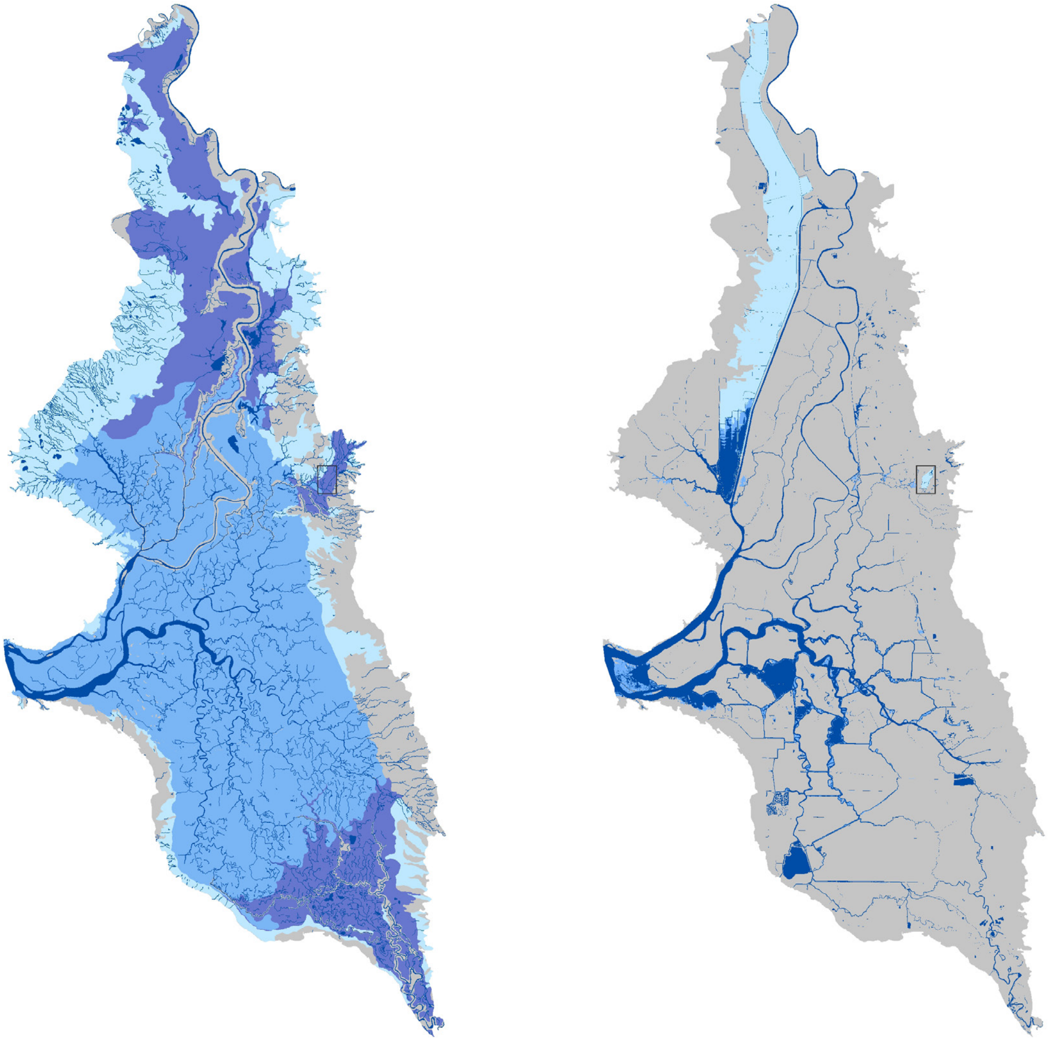
Figure 4 The three primary landscapes of the historical Delta. The map indicates the general extent of the north Delta (a landscape of flood basins, shown in green), central Delta (a landscape of tidal islands, shown in blue), and south Delta (a landscape of distributary rivers, shown in brown). Conceptual diagrams illustrating the variation in habitat mosaics among these landscapes are shown to the right. Source: Whipple et al. (2012).

with smaller tributaries entering from the east, and the tidal waters coming from Suisun Bay to the west. The intersection of these physical forces with varying climatic settings led to the development of distinctly different landscapes in the north, central, and south Delta (Whipple et al. 2012; Figure 4). In the central Delta, millennia of marshland peat formation created a flat topography where tidal inundation dominated and immense islands of tules grew between large tidal channels. These islands were wetted twice daily and flooded on spring tides. A dendritic network of tidal channels distributed nutrients, organic materials, and organisms into and out of the freshwater marshes. In the north Delta, strong seasonal flooding from abundant rain runoff and snowmelt in the northern Sierra watershed inundated extensive stands of non-tidal marshes for months at a time every winter and spring. Floods created broad, elevated natural levees that supported well-developed riparian woodlands. In the southern Delta, the snowmelt-driven flooding from the higher-elevation southern Sierra watershed peaked later in the year, providing spring-to-summer inundation that created a complex mosaic of oxbow lakes, off-channel ponds and slow-moving water. Natural levees were not as high as in the north Delta, and the topographic gradient was more gradual, creating a broad transition zone between fluvial and tidal influences. Around the edge of much of the Delta, wet meadows and small tributaries flooded for just a few days or weeks many times over the wet season, creating a soft transition from the vast Delta wetland to the adjacent uplands. On the western edge, sand mounds (remnants of Pleistocene dunes) rose above the marsh, providing high-tide refuges for terrestrial species in an otherwise wet landscape.

Across the Delta, these different types of floodplain habitat constantly shifted from wetter to drier and back again on different time-scales and at different times of year. These spatial and temporal dynamics supported a complex set of ecological functions. As an example, we can surmise how food webs might have been affected by inundation, using our current knowledge of wetland ecology to fill in the blanks where historical records are lacking. During the driest and warmest times of the year, in late summer and early fall, the central Delta marsh would have been flooded with the tides, while lakes in the north Delta would remain wet. Then, as rains came in the winter, the extensive northern flood basins would start to fill, activating food webs based on algae, wetland plants, and fluvial inputs that supported abundant invertebrates. Fish from the lakes, rivers, and tidal channels would spread out across the flooded basins to eat, followed quickly by wading birds, diving birds, mammalian predators, and any other consumers that could arrive to the feast (including indigenous people). This productivity throughout the spring would be punctuated by the shorter-duration floods at the edge of the Delta, which would activate food webs for cranes, amphibians, reptiles, and smaller terrestrial carnivores. As the north Delta inundation began to wane, the south Delta would flood from the San Joaquin River, and the complex distributary river habitats would feed invertebrates, fish (especially salmon; Sommer et al. 2001; Jeffres et al. 2008), and a variety of terrestrial consumers that could access the mosaic of shallow habitats. Thus, landscapes in different parts of the Delta would support food webs in different ways year-round, always characterized by extensive land–water connectivity driven by inundation.

The functional importance of this floodplain connectivity is illustrated by the consequences of recent breaching of levees at several locations within the Cosumnes River Preserve (Swenson et al. 2012), which allowed seasonal flooding of the land behind the levees. Juveniles of numerous fish species rapidly moved into the floodplain to feed in the seasonally available habitat. Juvenile salmon grew better in the seasonally flooded habitat than in either permanent ponds on the floodplain or in the adjacent river channel (Jeffres et al. 2008). Native and alien species also responded differently to inundation, native species being most abundant on the floodplain during larger scale flooding in spring when water temperature was cool (Crain et al. 2004).

Overall, the changes in inundation patterns of Delta landscapes have been profound (Figure 5). The wetland components of the landscape are mostly gone. The scales of floodplain inundation over space and time are now orders of magnitude less than they once were. Delta landscapes have changed from a dynamic, ceaselessly shifting wetland and aquatic mosaic of intricate complexity to a terrestrial landscape with stable patchiness (Figure 1), in which the aquatic



🟦 **SEASONAL SHORT-TERM FLOODING**

Short-term fluvial inundation

- intermediate recurrence (~10 events per year)
- low duration (days to weeks per event)
- generally shallower than seasonal long-duration flooding

🟦 **SEASONAL LONG-DURATION FLOODING**

Prolonged inundation from river overflow into flood basins

- low recurrence (~1 event per year)
- high duration (persists up to 6 months)
- generally deeper than seasonal short-term flooding

🟦 **TIDAL INUNDATION**

Diurnal overflow of tidal sloughs into marshes

- high recurrence (twice daily)
- low duration (<6 hrs per event)
- low depth (“wetted” up to 0.5 m)

🟦 **PONDS, LAKES, CHANNELS, & FLOODED ISLANDS**

Perennial open water features (with the exception of historical intermittent ponds and streams)

- recurrence not applicable (generally perennial features)
- high duration (generally perennial features)
- variable depth

Figure 5 Approximate maximum extent and type of inundation in the historical (left) and modern (right) Delta. While the extent of perennial open-water features has increased over time, areas that experience tidal inundation, seasonal short-term flooding, and seasonal long-duration flooding have all decreased in extent. Source: SFEI-ASC (2014).

components are spatially well defined, temporally much less dynamic, and generally closely regulated. The largest floodplain of the Sacramento River, the Yolo Bypass, rarely floods enough to achieve significant food-web activation (SFEP 2015). In the rare years when the Yolo Bypass is fully inundated, the flood lasts for just a few days and covers only a small fraction of the extent of the historical north Delta flood basins (Figure 5). The San Joaquin River has little active floodplain (although some areas have been re-established on the Cosumnes River).

Given the magnitude of these changes, the goal of management and restoration should not be to replicate the historical hydrodynamics of the Delta, but instead to use this historical information to help determine where in the landscape re-establishment of more natural hydrodynamic processes might most effectively support ecosystem functions such as food-web dynamics.

Riparian Woodlands

Although the loss of riparian woodlands since the early 1800s may seem moderate in comparison with loss of marshes, the changes in the landscape structure of riparian patches are arguably more profound (Figure 6). Historically, the woody riparian areas of the Delta were connected, dendritic networks that were built and maintained by sediment from flooding rivers. They were like long, spidery fingers that spanned enormous distances along fluvial channels. With its massive floods and high sediment load, the Sacramento River created by far the largest of these riparian networks—gallery forests of oak and sycamore with multi-layered understories that provided structurally complex habitat for wildlife. The San Joaquin River maintained a smaller network of narrower woody riparian areas dominated by willows and other shrubs. The Cosumnes River had a still smaller woody riparian network.

The structure of riparian habitats influenced ecological functions at several scales. At the landscape scale, woody riparian habitats were highways for terrestrial animals to move deep into the marsh and floodplains—a way to get to the wetland food resources on offer. Larger species like mule deer and coyotes could travel down the riparian corridors and then work along the marsh edge to forage. Smaller species like insectivorous bats and birds would have used the riparian structure for cover while hunting along the edge of the marsh or the channel. Thus, woody riparian tendrils greatly increased the amount of wetland edge accessible to terrestrial wildlife. At the local scale, the structural complexity of woody riparian areas offered cover from predators, shelter from the elements, and reproductive sites for a diverse suite of animals, from spiders to birds to medium-sized carnivores.

Woody riparian areas were shaped by regular flooding regimes that varied in intensity according to the water year. While the main channels within the tidal zone were probably fairly stable, flooding could scour and rebuild physical substrate, resetting plant-community succession. The floods would also have shifted the entire landscape to a temporary semi-aquatic state, with rapidly increasing productivity, and a host of animals arriving to consume it.

Although woody riparian areas still occur widely in the Delta, their structure is greatly altered, especially at the landscape scale. Large natural levees are now occupied by orchards and towns along the Sacramento River, and are used for agriculture along the San Joaquin. Where two large, contiguous woody riparian networks once flanked the great rivers in the north and south Delta, thousands of tiny riparian fragments are now scattered widely across the Delta's artificial levees, mostly in places where woody riparian plants did not historically occur (SFEI–ASC 2014; Figure 6). These fragments are much narrower than the historical gallery forests, and the adjacent habitats have largely changed from marsh to agriculture. At a finer scale, the riparian structure has shifted to younger and smaller trees, often of non-native species. Present-day woody riparian areas still support some riparian wildlife, but the ecological functions have diminished as the structure and flooding regimes have been altered. Riparian corridors no longer provide uninterrupted pathways to productive areas for terrestrial animals to feed. Animals living in most woody riparian fragments are subjected to the effects of diminished patch size, severed connections, and increased threats from the surrounding landscape.

The most obvious management and conservation solution to these problems is to restore more riparian

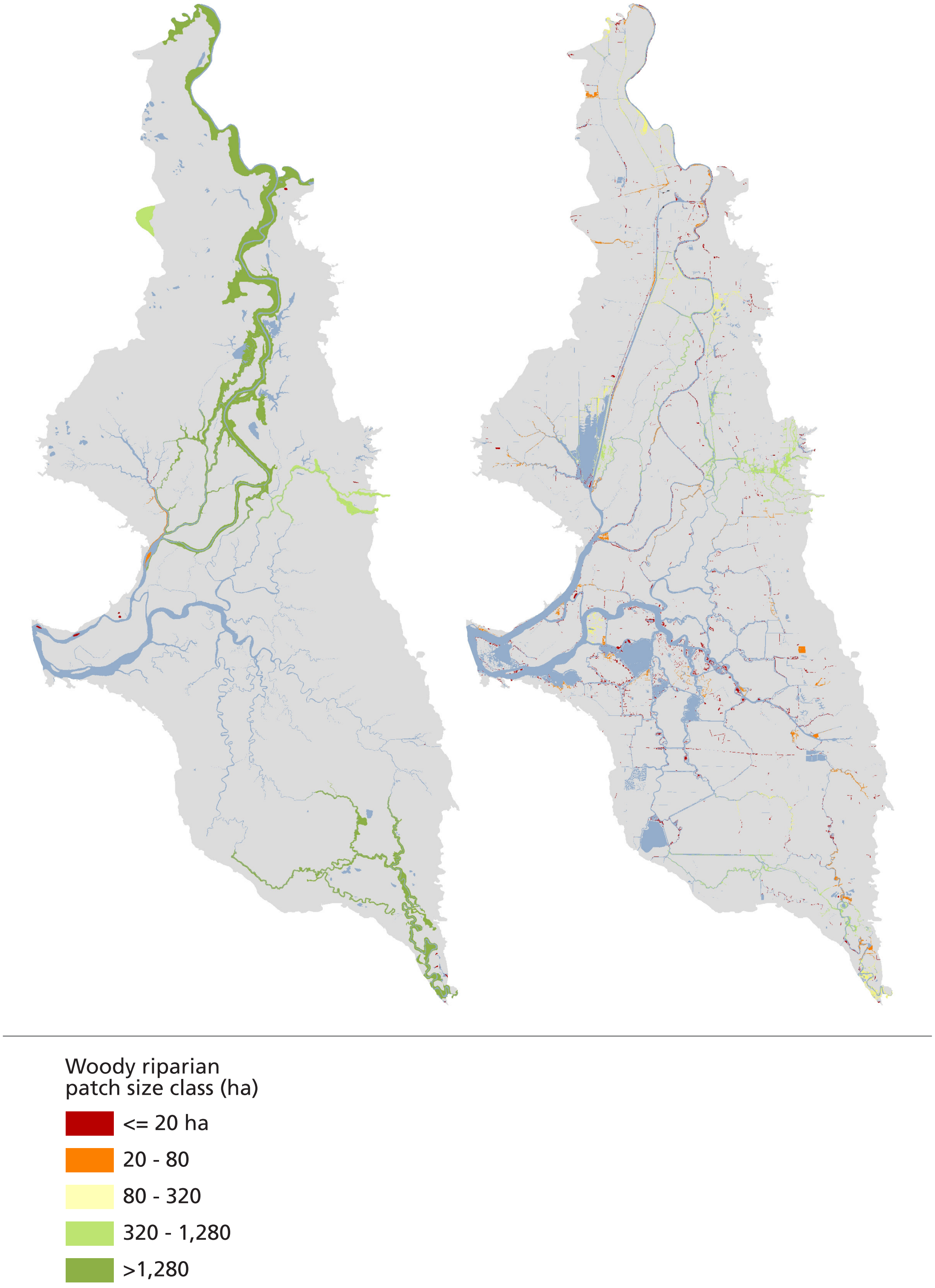


Figure 6 Historical riparian habitat was predominately continuous forest (left), while today woody riparian habitat is scattered throughout the Delta in small isolated patches (right). The longest stretch of contiguous riparian forest historically spanned more than 55 km, providing a migration corridor across much of the Delta. The longest current stretch of woody riparian habitat extends 16 km. Source: SFEI-ASC (2014).

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woodland habitat in contiguous networks adjacent to marsh. But there are also obvious constraints. Most levees in the Delta are, at best, suitable only for narrow strips of riparian vegetation, and there is continuing controversy about whether woody vegetation on levees is a good or a bad idea (i.e., providing wildlife habitat versus weakening levees by rooting or harboring burrowing mammals). The opportunities to expand riparian woodlands may be greatest where levee set-backs are part of a restoration plan. However, re-establishment of riparian woodlands should consider the adjoining hydrology (e.g., seasonal flooding, sediment deposition or erosion) and the composition of the surrounding terrestrial or wetland landscape—whether it will support predators that prey on animals in the riparian zone or provide additional food sources. Placing riparian management and restoration in a landscape context requires data and careful thought (and spatial modeling wouldn't be a bad idea), but it can help to determine the potential effectiveness of actions.

Changes in a Delta Island: The McCormack–Williamson Tract

A landscape perspective is particularly relevant to habitat restoration. Restoration is generally undertaken on small parcels because the availability of suitable places is limited and the per-acre costs of restoration can be large. However, the parcels are parts of broader landscapes, which can alter the effectiveness of the restoration.

One of the largest restoration efforts underway in the Delta is the McCormack–Williamson Tract (MWT), a 1,645-acre (6.6-km^2) property along the Mokelumne River in the northeast Delta (Figure 1). Historically, the MWT lay at the transition between tidal and fluvial influences (Figure 3) (Beagle et al. 2013). Shallow but frequent tidal flows entered the island on its western side. Deeper and longer-duration riverine flood flows would spread across the MWT from the north as the Sacramento flood basin filled with snowmelt and runoff. The eastern side of the MWT was defined by the natural levee of the Mokelumne River, which supported a broad riparian forest that contrasted with the tules and freshwater wetland vegetation of the rest of the island. Because of this natural levee, hydrological connectivity to the Mokelumne was probably restricted to high-flow events that would overtop the levee and flow through the forests into the MWT. This landscape structure of varying elevations and modes of hydrologic connection supported a dynamic and complex array of floodplain and riparian functions.

The MWT is now hemmed in on all sides by artificial levees. Except for unusually extreme flood events, the levees block hydrologic connectivity, creating a terrestrial environment suitable for agriculture. The restoration efforts aim to reintroduce tidal and fluvial flood flows to the island by opening strategic breaches in the levee system. Re-establishing hydrologic connectivity will allow these flows to restructure the landscape into spatial patterns organized by a dendritic tidal-channel network with varying water depth and chemistry that change with tidal and seasonal cycles. Hopefully, this new structure will support aquatic species and food webs that have long been missing.

Of course, the MWT is also part of a larger landscape. This limits how far restoration of connections can proceed, at least over the short term. The perimeter levee must be maintained to ensure that adjacent properties are protected from flooding. This precludes the potential for restoring habitat connectivity to the mature Delta Meadows marshland immediately to the west, which would create a larger wetland complex with greater diversity. It also precludes the re-establishment of a self-maintaining riparian forest on the natural levee of the Mokelumne River, one of the few locations in the Delta suitable for such restoration at a significant scale. These current barriers to landscape linkages also prevent connecting the marsh plain and potential riparian forest to adjacent landscape features immediately upslope, which would enable tidal and low-elevation species and habitats to move upstream as sea level rose.

Although the MWT is large as restoration projects go, it is small compared to the expanse of marshes in the historical Delta, where 98% of the marsh was in areas of 2500 acres (1000 ha) or larger. Today, there is not a single marsh patch of that size. This fragmentation limits the ability of Delta marshes to support physical and ecological processes (SFEI–ASC 2014). If the MWT could be connected to neighboring existing (and future) marshes, it could create a large marsh complex that supported landscape processes at a scale currently not represented in the Delta.

Thus, while some of the natural structure, function, and dynamics of Delta ecosystems can be restored within the landscape of the MWT, the restoration can be only a piece of a broader landscape subject to multiple uses (Figure 1). Expanding the scale in space and time indicates several actions that could be undertaken within or beyond the MWT to enhance the restoration effectiveness (Figure 7). For example, when the lease on a radio tower located within the MWT expires, the parcel could become available for expanding wetlands or other landscape elements. At a broader spatial scale, acquiring properties that would link the MWT with other restored or protected lands, such as the Cosumnes Preserve, could help to restore overall landscape functionality. In a similar fashion, the Regional Restoration Strategies recommended in the Delta Plan (DSC 2013) and California EcoRestore[3] can be part of a larger vision to restore more functional and resilient landscapes in the Delta.

CONCLUDING COMMENTS

Landscape ecology has a well-established foundation as a basic and applied science. Yet its application to resource management and restoration has come slowly to the Delta. *The State of Bay–Delta Science, 2008* (Healey et al. 2008) acknowledged the holistic nature of the Delta, the importance of land–water linkages, the importance of connectivity, and the reality of landscape change. *Luoma et al. (2015)* emphasize similar points. But the specifics of just *how* differences in particular features of landscape structure can influence specific functional properties of ecosystems; *how* the dynamics of change differ in different places in a landscape; *how* linkages or boundaries among landscape elements affect movements of contaminants or invasive species; *how* different scales of management or analysis may affect the outcomes of actions—these were, and still are, largely missing from Delta science. Even though the Delta is one of the most intensively studied ecosystems in the world, applications of landscape science, concepts, and thinking have lagged behind.

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[3] *http://resources.ca.gov/ecorestore/*

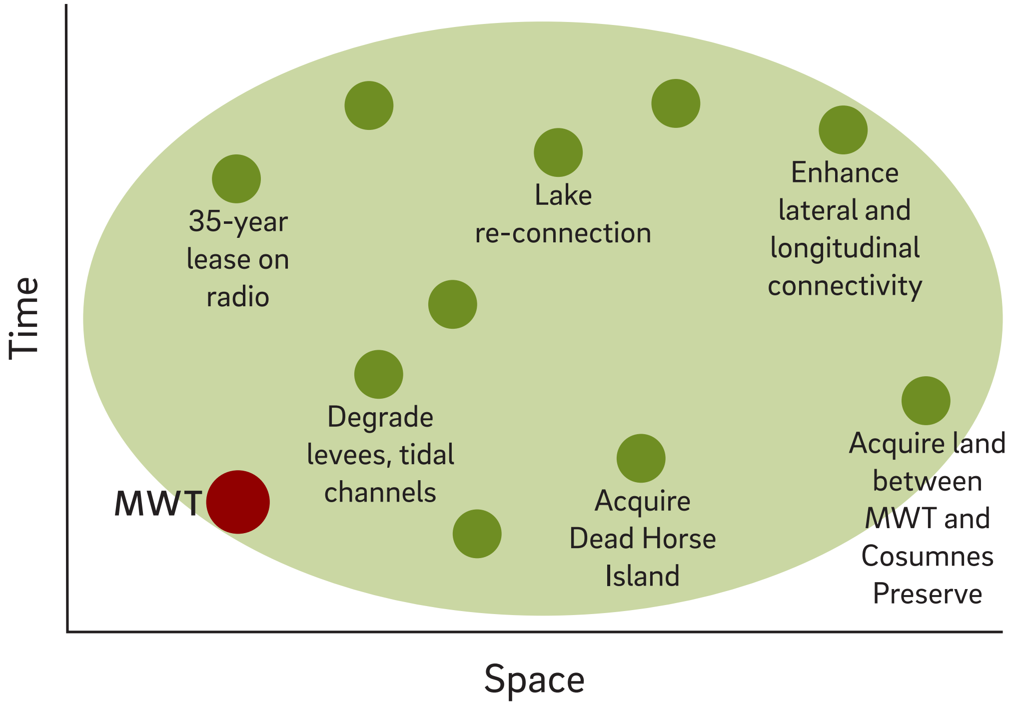

Figure 7 Several options for expanding the time and/or space scales of restoration of the McCormack–Williamson Tract (MWT). Adapted from Beagle et al. (2013).

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There are many reasons, not the least of which is the combination of the complexity of Delta ecosystems, the decades of controversy over water allocations and management, and the byzantine web of agencies, jurisdictions, and agendas that determine management practices. All of these reinforce a tendency to focus on individual sites or projects, divorced from their broader landscape context. The overwhelming emphasis on aquatic systems and the associated focus on getting hydrological flows "right" (however defined) has also fostered a neglect of landscapes that integrate land, water, and the places in between. A synthetic, landscape approach is needed in Delta science.

RECOMMENDATIONS

We suggest that several actions might help us reach this goal. These echo the recommendations offered by *Luoma et al. (2015)*, but with an emphasis on landscape and spatial data and analysis.

- Develop a holistic landscape vision across broad areas or regions of the Delta, to integrate aquatic habitats with terrestrial and wetland habitats, emphasize functional interconnections, and capture synergies among individual projects;
- Foster inter-agency collaboration for landscape structure and functions rather than (or in addition to) traditional agency domains and agendas. Agencies cannot afford to collaborate everywhere, so orienting their shared activities about shared landscapes makes sense;
- Develop a spatial information management system. Common libraries of digitized, spatially explicit information on multiple aspects of landscapes (e.g., Figure 1) can help to show how actions on some elements of a landscape in some places will affect and be affected by the structural configuration of other elements or places in a landscape;
- Analyze spatial data on multiple physical, chemical, and ecological factors to identify the spatial relationships of opportunities and constraints, and show where the return on investment in habitat restoration may be greatest;
- Enhance scientific capacity in landscape modeling and quantitative analysis. Spatial modeling is often the quickest and most efficient way to integrate disparate kinds of information into a common landscape setting, and to explore alternative restoration or management options;
- Use spatial analyses and landscape maps to overlay projects, agency responsibilities, key resources, land uses, ownership, species distributions, or ecological functions to show where opportunities to integrate projects and actions might exist, or which habitat patches and physical processes need to be in place in which areas of the Delta for the landscape to support key life stages of a given species;
- Finally, consider the scale(s) of management or restoration actions and the anticipated and actual responses, and use landscape analyses to ensure the compatibility of the scale(s) of actions and desired outcomes.

Currently, landscape science in the Delta might be characterized as a state of general awareness of landscapes and multiple perspectives about what is important about them. Building on this awareness requires a greater depth of understanding of the details of landscape structure, function, change, and scale and how they apply to the Delta. The concepts and tools of landscape ecology are well developed; they now need to be applied and integrated to determine how a landscape approach can enhance the effectiveness of management and restoration in the Delta.

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