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The Science of Non-native Species in a Dynamic Delta

Delta Independent Science Board

Draft Report (October 26, 2020)

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Executive Summary

The invasion of non-native species is considered one of the greatest global threats to the ecological integrity of ecosystems. Non-native species impact nearly every facet of ecosystem services and sustainability, including habitat structure, nutrient and contaminant cycling, water transportation, drinking-water quality, food-web dynamics, endangered species, fisheries, and even the consequences of water flow on species. The breadth and interdependent nature of these impacts means that non-native species impinge on the responsibilities of many agencies and affect a broad range of stakeholders.

The California Bay-Delta is one of the most invaded estuaries in the world. Indeed, non-native species are a large part of what is now the Delta ecosystem. The invasion of new non-native species threatens the Delta Plan's coequal goal of "protecting, restoring, and enhancing the Delta ecosystem." The importance of this issue was recognized by The Delta Reform Act, which stipulated that the Delta Plan should restore a healthy ecosystem by promoting "self-sustaining, diverse populations of native and valued species by reducing the risk of take and harm from invasive species."[1] Reducing the impact of non-native species is also one of the core strategies highlighted in the Ecosystem Amendment to the Delta Plan.

The Delta Independent Science Board (Delta ISB) undertook this review to better understand the scientific needs related to this complex issue. The Delta ISB is charged with the "oversight of the scientific research, monitoring, and assessment programs that support adaptive management of the Delta

[1] California Water Code Section 85302(e)(3).

through periodic reviews…” The comments, findings, and recommendations from the Delta ISB are designed to increase scientific credibility, improve research clarity, advance the debate about Delta issues, and seek better connectivity among science, management, and policy.

The science related to invasions and non-native species is extensive and spans over half a century. Research on and advances in invasion theory, ecosystem function, invasive pathways, taxonomy, eDNA, risk assessment, monitoring and detection technology, impact assessment, control, and adaptation continue to grow. The basic scientific needs to better prevent, control, and ultimately manage invasive species are similar across ecosystems. Many of the technologies and analytical techniques used in estuarine and aquatic systems elsewhere have direct applications to the Delta and there has been a tremendous amount of research done on non-native species in the Delta. What is unique in the Delta are the institutional arrangements, responsibilities, scientific collaboration mechanisms, and funding structures to handle this issue.

It is beyond the scope of this review to summarize all of the scientific information or to list all of the project-, species-, geographic-, or technology-specific science or monitoring that has or should be done. Rather, we focus our findings and recommendations on a higher-level approach to Delta-wide needs that span multiple agency responsibilities. We aim to provide managers with a science-based prioritization framework to make decisions. We use examples from the Delta to support our findings.

Our approach in this review differs somewhat form other Delta ISB reviews because the topic has such a wealth of published information and ongoing studies. The review process included an extensive literature review, two panels each composed of five experts who explored the status of science relative to non-native species in the Delta and public comment. Additionally, Delta ISB members participated in several invasive-species workshops and scientific sessions, presentations, and discussions with managers.

We begin the review by providing a broad context for considering non-native species in a dynamic Delta. We point out that the Delta is one of the most modified estuaries in the world and that the major forces driving environmental changes in the Delta continue, some at an accelerated pace. These changes affect the vulnerability of the Delta to new invaders. We then define terms and discuss the invasion process. We point out the essential ingredients of a successful invasion and introduce the concept of a continually changing species pool within the Delta ecosystem that is tightly connected to the drivers of ecosystem change (e.g., climate, resource use, habitat alterations, pollution) and ecosystems services. We provide an overview of the individual-species approach to invasive species prevention and management. We illustrate how science informs management decisions at each of the stages in dealing with a potential invader, from threat assessment to early detection and rapid response to control and, ultimately, adaptation.

We consider how ecological restoration may affect and be affected by non-native species, and how the continual threats from non-native species affect and are affected by the practice of adaptive management. We highlight areas in which scientific knowledge or its application in the Delta relative to the influx of non-native species could be expanded and better coordinated.

Throughout, we offer recommendations to strengthen the prevention and management of non-native species in the Delta.

Detailed findings and recommendations can be summarized into five categories;

1. **Improve the science capabilities for the Delta**

   - **The Delta ISB recommends the development and testing of a comprehensive, spatially explicit, food-web model for the Delta. This model should be Delta-wide in scope, tied to environmental driving forces and conditions, and be available for use by decision-makers.** Such a model would help to identify gaps in knowledge and could be used to:

     - Improve our mechanistic understanding of the role of non-native species currently in the Delta.
     - Predict potential impacts of new invaders on ecosystem structure and function and ecosystem services.
     - Assess threats of invasive species in the context of a changing environment and multiple drivers, especially climate change.

   - **Conduct a series of focused workshops or syntheses to develop a detailed set of Science Priorities for dealing with non-native species that defines short-term and long-term science needs and improved understanding of the impacts of established invaders.**

2. **Prioritize current management actions**

   - **Develop a prioritized list of species that pose the greatest threat to the California Delta in the immediate and long-term future.** This should include an evaluation of the expected ecosystem and economic impacts of each high-risk invader and an evaluation of likely pathways of introduction. A quantitative assessment would allow monitoring and rapid response efforts to be prioritized for species that need the most attention.

3. **Shift focus to an ecosystem level**

   - **The Delta ISB recommends that management needs to move beyond individual species management to address how to set ecosystem goals in recognition of an ever-changing species pool and high uncertainty. This would include the formal implementation of non-native species management and research into ecosystem restoration programs.** The management protocols for preventing, detecting, minimizing the impacts, and adapting to individual non-native species are well established and largely adopted at the state and national levels. The approach of focusing on individual invader species one at a time has been valuable, although not always effective. However, the rate of invasions and the impact of non-natives on ecosystem structure and function are closely linked to other fundamental drivers of ecosystem change, including climate change, resource use, pollution, habitat alteration, and extreme events. Given that the Delta ecosystem has been greatly modified, is already highly invaded with a host of well-established non-native species, and, like many other ecosystems, is undergoing continual and increasingly rapid change, one might ask: What is the appropriate goal for non-native species management? We can expect that the species pool will continually change and management will need to adapt to the changes. Setting ecosystem-level performance measures for restoration and adaptive management in a dynamic Delta would improve "protecting, restoring, and enhancing the Delta ecosystem."

4. **Consider future changes in the Delta**

   - **Ongoing threat assessments for invasive species should be evaluated in the context of a changing environment and multiple drivers, especially climate.** Climate change can alter the types and rates of invaders and impacts. We recommend that climate-change scenarios be incorporated into all management or policy actions regarding non-native species and that a standard climate-change model for the Delta that includes sea-level rise, hydrodynamics, and changes in temperatures should be developed to enhance threat assessments for future invaders and changes in populations of current non-native and native species.

5. **Implementation**

   - **Form a Non-native Species Task Force or Non-native Species Science Center to complement or expand the communication and coordination functions of the Delta Interagency Invasive Species Coordination (DIISC) Team by developing a single 'go to' science**

source of expertise, and information with proper authorization and funding.

- **Develop a comprehensive invasive-species coordination plan with an outline of responsibilities and authorities that span monitoring, rapid response, control and science expertise.**

The Delta ISB's overall recommendation is to **encourage a broader, more forward-looking, integrated approach to non-native species science in the Delta to inform management goals.** Multiple agencies, workgroups, and committees have some coordination, communication, and planning responsibilities within the Delta (and the State of California). Non-native species are a fundamental part of the Delta ecosystem and a fundamental driver of ecosystem change. New invaders could disrupt essential services to Delta stakeholders. A high-level, coordinated approach to the science and management of invasive species would address this growing problem.

Introduction and Rationale

The invasion of non-native species is considered one of the greatest global threats to the ecological integrity of ecosystems and may have contributed to 25% of the global plant extinctions and 33% of the animal extinctions (Pysek et al. 2020). Invasive species[2] are considered to be one of the fundamental drivers of ecosystem change and have decimated populations of native species and disrupted natural and managed ecosystems throughout the world (Pysek et al. 2020). The introduction of Nile perch (*Lates niloticus*) to Lake Victoria in Africa in the 1950s, for example, caused the extinction of many species of endemic cichlid fish and indirectly led to the eutrophication of the lake ecosystem (Marshall 2018). Doherty et al. (2016) implicated invasive predators in 58% of the contemporary extinctions of mammals, birds, and reptiles worldwide. For example, Burmese pythons (*Python bivittatus*), first found in the Florida Everglades in 1979, have reduced populations of some native mammals by as much as 99%. The Great Lakes of North America provide an example of one of the most invaded ecosystems in the world where nearly every facet of management and regional economy is impacted by invasive species (see Box 1).

[2] We discuss what this term means on page 9.

Box 1. The Great Lakes and Invasive Species

The Great Lakes are one of the most well-studied and invaded ecosystems in the world where nearly every aspect of management is impacted by invaders (Egan 2018). Like the Sacramento-San Joaquin Delta, the Great Lakes' aquatic ecosystem developed following the last Ice Age, except in this case it was the recession of continental glaciers rather than rising sea levels that opened the Great Lakes to become a new aquatic ecosystem. The native species that developed were from remnants in local and regional streams, and a few that swam upstream. The Great Lakes' topography, particularly Niagara Falls, limited species introductions until commercial navigation expanded in the early 1800s with the construction of New York's Erie Canal and the Welland Canal in Canada that linked the lower Great Lakes to the upper Great Lakes.

Among these invasive species was the sea lamprey (*Petromyzon marinus*), which over several decades spread through the Great Lakes depleting native predator fish particularly the lake trout, which lacked any defenses. After years of scientific study, it was found that sea lamprey could be suppressed (but not eliminated) by treating specific stream reaches with a species-specific poison at specific times of year when they were most vulnerable. Sea lamprey populations were reduced by about 90% but control efforts continue, costing more than $20 million annually (Kinnunen 2018).

Alewife (*Alosa pseudoharengus*) also entered the Great Lakes, moving with commercial navigation and replacing intermediate species in the food web. With sea lamprey suppressing native predators, alewife boomed so high, they experienced massive annual dieoffs that had to be removed from Chicago beaches by bulldozers. Commercial fishing began on alewife. To help control the alewife population, several species of pacific salmon (*Oncorhynchus* spp.) were introduced (Parsons 1973). These species survived well in the Great Lakes and triggered a massive sports fishery that bought billions of dollars annually to the Great Lakes. Annual stocking of (non-native) salmon raised in hatcheries became a major fisheries management priority and rates are tied to production of its main prey, the non-native alewife.

The opening of the Saint Lawrence Seaway also brought larger, faster commercial ships and their ballast water to the Great Lakes, resulting in the new introduction of a wide range of species. Most notably, the introduction of Zebra mussels (*Dreissena polymorpha*) to the Great Lakes in the late 1980s is considered the poster child of a successful invader. It has had profound impacts on the ecology and economy of the Great Lakes that range from clogging of water intakes for drinking and water power operations (estimated costs into the billions) to loss of native clams to the decimation of primary production and disrupted food webs including the salmon recreational fishery. [Interestingly, the invasion of the Great Lakes by zebra mussels was predicted more than a century before, based on shipping connections between the Great Lakes and areas where the mussel was well established; Carlton 1991.] Quagga mussels (*Dreissena bugensis*) invaded similarly a few years later, and have largely out-competed Zebra mussels throughout the deeper portions of Great Lakes. Both mussels have since spread throughout much of the Midwest and well into the west including California, Nevada and Texas.

There is now concern about further invasions, including the movement of several Asian carp species (*Cyprinus* spp.) up the Mississippi River to the Great Lakes through the Chicago Sanitary and Ship Canal, built in 1900 to remove Chicago-area sewage from the basin and to promote commercial navigation.

The Sacramento-San Joaquin Delta (hereafter, "Delta") has not escaped the reach of invasive species; indeed, the San Francisco Bay-Delta ecosystem is one of the most heavily invaded ecosystems on the globe. Indeed, non-native species are a large part of what is now the Delta Ecosystem. Non-native species impact nearly every facet of ecosystem services and sustainability, including habitat structure, nutrient and contaminant cycling, water transportation (e.g. clogged waterways), drinking-water quality, food-web dynamics, endangered and native species, fisheries, and even the consequences of water flow on species. And, most recently, nutria (*Myocastor coypus*) threaten wetland vegetation, agriculture, and human infrastructure in the Delta (see Appendix A). The breadth and interdependent nature of these impacts means that non-native species impinge on the responsibilities of many agencies and affect a broad range of stakeholders.

The invasion of new non-native species also threatens the Delta Plan's co-equal goal of "protecting, restoring, and enhancing the Delta ecosystem." The importance of this issue was recognized by The Delta Reform Act, which stipulated that the Delta Plan should restore a healthy ecosystem by promoting "self-sustaining, diverse populations of native and valued species by reducing the risk of take and harm from invasive species."[3] Reducing the impact of non-native species is also one of the core strategies highlighted in the Ecosystem Amendment to the Delta Plan.

The Delta Independent Science Board (Delta ISB) undertook this review to better understand the scientific needs related to this complex issue to help agencies better understand, prevent and manage the threats and

[3] California Water Code Section 85302(e)(3).

consequences of non-native, invasive species (plants and animals) in Delta lands and waters. The Delta ISB is charged with the “oversight of the scientific research, monitoring, and assessment programs that support adaptive management of the Delta through periodic reviews…” The comments, findings, and recommendations from the Delta ISB are designed to increase scientific credibility, improve research clarity, advance the debate about Delta issues, and seek better connectivity among science, management, and policy.

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The Context of Non-Native Species in a Dynamic Delta

To understand, anticipate, and manage non-native species in the Delta, one must consider them in the context of a dynamic, globally-connected, and ever-changing environment. Two realities will influence the ability to prevent, predict, and manage invasive species.

First, today's Delta is not a pristine ecosystem. Far from it—it is one of the most heavily modified estuaries on Earth. Well before the arrival of European settlers, Native Americans altered the mosaic of species in the Delta by tending local plant species that bore acorns, fruits, and construction materials and by moving them into new locations (Zedler and Stevens 2018). Beginning with European colonization of the Americas, people mixed species between the eastern and western hemispheres (Mann 2011), a practice that has continued through to the economic globalization of today. The massive alterations that began in the mid-nineteenth century and the subsequent re-engineering of the Delta to support agriculture and manage water have accelerated successful establishment of non-native species.[4] Many non-native species have become "naturalized" members of Delta ecosystems.

Second, the major forces now driving environmental change in the Delta—climate change, sea-level rise, and human uses of land and water resources including restoration—are subject to a complex interplay of global, regional, and local influences, many of which are beyond direct management. As these driving forces mount, environmental changes are becoming more rapid, extreme events such as droughts or deluges are becoming more frequent and more extreme, and tipping points of ecosystem change are more likely to be passed—the pelagic organism decline (POD) that occurred in the Delta in 2002 is an example of a tipping point that has fundamentally altered how the ecosystem functions (Mac Nally et al. 2010). The environmental turmoil created by these forces of change will provide new opportunities for non-native species and challenge the capacity of native species to adapt, of scientists to understand and predict ecosystem dynamics, and of managers to shepherd their land and water resources responsibly.

The General Invasive Process

Findings

- The **invasive process** is the process whereby a non-native species gains access to and becomes established as a reproducing population in a new ecosystem. In general, managers have favored native over non-native species to conserve biodiversity, ecosystem services, and

[4] Whipple et al. (2012) and SFEI-ASC (2014) review the history and current status of Delta landscapes and ecosystems.

historical Native American cultural functions of land and water systems. Some general concepts about invasive species are well accepted.

- An **invasive species** is defined to be a non-native species that does or is likely to cause environmental or economic harm or harm to human health. This designation is based on a human value judgment. By this definition, all invasive species are non-native species, but not all non-native species are considered to be invasive species (i.e., cause harm).
- Non-native species are one of the five fundamental drivers of ecosystem change.
- Non-native species can disrupt food webs, nutrient and contaminant cycling, habitat structure, and ecosystem services.
- Once a new non-native species has become established in an ecosystem, the structure, composition, and likely the functioning of the ecosystem are changed.
- The species pool in an ecosystem is dynamic, leading to a continual reshuffling of native and non-native species.
- Two processes that humans can control in the invasive process are reducing or eliminating pathways and reducing ecosystem vulnerability to new non-natives.

Background and Definitions

The emergence of invasion ecology as an area of broad scientific and public concern dates from the publication of Charles Elton's book, *The Ecology of*

Invasions by Animals and Plants (1958).[5] Elton cast the challenge of invasive species using a military metaphor:

> *"I have described some of the successful invaders establishing themselves in a new land or sea, as a war correspondent might write a series of dispatches recounting the quiet infiltration of commando forces, the surprise attacks, the successive waves of later reinforcements after the first spearhead fails to get a foothold, attack and counter attack, and the eventual expansion and occupation of territory from which they are unlikely to be ousted again"* (Elton 1958: 109).

Although this militaristic metaphor may no longer be appropriate (Davis et al. 2011, Janovsky and Larson 2019), it does capture many of the features of the battle against invasive species and their characterization as harmful. Invasive species are considered to be one of the five direct drivers of ecosystem change along with climate change, resource use, habitat alteration (land use), and pollution (Millennium Report 2005). Accordingly, the literature on this topic is extensive.

The concepts of invasive and non-native species and related terms have been controversial since their beginnings. Controversies have arisen, in part, because many invasives were imported purposely to provide goods and services. The terminology for non-native species is also confusing, confounded and inconsistent (e.g., Shrader-Frechette 2001, Colautti and MacIsaac 2004). Various terms have been used to denote a non-native

[5] A collection of chapters in Richardson (2011) provides perspectives on the state of invasion ecology 50 years after Elton's book.

species, including alien, nonindigenous, exotic, invader, weed, aquatic nuisance species, introduced species, and foreign species.

The definitions are perhaps clearest in legislation and executive orders. A **non-native species** is a species that is not originally from the ecosystem in which it now occurs. The **invasive process or invasion** is the process whereby a non-native species gains access to and becomes established as a reproducing population in a new ecosystem. Following the National Invasive Species Management Plan (Beck et al. 2006), we use the definition of an **invasive species** as "a species that is non-native to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health." The National Invasive Species Council further added that invasive species are those introduced to an area as a result of intentional or unintentional human actions. In general, managers have favored native over non-native species to conserve biodiversity, ecosystem services, and historical Native American cultural functions.

By this definition, all invasive species are non-native species, but not all non-native species are invasive species. The two essential elements in the definition of an invader are that (1) the species is non-native and that (2) it causes harm. Whether a non-native species entering an ecosystem causes harm, however, is a matter of human values, which can change or differ among groups of people. Often the impact of a non-native species is unknown or not fully realized until the species is well established in the new ecosystem[6]. Any new non-native will have some impact merely because it occupies space and uses resources. The 'invader' status is subjective and ill-defined since there is no threshold of harm whereby a non-native species is redefined an "invasive" species. The degree of harm is perhaps best used as a threat assessment to prioritize management prevention, assessment and control actions.

Some species can be considered both detrimental and beneficial. For example, sport fishers in the Delta currently value non-native striped bass (*Morone saxatilis*) that were introduced and became established over a century ago, whereas others emphasize the harm the bass now may cause by preying on native fishes (Moyle 2011, 2020). Striped bass are now managed as a recreational resource in the Delta. Therefore, determining whether a species should be labeled "invasive" can depend on how people perceive the economic and environmental benefits and costs of the species and how these are balanced (Beck et al. 2006), and different people do it differently. Whether an invasive species can be managed depends not only on whether it is ecologically and economically feasible to do so, but also on whether it is socially desirable or acceptable. The continual stocking of the non-native Pacific Salmon in the Great Lakes for economic and arguable ecological benefit is a good example.

For management purposes, native species are generally considered to be those species present in an area when Europeans first arrived and described what they found. Pysek and Richardson (2010) suggest that native species

[6] For that matter, a native species may become harmful to human interests if its environmental context or human interests change.

“evolved in a given area without human involvement or … arrived there by natural means … from an area in which they are native.” Thus, species such as cattle egrets (*Bubulcus ibis*), which emigrated from their native Africa on their own and colonized much of the Americas, are not generally considered invasive. By this measure, a human vector must be involved for a species to be called invasive.

As more species expand their ranges from areas in which they are native into new areas in response to climate changes, however, determining whether a species is or is not native may be less important than determining whether it meets the second defining element: causing harm. For example, barred owls (*Strix varia*), native to eastern North America, have expanded into forests of the Pacific Northwest where they were historically not present. They compete with federally threatened northern spotted owls (*Strix occidentalis caurina*), displacing them from many areas and hastening their decline (Wiens et al. 2014). Should barred owls be considered an invasive species?

Ingredients for Establishment of a Non-native Species

The process of establishment of a non-native species in a new ecosystem can be broken into several phases (Keller et al. 2011). Here we highlight three essential ingredients for the successful establishment of a non-native species in an ecosystem.

1) There must be a **pathway or corridor** that allows the species to traverse the natural barriers that may prevent the species from getting to an ecosystem. These barriers can simply be the distance or the presence of inhospitable habitats. There are natural ways to break

through these barriers that vary from continual range expansion to changes in intervening habitat to accidental transport by another organism (e.g., aquatic organisms attaching to water birds). The success of establishment of a non-native species is often dependent on the number of introduction events and the number of individuals introduced (Pysek et al. 2020).

Human activity has created multiple pathways for invasions through deliberate release with or without intent (stocking, bait release), hitchhikers on commodities (e.g. insects) or on transport vectors (e.g. biofouling, ballast water, boats), escape from captivity (aquaria pets), or creation of anthropogenic pathways (e.g. canals and water diversions).

2) The second essential ingredient is **a match of the physical, biological, or chemical habitat requirements of the potential non-native species to those of the receiving ecosystem**. Are habitat and ecological conditions suitable for growth, reproduction and persistence of the non-native species in this ecosystem or do predators, competitors, or adverse habitat conditions restrict establishment of the new species? As ecosystems change, driven by climate, habitat alterations, pollution, extreme events, and resource use, the habitat receptivity to different types of non-native species can and will change.

   Humans have altered the receiving habitats and therefore have altered their susceptibility to invasion by different non-native species. Human alterations can include changes in hydrological flow amounts and patterns, habitat structure, species composition (resource exploitation), nutrient and pollution input, food-web disruption, and even the initial influx of non-natives that can change habitat vulnerability to additional non-native species.

Given the above, then prevention of new non-natives should be focused on reducing ecosystem vulnerability and pathway restrictions.

3) The third ingredient for the successful establishment of a non-native species is often related to the inherent biological and ecological traits of the individual species—**the habitat and reproductive requirements and abilities of the potential invasive species**. Some species are better adapted to expand and thrive in new environments because they are generalist feeders, have rapid reproductive capabilities, have high tolerance for a wide range of environmental conditions, or have greater resistance to predators. Ultimately, the success or failure of a species that enters an ecosystem will depend on these characteristics and their match/mismatch to the receiving ecosystem. These relationships are challenging to define quantitatively (e.g. Ricciardi and Rasmussen, Kolar and Lodge 2001, Marchetti et al. 2004).

Non-native Impacts on Ecosystems

Once a new non-native species has become established in an ecosystem, the structure, composition, and, likely, the functioning of the ecosystem are changed to some degree. To evaluate the science underpinning efforts to address non-native species problems in the Delta, establishment of a new non-native species can be considered as one aspect of the broader dynamics of the community of species occurring in the Delta—the “species pool” (Figure 1). The species pool of a location is a product of both the number and types of species present and their abundances at a given time (Wiens, personal commination). Understanding the dynamics of the species pool may help to resolve some of the ambiguity about what is a “native,” “non-native,” or “invasive” species. Understanding the process of invasion may, in turn, also contribute to a better understanding of the dynamics of the species pool.

Management is often focused on the preservation of a subset of species (e.g. ESA) or the preservation of certain ecosystem services (e.g. boat traffic and emergent vegetation).

Several forces drive changes in the species pool. These ecosystem drivers—climate change, sea-level rise, land-use change, habitat alteration, hydrological changes, resource use, pollution and nutrient loading, droughts, and a host of other environmental and human actions—all affect species and their habitats directly and indirectly. As a consequence, the species pool in an area of interest is in a continual state of flux, with changing population levels of species already present, additions of new species from elsewhere, and loss of species previously present in the pool. Additions come from immigration of species moving of their own accord, intentional human introductions of new species (e.g., assisted migration or stocking), or accidental or careless introduction through human-facilitated pathways (e.g., release of bait fish, clams hitchhiking on recreational boats, construction of canals and new flow regimes).

Whether a newly arriving species becomes established depends on abiotic conditions, the characteristics of species that moved into the area earlier, and how they assembled themselves into ecosystems. Once established, a non-native species may affect the persistence or decline of species already present and those that arrive subsequently. Losses of species from the pool occur when a species becomes extinct or is extirpated from the area of interest or when a species disappears because individuals and population centers have moved elsewhere (e.g., as a result of climate change). There are also transients in the species pool such as migratory birds and fishes such as migratory salmon in the Delta. The species pool of any location therefore contains a mixture of native and non-native species that changes over time, creating an ever-changing mosaic of ecosystems over a broader area as species move among locations.

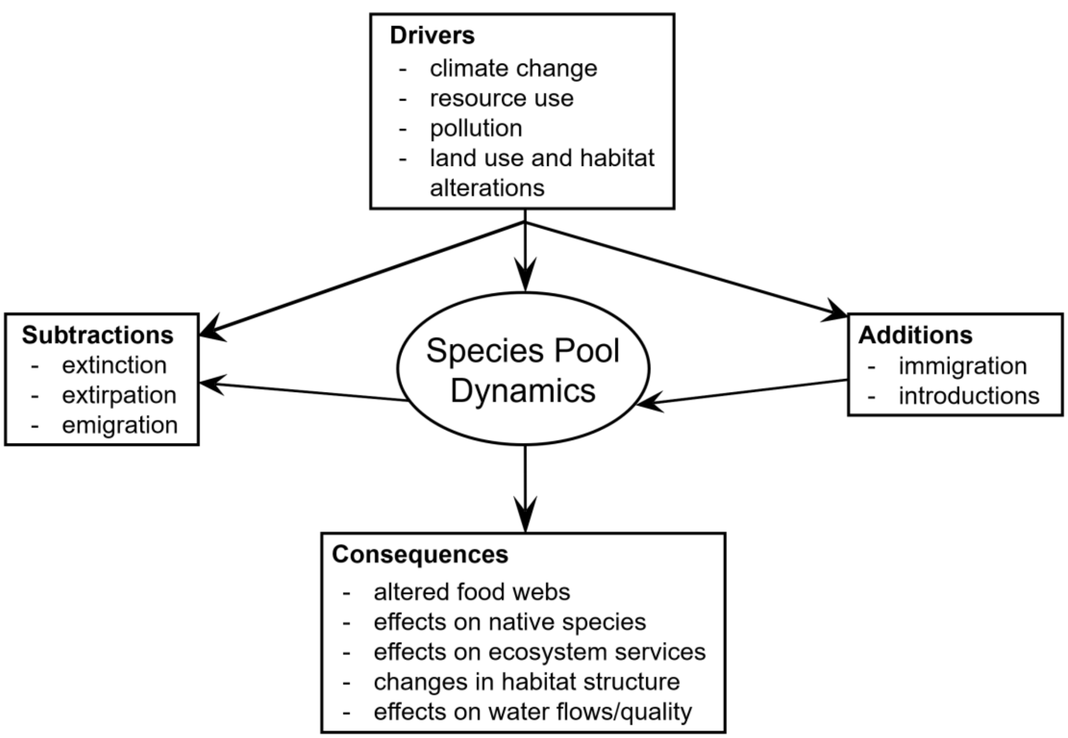

Figure 1. A conceptual model of changes in the species composition (the "species pool") of an ecosystem, leading to multiple consequences.

Compositional changes in the species pool can have a variety of ecological, economic, or sociological consequences (Figure 1). Ecologically, altered competitive or predator-prey relationships among species may disrupt food webs. The effects on native species that are rare or declining in abundance may be especially great, leading some to be extirpated. If these species are legally recognized as threatened or endangered, there will be political and economic as well as ecological consequences.

Other consequences of changes in the species pool may affect human interests more directly. Ecosystem services provided by existing species and biological communities may change. For example, new species may alter the biological, hydrological, or physical structure of the ecosystem (e.g., nutria burrowing into levees). Changes in the composition of aquatic vegetation, such as the recent dominance of the Delta by dense growths of Brazilian waterweed (*Egeria densa*), can alter water flows, temperature, and chemistry and can affect other elements of aquatic ecosystems as well as the quality and quantity of water available to people.

Changes in the composition of a species pool and their consequences, of course, are just changes. It is *people* who determine whether the individual or collective changes are good, bad, or benign, depending on how they affect something about the system that people value, for whatever reasons. In some instances, the introduction of a new species into an area may have little observed effect on other species, ecosystem processes, or how humans use or manage the system (Matern and Brown 2005) until it is too late (e.g., clams in the Delta). Some non-natives virtually thrive in the new ecosystem and begin to dominant certain habitats or food webs. The Zebra mussel in the Great Lakes is just one example. In other situations, a new species may be valuable to people, as are striped bass, or increase or alter the productivity of food webs (Liao et al. 2018).

Non-Natives in the Sacramento-San Joaquin Delta

Findings

- The Sacramento-San Joaquin Delta is one of the most invaded estuaries in the world.
- Reducing the impact of non-native species and protecting native species is a core strategy of the Delta Plan.
- Several factors have facilitated the introduction of new species to the Delta, including ballast-water pathways through the San Francisco Bay and severe habitat restructuring for land and water use.
- The vulnerability of disturbed environments to non-natives is well documented in other ecosystems and has been substantiated by studies in the Delta.
- Changes in the Delta over the past decades have generally favored non-native species (fish, at least) at the expense of native species.
- Science dealing with individual or groups of non-native species in the Delta has been extensive.
- Impacts of invaders on the Delta ecosystem have been large but attributing specific impacts to specific species is challenging

scientifically because science is reactive (done after a non-native has become established) and mechanistic understanding of ecosystems process is limited.

History and Status

The San Francisco Estuary (including the Delta) has been described as one of the most invaded estuaries in the world (Cohen and Carlton 1998). Because the Delta-San Francisco Bay Area is one of 25 global biodiversity hotspots of highest priority for conservation, the threat of invasive species is a major environmental concern. More than 200 non-native species have invaded the Delta’s aquatic and terrestrial habitats. The many transport pathways that bring non-native species into San Francisco Bay—international shipping, recreational boating and fishing, horticulture and pet industries, agriculture, and deliberate introduction—have facilitated their movement into the Delta (Luoma et al. 2015). These pathways, combined with the Delta’s highly altered landscapes and flows, have facilitated the establishment of many non-native species (Ruiz et al. 2011). About one quarter of non-native species introduced to the estuary are arthropods, followed by mollusks, fish, and vascular plants (Cohen and Carlton 1998).

Well before the arrival of non-European settlers in the Delta, Native Americans altered the mosaic of species by tending local plant species that bore acorns, fruits, and construction materials and by moving them into new locations (Zedler and Stevens 2018). Subsequent people introduced domesticated grazers (horses, cattle). Grasses were favored by grazing and by fires set by lightning and by Native Americans. With the settling of European immigrants, California's Central Valley was gradually converted from native to non-native grasses, and the Delta was engineered to support agriculture.

Introductions began to accelerate as ships started entering San Francisco Bay in 1775. As global shipping into the Bay increased around 1850, introduction pressure intensified (Cohen and Carlton 1995, Ruiz et al. 2000). Introduction rates have increased since the mid-1900s; about half of non-native species recorded in 1995 were introduced after 1960 (Cohen and Carlton 1998). This increase coincides with a time of growing international commerce from East Asia, the opening of new ports in the 1970s, faster ships, and increasing anthropogenic disturbance (Carlton et al. 1990, Carlton 1996). In particular, habitats were altered by increasing hydrological management through freshwater diversions beginning in the 1920s and major dam construction on the Sacramento River and its tributaries between 1945 and 1968 (Arthur et al. 1996, Winder and Jassby 2011). Changes in hydrological management are expected to continue (Lund et al. 2010). Salinity will change in different parts of the Delta with changes in hydrological regimes (Fleenor et al. 2008), with cascading effects on Delta ecosystems and fish (Moyle and Bennett 2008). These transformations of the Delta facilitate the establishment and persistence of new non-native species by creating pathways of invasion and disturbance (see Appendix A for further discussion).

The vulnerability of disturbed environments to the establishment of non-native species is well documented in other ecosystems and has been substantiated by studies in the Delta (Leidy and Fiedler 1985, Feyrer and Healey 2003, Conrad et al. 2016). Hydrologic alterations—especially water diversions, altered flows, and increased water temperatures—have exacerbated drought-like conditions, which are linked to the increasing establishment by non-native zooplankton that have in turn created conditions more favorable to non-native fish (Feyrer and Healey 2003, Winder et al. 2011).

Appendix A summarizes some examples of the impacts of non-natives in the Delta. Non-native species can often outcompete, prey upon, and exclude native species. The continuous arrival and spread of non-natives have displaced native aquatic vegetation, decimated native fish populations, contributed to the decline of native biodiversity, altered food webs and ecosystems, structurally damaged both natural and constructed habitats, and affected ecosystem services such as the provision of clean water (Simberloff and Rejmanek 2011). The range of salinity conditions exposes the Delta to potential invasion by non-native species through a multitude of vectors and creates conditions favoring establishment once they arrive (Cohen and Carlton 1998, Wolff 1998, Cloern and Jassby 2012).

Some introduced species have had more substantial environmental and economic impacts than others due to their capacity to reshape their environment, with cascading effects on habitat, nutrient and contaminant cycling, and trophic structure (Kimmerer at al. 1994, Crooks 2002, Sousa et al. 2009). Significant habitat-altering invasive species include several species of aquatic plants that alter flows and create novel habitat for non-native fish (Brown and Michniuk 2007, Loomis 2019). Filter-feeding bivalves have altered benthic and pelagic food-web structure and nutrient cycling. Species that exhibit a boom and bust invasion in which abundances and impacts can change significantly, as with the Chinese mitten crab, can create new predator-prey dynamics (Box 2).

Box 2. The Chinese Mitten Crab: A Boom and Bust Invasive in the Bay and Delta

Chinese mitten crabs are medium-sized crabs named for their hairy, mitten-like claws (Rudnick et al. 2005). They are native to coastal rivers and estuaries of central Asia and have invaded several European countries over the past century. Discovered in South San Francisco Bay in 1992, the mitten crab spread rapidly to cover several thousand squared kilometers surrounding the Bay and Delta (Rudnick et al. 2000). Introductions may have occurred through ballast-water discharges, although there was initial speculation that it was purposeful because of the value of their roe.

Chinese mitten crabs are catadromous (species that live in freshwater but migrate to more saline habitats to breed). They are associated with tidally influenced portions of Bay tributaries as young juveniles; with freshwater streams $\leq$ 250 km from their confluence with the Bay) as older, migrating juveniles; and with the open waters of the Bay as reproductive adults after migrating from fresh water to reproduce between late fall and early spring (Rudnick et al. 2000, 2003). Chinese mitten crabs have been of widespread environmental concern because of their extreme abundance and burrowing behavior, which causes bank erosion. Between 1995 and 2001, burrow densities increased five-fold in tidal portions of the banks in South Bay tributaries (from a mean of 6 burrows per m^2 in 1995 to >30 burrows per m^2 in 1999). Population size peaked in 1998, with 750,000 crabs counted in fall migration in a North Bay tributary. Abundance subsequently declined greatly; 2,500 crabs were counted in the same river system in 2001 (Rudnick et al. 2003). They are rarely encountered in the Bay and Delta today.

Chinese mitten crabs are also of concern because they accumulate higher concentrations of mercury than crustaceans living in the water column (Hui et al. 2005). Because their predators include fish, birds, mammals, and humans, their mercury burdens have an exceptional potential to impact the ecosystem and public health. Chinese mitten crabs also damage nets used in commercial fisheries (Rudnick and Resh 2002).

Management and Coordination

Given the prevalence of non-native species in the Delta, the Delta Plan identifies reducing the impact of non-native species and protecting native species as a core strategy in the Ecosystem Goal (Box 3). Several interagency programs have also been formed to prevent, detect, and manage non-native and potentially invasive species, including the Delta Interagency Invasive Species Coordination Team (DIISC), which is organized by the Sacramento-San Joaquin Delta Conservancy and aims to strengthen coordination among agencies to detect, prevent, and manage invasive species.

The California Invasive Plant Council is a non-profit organization that catalogs invasive plants present in California, and the California Department of Food and Agriculture has lead authority to control of noxious weeds in California. In addition, the Delta Region Area-wide Aquatic Weed Project is a collaboration among academic and governmental agencies tasked with sustainably managing aquatic weeds in the Delta. More broadly, the Invasive Species Council of California (ISCC website, http://www.iscc.ca.gov/) aims to coordinate and strengthen the various organizations that address invasive species in the state of California.

Box 3. Reducing Impact of Non-native Species is a core strategy in the Delta Plan.

Reducing the impact of non-native species and protecting native species is one of the five core strategies discussed in the Delta Plan's Chapter 4 amendment ("Protect, Restore and Enhance the Delta Ecosystem"). Within this strategy, the Plan recommends that state and federal agencies should prioritize and implement actions to control non-native species (ER R7), including communication and funding for a rapid response to invasive species (Delta Stewardship Council 2020). The Plan classifies non-native species into four categories: naturalized species, widespread and unmanaged species, widespread and managed species, and emerging species of concern. Invasive species are described as non-natives whose introduction may cause harm to the economy, environment, or human health.

The Plan addresses the specific threats posed by several invasive species, including aquatic weeds (water hyacinth, Brazilian waterweed, water pennywort, Eurasian water milfoil, and parrot feather), overbite clams, and zooplankton. In addition, it explains the potential threat of invasions by zebra mussels, quagga mussels, and nutria. The Plan also discusses measures and entities that have been established to prevent introduction of non-native species. California law requires that ships entering from outside the United States Exclusive Economic Zone either retain, properly exchange, or discharge ballast water to a treatment facility to reduce the chances of introduction. In addition, the California State Lands Commission limits the allowable concentration of living organisms in discharged ballast water.

The Delta Plan recommends increasing funding and communication among agencies for invasive species management.

Recommendations to Improve Science Capabilities in the Delta

The Delta ISB recommends the development and testing of a comprehensive, spatially explicit, food-web model for the Delta. This model should be Delta-wide in scope, tied to environmental driving

forces and conditions, and be available for use by decision-makers. Such a model would help to identify gaps in knowledge and could be used to;

- Improve our mechanistic understanding of the role of non-native species currently in the Delta.
- Predict potential impacts of new invaders on ecosystem structure and function and ecosystem services.
- Assess threats of invasive species in the context of a changing environment and multiple drivers, especially climate change.

Impacts of invaders on the Delta ecosystem have been large but attributing specific impacts to specific species is challenging scientifically because science is reactive (done after a non-native has become established) and mechanistic understanding of ecosystems process is limited. One of the primary impacts of non-native species is to disrupt or change food webs and nutrient cycling. Understanding the role of non-native species (potential, existing, or outgoing) in the food web is fundamental for predicting and evaluating impacts (David et al. 2017). This type of model is most effective for policy if it is spatially explicit, can be driven by changing environmental conditions, and is open source (e.g., DeMutsert et al. 2018, Schuckel et al. 2018). Several shelf-ready models already exist (Vasslide et al. 2016); for example, Bauer (2010) used the ECOPATH/ECOSIM software to construct a food-web model of the Delta. We believe a coordinated effort to evaluate the most appropriate approach for the Delta is needed (Schuckel et al. 2018). These food web models can be used to identify data gaps (e.g., diets) and knowledge gaps (e.g., impacts of temperatures and flows on productivity and nutrient flow) that can guide and help prioritize future studies.

Conduct a series of focused workshops or syntheses to develop a detailed set of Science Priorities for dealing with non-native species that defines short-term and long-term science needs and improved understanding of the impacts of established invaders.

The science dealing with **individual** or groups of non-native species in the Delta is extensive and has largely emphasized: 1) prevention, early detection and rapid response, eradication, assessment and monitoring, and control of individual species (e.g., nutria) or groups of similar non-natives (e.g., emergent aquatic vegetation); 2) retrospective impact assessment (e.g., the effects of invasive clams); and 3) development of new technologies for monitoring (e.g., remote sensing and eDNA) (e.g., Jerde et al. 2011, Baerwald et al. 2012, Stoeckle 2016, Hosler 2017, Khanna et al. 2018b). See Appendix A.

We recognize that there are many additional scientific needs at the project level, species level, monitoring level, or technology level. These span topics such as the development of safe control measures (e.g., herbicides), development of new monitoring tools (eDNA, remote sensing), and evaluation of pairwise species relationships (e.g., striped bass and delta smelt) to more challenging questions like better defining the role of an individual invader (e.g., *Corbicula*) in nutrient cycling. Clearly, all of these types of projects are important but need better prioritization. Recent workshops like the 2019 Delta Invasive Species Symposium on the assessment of remote sensing technology and status for invasive aquatic vegetation[7] are good examples of the type of approach that is needed.

Individual Non-native Species: Prevention and Management

Findings

- A major goal of management in the Delta is to prevent the introduction of potential invaders to the ecosystem. Decisions are thus mostly focused on the different phases of an individual species invasion: threat assessment, early detection, and rapid response to eradicate, control, and (if all else fails) adapt.
- Attempting to control every non-native species is cost infeasible and most likely undesirable, which is why government agencies tasked with managing lands and estuaries use a variety of criteria to prioritize invasive species for control and to monitor for new invasive species.
- It is up to management to decide action levels: At what level of risk does one decide whether to take action or take no action.
- Science and management are clearly linked and must be integrated. Each management goal/action requires science.

[7] See 2019 Delta Invasive Species Symposium recording: https://ats.ucdavis.edu/ats-video/?kpid=0_r0sqvh85

- Identification of shared non-native pathways of introductions for multiple species can enhance prevention efforts.

- Monitoring is essential to assess the effectiveness of prevention, to detect new non-natives, and to map the spread and abundance of established non-natives.

- Rapid response for eradication or control requires resources and agency preparation, commitment and coordination.

The Overall Process and Scientific Needs

The general management protocol for dealing with individual identified invasive species is most commonly used and is well established at local, state, and national levels. The responses progress from prevention, early detection, and rapid response to eradicate individual species at the early stages to the control or eventual adaptation to dealing with a well-established invader if all else fails (Dunham et al. 2020; Figure 2). Each stage in the management decision process requires scientific information.

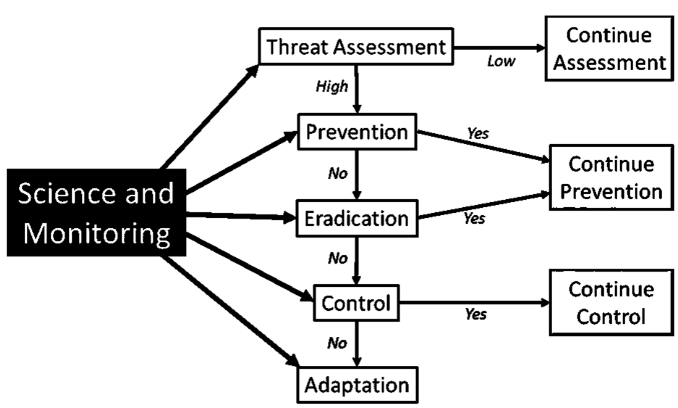

Figure 2. Stages of management and responses in dealing with a potential invasive species. Ideally, all of the stages and responses are informed by science and monitoring.

Threat Assessment and Prevention

Ultimately, the primary goal of management of non-native species is to prevent the introduction of potential new species to the ecosystem. The process is similar for all non-native species, but the focus is often on species identified as potential 'invaders' because of their higher impact. Efforts are usually targeted at primary pathways for transport and entry. A prioritized list of potential invaders is critical for setting prevention and detection goals and for managing public expectations. This list can be built through a robust threat assessment.

When a non-native species is newly identified, the first step is to conduct a **threat assessment** for the species (Figure 2). There are two components to a threat assessment; 1) what is the probability or risk of a particular species of becoming established in the new ecosystem and 2) what level of harm will it cause if established? Science should be used to assess risks and identify species that have a high probability of entering the ecosystem of interest, becoming established (Srebaliene et al. 2019). Elements of a scientific risk assessment should include: 1) an assessment of the ability of the potential invader to thrive in the new ecosystem, which might include inherent characteristics of the species and a comparison of the habitat requirements of the potential invader (e.g., including growth and reproductive potential, food and habitat availability, and risk of predation) relative to the habitat characteristics of the ecosystem; and 2) an evaluation of the potential and realistic pathways of entry (e.g., how porous are the boundaries of the ecosystem to this particular species?). If the management goal is to eliminate all new non-natives, then actions can be taken on this assessment. A second level categorization is often done to estimate the degree of harm from a successful invasion.

Several tools are available to assess the risks and impacts of potential invaders. Over 70 tools were identified in a review of the topic by Srebaliene et al. (2019). The principal aim of these tools is to identify and prioritize the major species of concern and the major pathways so that prevention techniques can be employed and monitoring can be established to detect the presence of new species. Forecasting a new non-native requires a comparison of the habitat requirements of the potential invader with the habitat characteristics of the receiving ecosystem and an evaluation of the spread potential of the species.

Gauging the harmful or beneficial impacts of a non-native species is a judgment that can draw on a variety of quantitative and qualitative tools. These can range from expert opinion and ratings (developed for the State of California by the California Invasive Species Committee (ISCC): http://www.iscc.ca.gov), to observations of the species in nearby or similar habitats (e.g., zebra and quagga mussels, nutria, although a species might be harmful in one ecosystem but less so in another), to a more scientific and quantitative approach including comparison of the species' habitat requirements to habitat availability in the ecosystem of interest, to risked-based decision models (e.g., Wu et al. 2010). For example, the ISCC was asked to create a list of "invasive species that have a reasonable likelihood of entering or have entered California for which an exclusion, detection, eradication, control or management action by the state might be taken" (CISAC Charter, Article IIIB). In 2010, expert opinion and comments were used to rate individual species (scale of 1 to 5) on criteria such as spreading rate and amount; damage or benefit to culture, health, ecology, agriculture, and infrastructure; and the state's ability to detect and control an invader. We could not find a similar list for the California Delta. The California Department of Fish and Wildlife has also listed 21 species of concern[8] and has active (mainly educational) programs that strive to prevent these species from invading additional wildlands and waterways.

Science can define the risk levels, but it is up to management to decide action levels. How great does the risk need to be (and in what units) to trigger a response or how small does the threat need to be to take no action? How does one balance the threat of a species that has a high probability of entering the ecosystem but low (identified) human impact against a species that can cause extreme harm or damage but has a low probability of introduction? At what point in the invasion is it most cost-effective to intervene, given that ultimate harm is uncertain?

Once a species has been identified as a threat, managers may choose to enact **prevention** when expected harm of a new introduction is high (Figure 2). Prevention is usually targeted at eliminating the primary pathway(s) for the species to enter the ecosystem. Science is needed to identify the likely pathways and the most effective methods to restrict that pathway for the target species. In some cases, this might be done through an approach targeted on specific species, such as inspecting boats traveling into a region or a particular ecosystem.

[8] California Department of Fish and Wildlife website on invasive species: https://wildlife.ca.gov/Conservation/Invasives/Species

One of the best national examples of threat assessment and pathway interdiction involves zebra and quagga mussels. These mussels entered the Great Lakes via ballast water and have had ecosystem-level impacts on water quality, fisheries production, and even water supply and power intakes. The economic cost has been large.[9] The species have spread throughout much of the country (see references). Studies have focused on predicting the potential for invasions into different ecosystems by comparing the habitat requirements and restrictions of zebra mussels (based on temperature, salinity, pH, flow rates, and calcium concentrations) to potential receiving waters (Whittier et al. 2008). Other studies have developed risk-based decision models focused on potential food-web disruption and other impacts (Wu et al. 2010).

Managing pathways has ranged from boat inspections for overland transport to extensive education programs and outreach, such as the nationwide 100th Meridian Initiative.[10] Dreissenid mussels have entered the state of California and the California Department of Fish and Wildlife has produced Guidance for a Dressenid Prevention Program.[11]

Pathway analyses can be effective to identify and block the potential corridors for multiple species introductions. For the Delta, the legislation controlling ballast-water release into the San Francisco Bay is an example of

[9] See AIS Economic Impacts WebsiteAIS Economic Impacts Website: http://www.aquaticnuisance.org/resources/ais-economic-impacts
[10] See The 100th Meridian Initiative website: https://www.fws.gov/fisheries/ANS/pdf_files/100thMeridian.pdf
[11] See Guidance Document: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=140345&inline

controlling a key pathway. The California Marine Invasive Species Program (CMIS) was designed to reduce the risk of introducing non-native species through ballast-water discharge and was established through legislation (Ballast Water Management for Control of Nonindigenous Species Act of 1999, reauthorized and expanded in the Marine Invasive Species Act of 2003). These and subsequent regulations have helped to regulate ballast-water discharge and biofouling (Scianni et al. 2019).

Monitoring targeted toward individual species or as part of a more general sampling program is required to provide the data needed to map and assess the effectiveness of a prevention program. This requires knowing the potential habitats of a species and effective means to assess its abundance. Monitoring can be done on a broader scale to look for non-natives using eDNA, remote sensing from satellites, planes and drones, citizen science, or inclusion in routine agency monitoring programs (see recent review by Larson et al. 2020).

Rapid Response and Eradication

Once a species has established an initial population, **rapid response to gather more information (e.g. surveys) and eradicate an invader** is the next potential management step. Eradication means that no individuals remain of the invading species and requires rapid detection at the earliest stages. A science based, species-specific rapid-response plan is required so that effective tools can be used to eliminate a species. A team that includes multiple agencies and citizen advisories can establish rapid response protocols if established prior to an invasion.

Few invaders have actually been eradicated. Success has been greatest when invaders have been detected at an early stage and in a small region. An example is *Caulerpa taxifolia*, a macroalga that has been highly invasive in the Mediterranean Sea. Prompt action was taken to eradicate the species when it was discovered in Southern California in 2000 (Anderson 2005) and it was ultimately declared eradicated in 2006. Currently, there is an integrated program to survey the Delta and eradicate any new appearances of nutria. The California Multi-agency Response Team is coordinating efforts to eradicate nutria in the Delta. The efforts began as an emergency Incident Command System in 2018 and became a formal Nutria Eradication Program in 2019. The Nutria Eradication Program had caught over 1,000 nutria by May 2020 (See Appendix A).[12]

Control and Adaptation

At what point does one give up on total eradication? Once a non-native species has become established, science is needed to assess the impact of the new species and the most effective ways to map the spread and **assess, control, or limit the impact of the invasion**. Controls can limit the extent or slow the speed of the spread, reduce the abundance, or lessen the impact of the invader. But a history of successful management of many invasive species suggests that problems are not insurmountable, even if species are not eradicated. Many examples of successful control have helped people to maintain the aesthetics, transportation benefits, agricultural production values, and habitat qualities of land and waters. For example, the

[12] California Department of Fish and Wildlife's Nutria website: https://wildlife.ca.gov/Conservation/Invasives/Species/Nutria/Infestation

deployment of an insect biocontrol for alligatorweed (*Alternanthera philoxeroides*), an aggressive plant that prevented navigation of southern waterways, is widely acknowledged as a major success story for Florida and the Gulf Coast (Buckingham 1996). In addition to biocontrol, managers have had success when they took action to eradicate new invasive species (e.g., Anderson 2005) or used consistent herbicide or mechanical treatments, options that have a record of generating net benefits (Olson 2006, Lovell 2006).

Various control techniques have been used, including manual (hand removal), mechanical (backhoe, harvester, power tools, etc.), chemical (pesticides: herbicides, fungicides, rodenticides, etc.), cultural (changing a disturbance regime to favor desirable species through grazing, controlled burning, active revegetation), biological (biocontrol agents such as bugs or pathogens), and integrated pest management (using a combination of techniques for greatest efficacy; for example, mowing weeds first to reduce biomass then spraying re-sprouts with herbicides). In the Delta, continual mapping and control of emergent vegetation is an example of the degree of effort involved (See Appendix A).

A non-native species may be resistant to control efforts or the efforts may fail or come too late. Management must then shift to **adapting to the presence of the new species and altered species pool**. Often a new non-native species is not even detected (or recognized as causing harm) until it becomes well established and actually has an impact (e.g., *Corbicula* in the Delta). This can happen, for example, if the non-native species is small or cryptic or otherwise escapes notice until it has reached a level that allows it to persist and grow. It may take some time before a new species becomes established, its population expands, and it can be linked to a change in ecosystem services that we value. Perhaps other changes in ecosystem drivers (e.g. temperatures) can change the impact of the non-native species. Such time lags and delayed impact assessments complicate management responses and require ongoing monitoring (e.g., alligator weed (*Alternanthera philoxeroides*) in the Delta).

Finally, adaptation implies that the species has established itself in the ecosystem. Control is not feasible, so management must adapt to the presence of the non-native species in the ecosystem (Figure 2). In some instances, the non-native species may fit into an ecosystem with minimal observable effects on other species or little disruption of ecosystem functions—it has become integrated into the ecosystem ("naturalized") and no longer meets the definition of an invader (i.e., causing harm). Often, however, the invasive species may continue to have negative impacts. In such situations, Dunham et al. (2020) have proposed managing the impacts rather than attempting to control the invader directly. Their "managing impact modifiers" (MIM) approach focuses on identifying and managing the physical or biological factors that influence the impacts of the invader. By modifying factors such as stream flows, water temperature, habitat conditions, or food-web structure, the balance between native and non-native species may be shifted to favor the natives. The MIM approach recognizes that it is usually the impacts of the invasive species, rather than the invaders themselves, that are the management concern. The MIM approach, however, requires considerable information about both the environment and the species, suggesting that it may be most effective when implemented in conjunction with adaptive management so that practices can be adjusted as more information becomes available.

Recommendations to help Prioritize Management Actions

Develop a prioritized list of species that pose the greatest threat to the California Delta in the immediate and long-term future. This should include an evaluation of the expected ecosystem and economic impacts of each high-risk invader and an evaluation of likely pathways of introduction. A quantitative assessment would allow monitoring and rapid response efforts to be prioritized for species that need the most attention.

Attempting to control every non-native species is cost infeasible and most likely undesirable, which is why government agencies tasked with managing lands and estuaries use a variety of criteria to prioritize invasive species for control and to monitor for new invasive species. We suggest that one list be created that assesses the likelihood of successful establishment into the Delta and a second analyses be done to evaluate the degree of harm or overall impact that a successful establishment might cause. Such a list, based on ecological and life-history attributes of species, would allow funds to be directed to prevention, effective stakeholder engagement and education, monitoring, and early detection of those species most likely to enter the Delta and potentially cause harm. Such a list has not yet been developed for the Delta. Management agencies in the Delta are working within the context of statewide and national efforts but should consider the greatest potential threats to the Delta.

The Delta is highly vulnerable to invasion by new aquatic species entering from San Francisco Bay or elsewhere in or beyond California. A prioritized list of potential non-native species and pathways can be built through a robust threat assessment and the development of risk-based decision models (e.g., Wu et al. 2010). A conservative management approach would presume that all non-native species are potentially invaders.

Quantitative models can be developed to predict potential impacts of new invaders on ecosystem structure and function, including habitat occupancy (cf. Durand et al. 2016; Tobias et al. in press). Forecasting the impacts of a potential invader requires better mechanistic understanding of food-web disruption and interactions and insights into predation, competition, energy and nutrient flow, and habitat structure. As mentioned before, a quantitative, spatially and temporally explicit food-web model (such as ECOSIM with ECOSPACE) for the Delta would be a good place to start.

A uniform framework for applying spatially explicit habitat models for current and potential non-native species should also be developed. These can be similar to life-cycle or bioenergetics models but be generalized so that individual species needs can be inserted. These models can be used to assess the probability of successful establishment and potential ecological or environmental impacts.

An analysis could also be undertaken of the anticipated economic impacts of the highest priority new invasive species should they become established in the Delta. Such an analysis will allow actions to be further prioritized on the most harmful species, allow for enhanced stakeholder engagement, and set expectations and minimize surprises to the broader community. An analysis that integrated threat assessment, economic effects (including all relevant public and private harms and benefits) and uncertainty analysis could support choices on how to prioritize management using the best available science.

Non-native Species in the Context of Ecosystem Management

Findings

- Expanding the focus of management beyond individual species allows their impacts and functional roles in ecosystems to be considered in an ecosystem context.
- After-the-fact analyses of non-native impacts are challenging because of multiple, interactive drivers in the ecosystem. The rate, type, and impact of new introductions are intertwined with other major driving forces that change ecosystems, including resource use, climate change, pollution, and habitat alterations.
- Non-native species can have ripple effects that facilitate further invasions.
- Management of non-native species must be undertaken in the context of ecosystem dynamics; the species pool is in flux, leading to a continuing reshuffling of native and non-native species and changes in ecosystem structure, function, and services.

- Ongoing, targeted monitoring is essential; new and emerging technologies should be used.
- Changing habitats will alter the suitability of the Delta to different species and therefore change risk assessment. Anticipated future changes in climate, sea level, and other factors must be considered in forecasting future invaders in the Delta.
- With climate change, predicting new non-natives and the course of the invasions will be more difficult and require ecological and life-history information on potential new non-native species.
- Restoration actions often entail disturbances that allow non-native species to become established.
- Habitat restoration provides an opportunity to use experimental adaptive management approaches to test and select control or management methods that favor native species over non-natives.

Ecosystem Management and Non-native Species

The coequal goals of the Delta Plan call for “protecting, restoring and enhancing the Delta Ecosystem.” As mentioned earlier, Delta ecosystems, defined in part by the species pool, are undergoing continual and increasingly rapid changes.

If a non-native species becomes established, it becomes a participant in the functional processes of the ecosystem—as a competitor or predator of other species, a node in the ecosystem food web, a user of resources, a contributor to biogeochemical cycles, as habitat for other species, or other functional roles. Functionally, the line between a native species and an established non-native species begins to blur (Aquilar-Madrano et al. 2019). It may then be less important for managers to focus on the degree of nativeness of a species than on the functional role it plays in the ecosystem and well as the ecosystem itself.

As many of the examples we describe in Appendix A illustrate, the roles of non-native species are often disruptive. They alter aspects of the structure, composition, and function of ecosystems that we wish to maintain. In some situations, however, the impacts of a new non-native are benign from a human perspective or do not warrant the costs of eradication, control, or ongoing management. Consequently, we must adapt to the presence of the non-native species. Determining an appropriate course of action should include an assessment of the functional role the non-native species has come to play in the ecosystem. This requires that we not only know the ecology and habitat requirements of the non-native, but that we also understand the strengths of its interactions with other species, its food-web relationships, how it affects water quality and nutrient cycling or hydrological flows, and how it fits into a myriad of ecosystem processes. Our present mechanistic knowledge of the details of how Delta ecosystems function, however, is generally inadequate to support such assessments.

Non-native species become established in an ecosystem because conditions there fulfill their ecological niche requirements, either because the non-native excludes some native species that previously occupied that niche or because there was no species present that had the same ecological niche requirements. Absence of natural, controlling predators can also be important. Perhaps the non-native species replaces a species that became extinct centuries or millennia ago (Perino et al. 2019) or environmental changes have created new habitats (like rivers turning into calm ponds or lakes). Whether the species are functional equivalents can only be hypothesized based on structure but, by definition, are not exact replicas.

Ecosystem “sustainability” or protection does not mean unchanging stasis. As the species pool changes, managers need to assess species’ functions and determine the benefits and costs of changes in dynamic ecosystems. New tools are becoming available for predicting, tracking, and controlling non-natives. Dick et al. (2017) created a Relative Impact Potential metric to predict the likelihood and magnitude of ecological impacts of invasive species, using data on the numerical responses and functions derived from other populations elsewhere. Foxcraft (2009) established “thresholds of potential concern” as triggers to begin controlling non-native species in the adaptive management of South Africa’s Kruger National Park. Such approaches may help to shift the management of invasive species from response to prevention.

Godoy (2019) challenged researchers to uncover “emergent properties” of ecosystems being invaded by considering multispecies assemblages and learning how communities change once invaded. Efforts focused on just two competing species at a time (e.g., a native and non-native) miss the emergent properties of ecological communities. Researchers and modelers need to understand the risks of invasion impacts at species, multispecies, and ecosystem levels (Vila et al. 2011). That is the context in which invasions occur. Casting non-native species in a broader community and ecosystem context could help to identify new management options.

The challenge to develop scientific methods to monitor the spread, control, and assess the impacts of individual invaders or invasive types (e.g., emergent aquatic vegetation) is ongoing and often boils down to specific situations (see review by Larson et al. 2020). Of necessity, most research has focused on correlations, such as that between invasive clams and the decline of pelagic fish species. Carefully designed experiments to establish causal relationships are difficult.

There does not seem to be an operational food-web model of the Delta or the necessary components to develop spatially explicit species-habitat models through which the impacts of established or potential invaders can be assessed. Developing quantitative, spatially and temporally explicit species-habitat models could help to evaluate the current impacts of established non-native species and assess the potential impacts of high-risk invaders. Assessments of non-native species impacts are also confounded by other ongoing changes in environmental drivers, so management must be undertaken in the context of a continually changing ecosystem and species pool.

Non-native Species and Climate Change

The rate, type and impact of new introductions are intertwined with the other major driving forces that change ecosystems, including resource use, climate change, pollution, and habitat alterations (Pysek et al. 2020 and references therein). Rapid and accelerating changes in the Delta—the effects of climate change, sea-level rise, changes in water management, salinity intrusion, and so on—will affect virtually all of the factors driving changes in species pools shown in Figure 1. For aquatic introductions, the changes will affect the vectors and dispersal patterns, characteristics of the receiving habitats, water flows, salinity, seasonal pulses of floods and food-web dynamics, water temperature, and human activities. These will all influence the probability of entry and establishment of non-native species as well as their impacts, creating complex management challenges (Rahel and Olden 2008).

Changing habitats will alter the susceptibility of the Delta to different species and therefore change risk assessment. Pathways may also change. Vulnerability to new non-natives may differ among habitats and broad taxonomic groups. For example, in a broad meta-analysis, Sorte et al. (2013) found that non-native species were more likely to benefit from the effects of climate change than native species in aquatic ecosystems, but not in terrestrial ones. Non-native fish are generally able to tolerate warmer temperatures, giving them an advantage over native species as the climate warms. Moyle et al. (2013) found that 82% of native fish are vulnerable to the effects of climate change, versus 19% of non-native species.

Consideration of the consequences of predicted climate change in the Delta will be important in forecasting future establishment of new non-native species. Sea-level rise will increase salinity intrusion and inundation in the Delta. Mapping maximum tidal inundation will enable managers to evaluate changes in habitats that will favor the establishment of new species. Climate warming also will change habitat availability. Some species will likely be extirpated from the Delta as their temperature limits are exceeded (e.g., delta smelt), while other species may invade or encroach as higher temperatures or disruptions benefit them, producing the subtractions and additions of species to the species pool shown in Figure 1. Part of this process will involve range expansions of species occurring elsewhere in California.

Warming climate, especially warmer surface water, is expected to shift species distributions and allow non-native species to invade new areas (Walther et al. 2009). Of arguably greater concern are extreme events (e.g., floods, droughts, storms) that will disturb aquatic and wetland ecosystems and facilitate non-native species at every invasion step (Diez et al. 2014). Cloern et al. (2011) modeled how the Delta might change in both average conditions and extreme events. They advised Delta managers to strategize how to adapt to warmer temperatures, higher sea levels, and salinity intrusion and to plan for more runoff in winter and less in spring-summer. They viewed their projections as a starting point, warning “Today's extremes could become tomorrow's norms.”

Changes in temperature and precipitation are expected to affect all aspects of invasion: dispersal pathways (as trade and transport change), establishment (as species ranges shift), impacts (more insect pests, greater food requirements as animals experience stressful conditions, lower stream flows as trees increase evapotranspiration rates), and efforts to manage and control (e.g., shifts in biocontrol-prey interactions, shifts in herbicide tolerance, and more fire-tolerant weeds as drought and fire increase) (Dukes 2011). Along the coast of southern California, invasive non-native plants expand their distributions in years with greater rainfall and lowered soil salinity, which trigger seed germination of upland weedy species as well as native plants (Noe and Zedler 2001a, 2001b; Noe 2002).

Sea levels and climate are expected to change faster than native plants and associated animals can migrate to escape changing conditions. Even a single storm can bring saltwater well inland of normal high tides, killing salt-intolerant species and opening space for non-native species. As Callaway and Parker (2012) noted, management of non-native species is already extremely difficult, but “shifting climates will create additional challenges to consider, as changing conditions could create opportunities for a different group of nonnative species, and the future spread of existing invasives will be even more difficult to predict.”

Some non-native and invasive species seem pre-adapted to thrive with changing climate. For example, common reed (*Phragmites australis*; Appendix A) is well adapted to varied climatic conditions where it is native: each lineage has multiple genotypes and grows in diverse habitats and its plastic traits respond to changes related to global warming (temperature, CO_2). Responses to co-occurring environmental changes (drought, salinity, flooding) vary by genotypes within lineages (Skálová et al. 2014, Lambertini et al. 2014). As pointed out by Pysek et al. (2020), there are synergies among the interactive drivers affecting new invasions and synergies in the impacts of multiple invaders (e.g., Gaertner et al. 2014).

Restoration in the context of Non-native Species

The connection of non-native species to restoration is two-fold. First, restoration can create opportunities for non-native species to invade a site, so restoration often include targeted efforts to control or reduce the abundance of non-native species (e.g., by harvesting vegetation). Second, habitat restoration provides the opportunity to use adaptive-management approaches to test and select effective methods that favor native species over non-natives. This includes intentional restoration of invaded sites.

Restoration actions are often accompanied by disturbances that allow non-natives to become established. Once non-native plant species become dominant, for example, they often form monotypes that resist eradication. Most attempts to eradicate species covering >1 ha have not achieved their goal (Rejmanek and Pitcairn 2002). The multimillion-dollar attempt to eradicate hybrid cordgrass (*Spartina foliosa X S. alterniflora*) along the shores of San Francisco Bay (San Francisco Estuary Invasive Spartina Project: http://www.spartina.org/) sparked debates over costs versus benefits (such as restored habitat for shorebirds, endangered species of rails, or salt marsh harvest mice, *Reithrodontomys raviventris*).

Combinations of co-occurring events and sequences of extreme events may also create opportunities for non-natives to become established at restoration sites. Such “sequence events” may have different outcomes when the sequence is reversed (e.g., flood-then-drought effects differ from drought-then-flood effects; Zedler 2010a). Coinciding extremes, such as the co-occurrence of high river discharge and high coastal water levels, must be considered in risk assessments (Khanna et al. 2018). It is important to include such worst-case scenarios in restoration planning, as there will be surprises and decision protocols will be needed throughout implementation and monitoring.

Restoration often involves transplanting plants into newly restored sites. This may create opportunities for the spread of disease. For example, native plants in northern California nurseries were infected with a non-native fungus, *Phytophthora tentaculata*, which caused root and stem rot. When the native host was planted into restoration sites, the disease spread. While there are now effective guidelines for nurseries to follow, future non-native pathogens await detection (Hunter et al. 2018).

Substantial knowledge is available for replacing non-native plants with former natives. Researchers know where non-native species do and do not dominate (Hickson and Keeler-Wolf 2007). Local ecologists often know where there are opportunities to effect control, how to attempt eradication, and what to expect as outcomes. Although preventive programs are envisioned for new invaders, these have not yet been developed or implemented for aquatic invasive plants and wetlands. Inspections, education, and training of people who use Delta waters are essential ingredients of early detection (Ta et al. 2017).

Many researchers with experience in upland vegetation assume that restoring diverse vegetation will resist invasion. Reviews by D’Antonio et al. (2016) and Guo et al. (2018) suggest that aiming for high biodiversity, biomass, and productivity will reduce invasions. However, this is not necessarily true everywhere; Stohlgren et al. (2003) reported the opposite, finding that some diversity hotspots have also been hotspots for invasion.

Restoration projects can be designed as adaptive-management experiments (Zedler 2017). Large adaptive-management experiments can reveal best methods for restoring habitats and managing invaders. Because new invaders will likely appear during restorations, an experimental approach may reveal reasons for their expansions, helping to inform effective management. Adaptive-management experiments may also be the most practical way to determine the effectiveness of new methods to control invasive species, although Conrad et al. (2020) caution that such experimentation may not be possible in some restoration sites because of regulatory restrictions (e.g., protection of endangered species).

In some situations, non-native species may actually benefit ecological restoration. Where non-native species do not unduly threaten other species, ecosystem functioning, or human interests or provide essential ecological or socioeconomic services, they can be tolerated or even used to good advantage (Ewel and Putz 2004). In highly degraded habitats, carefully selected non-native species could be used to accelerate restoration by nitrogen fixation or by acting as nurse plants for native species (Guo et al. 2018). There are always risks where potentially invasive non-native species are involved, but greater risks can be accepted by considering the functional properties of ecosystems rather than using the reconstruction of an existing biological community as the sole goal of restoration (Ewel and Putz 2004). Both ecosystem functions and the ecology of individual species should be considered in decisions about how (or whether) to manage non-native species.

Ecological restoration is always a long-term process and adaptive management requires monitoring to determine whether and when adjustments of management practices may be necessary. Norton (2009) offered cogent advice: “Restoration outcomes in the face of biological invasions are likely to be novel and will require long-term resource commitment, as any letup in invasive species management will result in the loss of the conservation gains achieved.”

Recommendations

The Delta ISB recommends that management needs to move beyond individual species management to address how to set ecosystem goals in recognition of an ever-changing species pool and high uncertainty. This would include the formal implementation of non-native species management and research into ecosystem restoration programs.

The management protocols for preventing, detecting, minimizing the impacts, and adapting to individual non-native species are well established and largely adopted at the state and national levels. The approach of focusing on individual invader species one at a time has been valuable, although not always effective. However, the rate of invasions and the impact of non-natives on ecosystem structure and function are closely linked to other fundamental drivers of ecosystem change, including climate change, resource use, pollution, habitat alteration, and extreme events. Given that the Delta ecosystem has been greatly modified, is already highly invaded with a host of well-established non-native species, and, like many other ecosystems, is undergoing continual and increasingly rapid change, one might ask: What is the appropriate goal for non-native species management? We can expect that the species pool will continually change and management will need to adapt to the changes. Setting ecosystem-level performance measures for restoration and adaptive management in a dynamic Delta would improve the “protecting, restoring, and enhancing the Delta ecosystem.” Any new species that becomes established will change the ecosystem in some way. Management must adapt to a continually changing ecosystem and science must be able to forecast future changes to help set expectations and continually evaluate the impacts of a changing species pool on ecosystem structure, function, and services.

One of the fundamental recommendations from Pysek et al. (2020) is that “Forecasting and scenario development must give more attention to synergies of invasions with climate change and other environmental changes.” We support that recommendation for the Delta. Species distribution data and models and climate models have been used to predict northward movements of fishes in coastal areas under climate change (references). Similar approaches should be used for other species in the California Delta.

Many restoration projects use adaptive management to approach restoration goals as an iterative process. Linking non-native species with restoration efforts may enhance the effectiveness of restoration and provide opportunities for adaptive experimentation on control and management approaches. Proposed restoration efforts should identify pathways for non-native species to enter, implement early detection monitoring, and have an adaptive plan for responding to detections. Setting non-native species goals (like keeping non-native species below 50% of the community) will provide program incentives. When possible, restoration efforts should also take advantage of opportunities to include field experimentation as part of the project design.

The Delta DISB recommends that ongoing threat assessments for invasive species should be evaluated in the context of a changing environment and multiple drivers, especially climate. Climate change can alter the types and rates of invaders and impacts. We recommend that climate-change scenarios be incorporated into all management or policy actions regarding non-native species and that a standard climate-change model for the Delta that includes sea-level rise, hydrodynamics, and changes in temperatures should be developed to enhance threat assessments for future invaders and changes in populations of current non-native and native species.

Climate warming, sea-level rise, and more extreme environmental conditions will affect all species and habitats in the Delta, accelerating changes in species pools and facilitating the establishment of new non-native species. Human behavior will also change in response to climate change and may need to be included in models designed to project climate change, to fully characterize risks and outcomes.

Management Coordination, Integration and Implementation

Our overall recommendation is to **encourage a broader, more forward-looking, integrated approach to non-native species science in the Delta to inform management goals.**

"Broader" means expanding to multiple species and ecosystems; "forward-looking" means developing predictions and scenarios and forecasting in the context of ongoing and projected changing drivers; and "integrated" means coordinating efforts across interdisciplinary management/enhancement efforts.

Previous recommendations in this review should provide managers with;

1) a prioritized list of potential non-natives for the immediate and long term that is produced by a robust risk assessment;
2) an evaluation of the expected impacts of each high-risk invader;
3) a monitoring strategy to detect new non-natives and map the spread of current non-natives; and
4) a prioritized list of science actions to help control and understand the impacts of established invaders.

Multiple agencies, workgroups, and committees have some coordination, communication, and planning responsibilities within the Delta (and the State of California). Non-native species are a fundamental part of the Delta ecosystem and a fundamental driver of ecosystem change. New invaders could disrupt essential services to Delta stakeholders. A high-level, coordinated approach to the science and management of invasive species would address this growing problem.

In order to make this happen:

- **The Delta ISB recommends the formation of a Non-native Species Task Force or Non-native Species Science Center to complement or expand the communication and coordination functions of DSIIC by developing a single 'go to' science source of expertise, and information with proper authorization and funding.**
- **The DISB recommends the development of a comprehensive invasive-species coordination plan with an outline of responsibilities and authorities that span monitoring, rapid response, control and science expertise.** The plan should spell out who has the responsibility and how the efforts will be prioritized, supported and funded. Recommendations without responsibilities are unlikely to be implemented (Conrad et al. 2020). Efforts need to be effectively organized and managers prepared for action. This entails mobilizing the relevant scientific expertise and legal authorities, defining lines of authority, and ensuring that financial and logistical support is sufficient.

The wealth of knowledge and experience of Delta managers and researchers is a critical resource that should be brought to bear on future decision making about non-native species in the Delta. The plan should include criteria and performance measures for prioritizing or undertaking control measures by weighing and balancing costs and benefits of non-native or potential invaders and establishing protocols and lines of communication to deal with surprises or the unanticipated arrival of non-natives.

Currently, the Delta Interagency Invasive Species Coordination (DIISC) Team (part of the Sacramento-San Joaquin Delta Conservancy) acts to “foster communication and collaboration among California state agencies, federal agencies, research and conservation groups, and other stakeholders that detect, prevent, and manage invasive species and restore invaded habitats in the Sacramento-San Joaquin Delta”.[13] DIISC provides a foundation for building broader integration of actions directed toward anticipating, detecting, controlling, and adjusting to invasive species in the Delta. Coordination of monitoring programs, rapid response teams, and management of landscapes and waterscapes to limit invasion corridors cuts across agencies and across species.

Ultimately, management decisions can be strengthened by using protocols to prioritize actions based, for example, on feasibility, risks, costs, and benefits; by integrating modeling efforts; by testing the effectiveness of new techniques for detecting and controlling non-native species; by developing and using maps of plant and animal biodiversity hotspots and cold spots in the Delta to show where critical functions could be damaged by current or future non-native species; and by incorporating the information and lessons from efforts to deal with non-native species elsewhere and from the growing body of scientific theory and findings about invasive species and their effects.

[13] DIISC Team Website: http://deltaconservancy.ca.gov/delta-inter-agency-invasive-species-team/

A list of subject matter (and taxa-specific) experts for non-natives in the Delta would be valuable.

Conclusions

Imagine the following scenario: A particular species (let's call it "Newtrina") may be the next invader to the Delta. It enters undetected and become fully established before it is noticed. It disrupts food webs and causes a decline in native species. Management will try to eradicate this species, but it may become permanently established in the Delta and harm ecosystem services valued by people.

How should we deal with such a prospect? Did you learn about the invasion from the newspaper? We should be proactive and have monitoring systems and food-web studies and spatially explicit habitat models in place to be able to forecast the species' impact and its rate of spread, and we should have a central 'go to' base of scientific expertise. We should be able to predict changes in the food web and assess the changes once "Newtrina" has become permanently established. We should be able to tease out the impacts of "Newtrina" relative to ongoing and simultaneous changes in the ecosystem due to climate change, weather extremes, and other driving forces. We should develop protocols for dealing with unanticipated invaders like "Newtrina" that arrive unannounced.

The management protocols for preventing, detecting, minimizing the impacts, and adapting to individual non-native species are well established and largely adopted at the state and national levels. The science supporting these efforts needs to improve and be applied to the Delta. The approach of focusing on individual invader species one at a time has been valuable, although not always effective. However, the rate of invasions and the impact of non-natives on ecosystem structure and function are closely linked to other fundamental drivers of ecosystem change, including climate change, resource use, pollution, habitat alteration, and extreme events. Given that the Delta ecosystem has been greatly modified, is already highly invaded, and like many other ecosystems is undergoing continual and increasingly rapid change, one might ask: What is the appropriate goal for non-native species management? We can expect that the species pool will continually change and management will need to adapt to the changes. Some of these changes may be predictable and others not. **Management needs to move beyond individual species management to address how to set ecosystem goals in recognition of an ever-changing species pool and high uncertainty.**

Science can be used to better predict, detect, control, or adapt to non-native species and inform management to set priorities to minimize harm. Science, however, is only one element among many fiscal, sociological, and political considerations that ultimately drive allocations of resources to deal with non-native invasive species. Most species invasions, after all, are consequences of human activities. Indeed, the very recognition of a non-native species as invasive is a matter of human value judgments. Because these activities and values differ among ecosystems and among people, developing appropriate management and policy for invasive species depends on the specific ecological, biological, and sociological contexts. Unless these contexts are considered, it will be difficult to understand and predict biological invasions (Keller et al. 2011).

The fundamental role of science, then, is to provide management with enough information to set priorities and manage expectations. Developing more forward-looking predictive science will improve our ability to understand and adapt to changing conditions.

APPENDIX A: Examples of Significant Non-native Species in the Delta

The following examples highlight several important non-native species and their impacts on the Delta ecosystem. Although non-native species occur throughout the Delta, they have received by far the greatest attention in aquatic environments. The ecological boundaries of upland ecosystems are less well defined relative to the Delta. In agricultural systems, various "pests" and "weeds" (which are also invasive species) have been the focus of intensive prevention and control efforts. While many of our comments apply to non-native and invasive species in any ecosystem, our focus in this report is primarily on aquatic ecosystems.

Bivalves and their effects on the pelagic food web

The Delta has been invaded by several bivalve species that have significantly altered food webs through competition with native filter- and deposit-feeding invertebrates and by altering phytoplankton concentrations. The most notable and well documented of these invaders is *Corbula amurensis*, which was first sighted in the San Francisco Estuary in Grizzly Bay in 1986 (Carlton et al. 1990). The species was likely brought to California as larvae in the ballast of cargo ships. Benthic communities in invaded areas were significantly disrupted and species richness in these habitats gradually decreased during the late 1980s as *C. amurensis* came to dominate the community (Nichols et al. 1990). The combination of the high population growth rate of *C. amurensis* with its filter-feeding efficiency led to a nearly five-fold decrease in average phytoplankton biomass within 2 years of invasion, limiting food availability to zooplankton (Jassby et al. 2002, Thompson 2005). This reduction in phytoplankton biomass shifted food-web dynamics by directing primary production toward benthic consumers (clams) instead of zooplankton (Kimmerer at al. 1994). By depleting native zooplankton, *C. amurensis* facilitated the growth of non-native species in the Delta and shifted the system from a zooplankton community dominated by herbivores and omnivores to one dominated by predatory species. The decreasing food availability for pelagic fish is thought to have contributed to the decline of many fish populations (Nobriga 2002, Cloern and Jassby 2012, Brown et al. 2016). The decrease in productivity of pelagic species stemming from declining phytoplankton was likely due to the combined effects of diversions of freshwater from the Delta, drought conditions that altered salinity and favored non-native zooplankton species, and the *C. amurensis* invasion (Hammock et al. 2019). Thus, the increase in non-native zooplankton in the Delta and associated decline of native pelagic organisms followed multiple human alterations, including water diversions in the Delta (Winder and Jassby 2011, Winder et al. 2011).

Aquatic plants

Several species of non-native aquatic plants reduce native plant diversity and clog waterways, threatening water quality, altering nutrient cycles, and diminishing recreational values in the Delta (Borgnis and Boyer 2016). Of the 19 submerged and floating aquatic plants that occur in the Delta, at least half are non-native. Three of the most widespread non-native species are *Egeria densa* (Brazilian waterweed), *Ludwigia* spp*.,* (water primrose), and *Eichornia crassipes* (water hyacinth) (Khanna et al. 2018a). *Egeria densa* is an example of Submerged Aquatic Vegetation (SAV). It was introduced to the Delta in 1946 from aquarium release and became a species of concern in the 1990s. It forms thick-rooted mats that alter water flow and habitat while impairing recreational activities such as boating and fishing. These hydraulic alterations create a positive feedback loop in which the presence of *E. densa* facilitates its further growth and dispersal (Hestir et al. 2015). The species' low salinity tolerance limits its growth into the western Delta relative to native aquatic vegetation (Borgnis and Boyer 2016). *Egeria densa* cover increased 50% between 2007 and 2014 to about 2900 ha. It is now the dominant submerged aquatic plant, covering 11% of Delta waters (Ustin et al. 2017, Khanna et al. 2015).

Eichornia crassipes is an example of a Floating Aquatic Vegetation (FAV) species. It was introduced to California in 1907. It has invaded slow-moving waterways, where its growth changes water quality, displaces native vegetation, clogs channels and marinas, and increases water loss due to its high transpiration rate (Underwood et al. 2006). *Eichornia crassipes* cover increased four-fold between 2004 and 2014 to about 800 ha (Santos et al. 2011a, Dahm et al. 2016). However, use of herbicides was delayed in 2014 and it was a peak drought year. Since then, water hyacinth cover has been less than it was in 2004-2008 (Ustin et al. 2018).

In addition to *E. densa* and *E. crassipes*, several other non-native plant species pose a threat to Delta waterways. The aquatic alligator weed (*Alternanthera philoxeroides*) was new to the Delta in 2017 (DBW 2017) and is becoming established. It is well known as an aggressive invader in Australia. There, records are available soon after invading for 5 years. During that time, it expanded 4.3 m per year and produced an average biomass of 4.9 kg dry weight per m^2 per year (Clement et al. 2011). This plant both roots (in shallow water) and produces mats of interwoven of stems that cover waterbodies, restrict human use, exclude native plants, and alter ecosystem functions.

Ludwigia spp. (water primrose) is a FAV species that increased 4-fold in cover between 2004 and 2016 and encroached into both open water and emergent marsh habitat (Khanna et al. 2018a). *Ludwigia* has been recognized as an emerging problem only in the past decade and now consistently covers more of the waterways than water hyacinth. Coverage in 2014 was similar to that of *E. crassipes* (800 ha) (Boyer and Sutula 2015, Dahm et al. 2016). In 2018 (not considering the south Delta), water primrose occupied about 1200 acres (3.8% of waterways) while water hyacinth was 400 acres (1.3% of waterways) (Ustin et al. 2018).

An additional common non-native FAV species of emerging concern, *Limnobium laevigatum* (South American sponge plant), somewhat resembles water hyacinth and is often found alongside it. Common non-native SAV species include *Myriophyllum aquaticum* (parrot feather), *Myriophyllum spicatum* (Eurasian watermilfoil), *Potamogeton crispus* (curlyleaf pondweed), and *Cabomba caroliniana* (Carolina fanwort) (Ta et al. 2017). *Hydrilla verticillata* (hydrilla) is not yet present in the Delta but occurs elsewhere in California and could migrate into the Delta during high water periods (Ta et al. 2017).

Many non-native plant species in the Delta pose major threats to native plant biodiversity, and habitat; species richness of non-native vegetation has been correlated with a decrease in native vegetation species richness and biomass (Santos et al. 2011a). Despite decades of research and policy directed at managing invasive aquatic plant species, however, monitoring and controlling their spread remains difficult due to insufficient funding, the absence of consistent monitoring programs, and complex regulations that restrict treatment (Ta et al. 2017). However, monitoring using remote sensing and controls using chemical, mechanical, and biological approaches have been somewhat effective in managing invasive vegetation. For example, several studies have identified and mapped invasive vegetation with high accuracy using hyperspectral remote sensing (Underwood et al. 2006, Hestir et al. 2008, Khanna et al. 2018a). However, this method is subject to error due to spectral variation associated with plant phenology. Nonetheless, remote sensing may be an alternative to costly and time-consuming methods that require direct monitoring of vegetation in remote locations. Drones offer some potential to deliver herbicide to specific patches of invaders (Huang et al. Project: https://www.ars.usda.gov/research/project/?accnNo=427340).

Efforts to control vegetation may have unintended consequences (Khanna et al. 2012). For example, mechanical shredding of *E. crassipes* may increase overall carbon, nitrogen, and phosphorous levels in the water column up to 10% (Greenfield et al. 2007). Mechanical shredding may also facilitate the spread of many invasive aquatic species, as fragmented plants may re-propagate. Over half of the cut fragments of *E. crassipes* may survive mechanical control and reach a habitat suitable to produce new plants, suggesting that mechanical control may have limited effectiveness in the Delta (Spencer et al. 2006). Alternative uses for the shredded plant material, such as feed for livestock, may not be cost effective.

Non-native SAV species also differ functionally from native species. Their greater leaf area, denser canopies, and greater light-use efficiency give them a competitive advantage over native species (Santos et al. 2011b). Thus, the removal of one non-native species may result in colonization by another non-native species instead of the intended native vegetation. Inadvertent effects of control methods must be considered in management of invasive species in the Delta.

Non-native aquatic plants have substantial economic impacts in the Delta, affecting water quality, turbidity (and thus habitat suitability for species such as delta smelt), recreational and commercial boating and fishing, water exports, and virtually all human uses of water. Consequently, there are major ongoing efforts to control invasive plant species in the Delta, spearheaded by a variety of agencies and programs (Box 4). From 2013 to 2017, combined state and federal efforts in chemical control of invasive SAV and FAV averaged approximately $12.5 million per year (Conrad et al. 2020). Because of regulatory restrictions, control could not be applied everywhere it was needed, and even this level of expenditure was insufficient to achieve effective control of invasive aquatic plants (Conrad et al. 2020).

Box 4. Controlling Aquatic Plants

Management of invasive aquatic vegetation in the Delta involves several agencies, including the California Department of Food and Agriculture (CDFA), the California Department of Fish and Wildlife (CDFW), and the California Department of Parks and Recreation, Division of Boating and Waterways (DBW). DBW has the responsibility to control aquatic 'weeds' in the Delta. Because these are independent agencies, coordinating management strategies is often difficult. Several aquatic invasive species, including *E. crassipes* and *E. densa,* are frequently targeted by the DBW Aquatic Invasive Species Program, which is the principal state agency with the authority to treat invasive aquatic species in the Delta (Ta et al. 2017). Treatment typically consists of herbicide application between March and November. Mechanical and biological control measures are also taken to reduce coverage. Biological controls involve alien insects or mites that are introduced to lower the density of non-native vegetation (Ta et al. 2017). Three insect species have been introduced to target *E. crassipes* and two to target *Arundo donax* (giant reed), although only one of these, *Neochetina bruchi* (water hyacinth weevil), has become established in the Delta (Akers et al. 2017, Hopper at al. 2017). There are plans to release other species of weevils and planthoppers in the Delta to selectively feed on invasive vegetation (Ta et al. 2017).

Because managing invasive vegetation is an interagency effort, there are also several collaborative organizations in the Delta that aim to coordinate and manage invasive aquatic species. The Delta Interagency Invasive Species Coordination Team (DIISC) is an interagency group of individuals from agencies focused on preventing, detecting, controlling, and managing invasive species in the Delta (Ta et al. 2017). They aim to increase collaboration among agencies through meetings and facilitating symposia focused on invasive species. USDA sponsors the Delta Region Areawide Aquatic Weed Project (DRAAWP), which focuses on management strategies, control agents, mapping of weeds, and documenting their effects on ecosystem services. DRAAWP centers its efforts on *E. densa*, *E. crassipes*, and *A. donax* and how to best prioritize management practices and provide agencies with essential information.

Wetland vegetation

Wetlands such as tidal or freshwater marshes are a major component of ecological restoration programs in the Delta (e.g. California EcoRestore). Once disturbed, wetlands are vulnerable to invasion by non-native plant species; once established, the invaders are often difficult to control or eradicate. For example, a tall grass, common reed, is highly invasive in global wetlands and in the Delta, where it crowds out competitors and forms monotypes. Mapping and tracking distributions are difficult in the Delta because native genotypes (not usually invasive) and European strains (highly invasive) both occur and look alike from the air and on the ground (Hickson and Keeler-Wolf 2007). As it does elsewhere, common reed inhabits multiple habitats: palustrine emergent wetlands, freshwater drainage ditches, intertidal bay islands, muted tidal marshes, and wetlands with saline soils (Galatowitsch et al. 1999).

Because wetlands have been a major focus of restoration for a long time, there is considerable knowledge available about several widespread, aggressive invasive plants such as cattails, reed canary grass (*Phalaris arundinacea*), and common reed (Zedler and Kercher 2005). Such species reproduce vegetatively from rapidly spreading rhizomes (belowground stems). Their starchy rhizomes serve as reserves that help them resist control using herbicides and cutting and even superficial soil removal. Their tall leaves and stems enable them to outcompete native species. Wetland restoration provides opportunities for field experiments that can enhance our understanding of invader biocontrol methods, herbicide resistance, or the use of heterogeneous topography to facilitate diverse plantings that resist invasions.

Fish

Several studies have substantiated that more non-native than native fish species are present in the Delta and these non-natives have been introduced in a variety of ways. Many non-native fish species have been introduced through stocking to improve local food and sport-fishing opportunities and to diversify fish communities. One of the first species introduced was *Alosa sapidissima* (American shad), which was brought to the Sacramento River in 1871 and supported a commercial fishery until the 1950s (Dill and Cordone 1997). *Ameiurus nebulosus* (brown bullhead catfish) were introduced to the San Joaquin River in 1874, followed by several other species of catfish. Striped bass were then introduced to the Carquinez Strait in 1879, leading to a successful commercial fishery that recorded over one million pounds of catch within 20 years. Although large-scale stocking of hatchery-raised striped bass ended in 1992 due to threats to native fish, stocking continued at lower levels in later years.[14]

Several other bass species were introduced to California prior to 1900, with records indicating that smallmouth bass (*Micropterus dolomieu*) were first stocked in 1874 and largemouth bass (*Micropterus salmoides*) as early as 1891. Stocking continued for many years. Other bass, including the spotted

[14] In February 2020, the California Fish and Game Commission adopted a policy of striving “to maintain a healthy, self-sustaining striped bass population in support of a robust recreational fishery” while eliminating the policy of supporting artificial propagation.

and redeye bass (*Micropterus punctulatus* and *Micropterus coosae*), were introduced on a lesser scale during the 1930s to 1960s. The establishment of several species of bass in the Delta has resulted in a world-class bass fishery, leading to conflicting goals among individuals managing non-native fish in the Delta: many people wish to recover populations of native species, while others aim to maintain healthy populations of harvestable non-native species. Many of these species, like largemouth and striped bass, prey on or compete with native species like Chinook salmon (*Oncorhynchus tshawytscha*) (Brown and Michniuk 2007). Consequently, management of fish in the Delta involves balancing conflicting interests and ecological goals.

Some other fish species have been introduced as biocontrol agents. *Gambusia affinis* (western mosquitofish) were widely introduced for biological control of mosquitoes in the 1920s. *Menidia audens* (Mississippi silverside) were introduced in the 1960s as a biological control agent; they became widely established by 1975 and are now one of the most widespread and abundant fish species in the Delta (Mahardja et al. 2016).

Other fish species have been introduced as byproducts of human activity (Moyle and Marchetti 2006). One of the most abundant demersal fish in the Delta, *Acanthogobius flavimanus* (yellowfin goby), was first observed in 1963 and was likely introduced through ballast-water transport (Dill and Cordone 1997; Workman and Merz 2007). Their abundance is likely due to their generalist diet, but their inability to reproduce in freshwater has limited their expansion. More recent introductions through ballast water include *Tridentiger bifasciatus* (shimofuri goby) and *Tridentiger barbatus* (shokihaze goby), which were first recorded in 1985 and 1997, respectively.

Collectively, non-native species introduced since the 1800s have established populations exceeding the abundance of most native species, resulting in reductions in native fish biodiversity (Moyle 2002, Moyle et al. 2012). In one study that analyzed fish-catch data throughout the Delta between 1994 and 2002, 62% of the species caught and 59% of the overall catch were non-native (Brown and May 2006). Feyrer and Healey (2003) reported that only eight of the 33 species sampled in the southern Delta between 1992 and 1999 were native; no native species accounted for more than 0.5% of the total catch. Higher abundance of native species was correlated with high river flow and turbidity, whereas more non-native fish were associated with warmer water temperatures and low river flow—characteristics of the highly modified south Delta. Similarly, a majority of the overall catch of fish larvae collected between 1990 and 1995 was non-native species associated with low flow and high temperature conditions during the late season; native species were more abundant during early-season conditions (Feyrer 2004). Marchetti et al. (2004) suggested that restoring natural hydrologic processes could mitigate the invasion of non-native fish species while favoring native fish populations.

Historically, the Delta was managed primarily for non-native game fishes, especially striped bass, American shad, and various catfishes (Ictaluridae), with some attention also paid to Chinook salmon and steelhead (*Oncorhynchus mykiss*) (mainly through hatcheries) and to white sturgeon (*Acipenser transmontanus*) (Skinner 1962, Kelley 1966, Moyle 2002). Today, formal management of non-native fishes is minimal, even though they contribute substantially to fisheries (e.g., largemouth bass fishery in south and central Delta). Management instead focuses largely on species that are listed under state and federal Endangered Species Acts. However, non-native fishes dominate the fish fauna of the Delta and Suisun Marsh and they form surprisingly integrated fish assemblages with the remaining native species, with a few exceptions (Aguilar-Madrono et al. 2019). This has led Dahm et al. (2019) to suggest that fishes in the Delta should be managed as assemblages with common environmental requirements. For example, striped bass, American shad, delta smelt, and longfin smelt all require a fully functioning estuarine salinity gradient, including substantial outflows to maintain large populations. Historically, all found Suisun Marsh to be an important rearing area.

Non-native fish and submerged aquatic vegetation (SAV)

Both non-native fish and plants have significantly increased in recent decades. Several studies have linked the proliferation of invasive vegetation to the growth of non-native fish populations, but the causal relationship is unclear**.** One study found that *Egeria densa* is important habitat for juvenile largemouth bass, and the proliferation of this plant likely supported the growth of the largemouth bass fishery in the Delta (Conrad et al. 2016). *Egeria densa* habitat is very productive and several studies have correlated its presence with fish assemblages dominated by non-native species, some of which are predators of native fish such as juvenile salmonids (Brown 2003, Grimaldo et al. 2003, Nobriga et al. 2005, Brown and May 2006, Brown and Michniuk 2007, Loomis 2019). Nobriga et al. (2005) found that native special-status fish species were less abundant in SAV (primarily *E. densa*) habitat than in turbid open water. In contrast, Young et al. (2018) reported that *E.*

densa was not correlated with increased macroinvertebrate food for non-native largemouth bass when compared with other SAV species. Although it has been proposed that restoring tidal-wetland habitat would provide important habitat for native fish species, this may only be true where invasive SAV (*E. densa*) is not well established and therefore would not invade the restored habitat (Brown and Michniuk 2007). While restoration for native fish communities looked promising for the northern Delta in 2008, invasive SAV have since increased. For example, Liberty Island was mostly free of SAV in 2008 but now has more than 50% cover of SAV, and the change appears to be persistent (Ustin et al. 2017). Non-native fish might have been facilitated by a concurrent increase in non-native SAV (*Egeria densa. Myriophyllum spicatum* and *Potamogeton crispus*). The status and trends of invasive species should be considered when planning future management of both SAV and non-native fish.

Mammals

Nutria are non-native semi-aquatic rodents that are a major threat in the Delta. Although nutria were first introduced to California from South America in 1899 for fur farming, this attempt was commercially unsuccessful (Evans 1970, Carter and Leonard 2002). Subsequent introductions led to a small feral population by the 1940s (Schitoskey 1972), but nutria numbers remained low and the species was eradicated from the state by 1978 (Deems and Pursley 1978). However, a reproducing population was found in the San Joaquin Valley in 2017, and nutria are currently found in the Delta in San Joaquin and neighboring counties (CDFW 2019).

Nutria burrowing and herbivory damage habitats and infrastructure. Nutria burrowing is of great concern in the Delta because levee systems are subject to erosion. Breached levees could allow large agricultural fields to flood, perhaps permanently in subsided areas. Nutria feeding is also a threat in the Delta because each animal consumes up to a quarter of its body weight in plants per day. Damage to non-native cattails might not alarm farmers, but they are threatened by losses of rice, corn, and other grains, as well as vegetable crops. Nutria are also vectors for parasites and pathogens. The California multi-agency response team is collaborating to eradicate the Delta population. It began as an emergency Incident Command System in 2018 and a formal Nutria Eradication Program in 2019. The Nutria Eradication Program had caught over 1,000 nutria by May 2020 (see Footnote 12).

APPENDIX B: Panelists and Acknowledgements

To be completed

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