5

Ecology

Ecosystems of the Salton Sea and Surrounding Environments

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HIGHLIGHTS

- **Federal and California state air quality regulations, endangered species laws, and protections of migratory waterfowl will necessitate action as increasing salinity causes the die-off of all fish species within the next few years.**
- **Excessive nutrient flows into the Sea trigger harmful algal blooms and dead zones, threatening wildlife and human health.**
- **Planned construction of wetland habitats may benefit certain species of non-fish-eating birds; however, there are currently no official plans to maintain or restore a fully functioning lake ecosystem.**

The Salton Sea is host to a significant number of species of conservation importance, as well as the ecosystems that support them. These ecosystems include the lake itself, the lake margins—riparian zones and the increasingly exposed playa—as well as the vast agricultural ecosystems bordering the Salton Sea. The functioning of these ecosystems is essential for the survival of many valued species, including the federally endangered desert pupfish and hundreds of migratory bird species. The ecology of the Sea is dynamic and unstable, regularly fluctuating due to the extreme environmental conditions and biotic responses. The salinity of the Sea—already at 74 parts per thousand—will continue to rise as the sea shrinks, leading to a catastrophic collapse of the aquatic food web if the current trend is not halted (SSMP, 2021).

CONSTRUCTED WETLAND designed to provide bird habitat at the southern end of the receding Salton Sea. Jonathan Nye

Aquatic Primary Production

PRIMARY PRODUCERS in the Salton Sea include several photosynthetic and chemosynthetic organisms, ranging from wetland plants to free-floating algae and photosynthetic microorganisms in the Sea itself and its margins. These primary producers, which form the base of the Salton Sea food web, are supported by an overabundance of abiotic nutrients supplied to the Sea via agricultural runoff and untreated sewage originating from Mexico. This nutrient load results in high rates of primary production and subsequent die-off of aerobic organisms, such as tilapia, within oxygen-starved regions known as dead zones. These zones form when prolific primary producers die and sink into the water column, consuming oxygen during their decomposition (Beman et al. 2005, Chaffin and Bridgeman 2014, Heisler et al. 2008).

When there are blooms of algae species that produce toxins, the events are called harmful algal blooms, or HABs (Reifel et al., 2001; Tiffany et al. 2007a; Tiffany et al. 2007b). Harmful algal blooms are signs of polluted waters that occur from areas along California's coast to river systems to the Salton Sea. The Salton Sea's waters contain two major HAB organisms—dinoflagellates and cyanobacteria—that are toxic to organisms including humans (Carmichael and Li, 2006). Dinoflagellates are microscopic single-celled organisms that can grow by photosynthesis or by taking up organic molecules dissolved in nutrient-rich water. These organisms are coated by specialized armor plates made of calcium carbonate. At certain times of their life cycles, they excrete compounds known to be neurotoxins (Hackett et al., 2004). These toxins can accumulate in fish tissues and be passed to organisms consuming those fish, including pelicans.

Other HABs consist of species of cyanobacteria, primitive photosynthetic organisms, such as *Microcystis aeruginosa* that also produce toxins that cause fish and wildlife poisonings (Carmichael and Li, 2006;

Kenefick et al., 1993). Cyanobacterial toxins are tied to vast mortalities of eared grebes in the Salton Sea (Anderson et. al 2007). In particular, microcystin, a toxin produced by cyanobacteria, has been found in acute concentrations within the livers of *Podiceps nigricollis* (eared grebes), that perished at the Salton Sea (Carmichael and Li 2006). Organisms like this not only produce toxins but also create conditions whereby their biomass causes anoxic events (see Chapter 3 for a more detailed discussion of microbial metabolism in the water column).

In addition to toxins produced by the primary producers, agricultural chemicals and naturally occurring elements that have accumulated to potentially toxic levels in the Sea and are contained in the primary and secondary consumers can bioaccumulate in the tissues of predators such as fish and birds. For instance, selenium, DDT and PCBs were identified in fish muscle tissue having been passed through the food web from primary producers to small invertebrates and insects then into fish (Figure 5.1) (Sapozhnikova et al. 2004; Moreau et al. 2007).

High rates of primary production support an array of zooplankton in the Sea, including ciliates (Reifel et al. 2007). The overabundance of respiring microorganisms results in the consumption of a significant amount of oxygen, so much so that at depth, where atmospheric mixing does not penetrate, the Sea is low in dissolved oxygen. Microorganisms in the absence of oxygen operate using alternate metabolic pathways, producing hydrogen sulfide (H_2S), which is toxic to animal life in high concentrations. During high wind events, mixing of deep and shallow waters result in hydrogen sulfide release to the atmosphere (Chapter 3) and fish kills (Figure 5.1).

Agricultural Interfaces

THE SALTON SEA is connected closely with adjacent terrestrial and wetland ecosystems. It is embedded in the extensive desert ecosystem of the Sonoran Desert, which is characterized by shrublands dominated by *Larrea tridentata* (Creosote bush). While the desert ecosystem may have limited direct interaction with the Salton Sea, it does provide ecological context. Agriculture dominated ecosystems are also extensive in the Salton Sea region. Agricultural decision making has a major role in affecting water and nutrient inputs to the Sea. With increased efforts directed towards increasing both agricultural water and nutrient efficiency, and coupled with increasing agricultural land abandonment, unintended nutrient and pesticide inputs to the Salton Sea are decreasing (Box 5A).

Wetlands

THE IMPORTANCE of the Salton Sea's wetlands on the migratory and resident birds of North America was described famously in Shuford et al. (2002). Since then, however, increasing salinity and nutrient overloads have caused ecological disasters, including major fish

IRRIGATED FARMLAND in the Imperial Irrigation District, which drains into the Salton Sea. Caroline Hung

High-Temperature Agricultural Systems

BOX 5A

HIGH-TEMPERATURE AGRICULTURAL SYSTEMS such as those adjacent to the Salton Sea are prevalent in the southern United States and will become even more common with future warming (Hatfield et al. 2014). Most U.S.-grown winter vegetables are farmed in the Imperial Valley south of the Sea. Tree crops—for example, dates, grapefruits, and nuts—are grown in the Coachella Valley to the north. High-temperature environments are known to increase the potential for biological activity arising from highly non-linear responses to temperature and moisture. The Salton Sea region has become a case-study for improved understanding of agriculture in such conditions. Agricultural dynamics in the region depend extensively on irrigation, and during the summer, evaporation rates can be greatly elevated (Oikawa et al. 2015b; Lu et al. 2017).

High-temperature agricultural systems can be locations of unusually high nitrogen losses through soil trace-gas emissions, but these emissions may be reduced with readily achievable management changes (Liang et al. 2015). Funding mechanisms for such approaches are limited; however, one approach may be to connect emissions to either carbon markets or water markets. Initial estimates demonstrate that modifying fertilization and irrigation practices in a high-temperature environment can reduce losses of nitrogen to the atmosphere by 50%. By reducing these emissions, nitrogen-use efficiency can substantially be increased and thereby reduce the need for potentially polluting fertilizer. Implementing such changes to the Imperial Valley and Coachella agricultural areas could have positive impact on life in the Sea itself.

Soil nitrogen oxide (NOx) emissions nearby the Salton Sea are more than an order of magnitude greater than standard agricultural NOx model predictions. These emissions are associated with standard management practices for summer forage crops: the combination of high temperatures and pulsing dynamics associated with drying and rewetting of irrigated soils. For example, soil NOx emissions observed in a high temperature, fertilized agricultural area of the Imperial Valley ranged between 5 and 900 nanograms of nitrogen in a square meter within a second, some of the highest instantaneous fluxes ever measured. These emissions were associated with an increase in regional ozone, an important component of poor air quality. Reducing NOx and nitrous oxide emission pathways could improve nutrient-use efficiency, reduce demands for fertilization, and minimize the negative life cycle impacts of these trace gases to human health, adjacent natural habitats, and greenhouse gas concentrations (Chen et al. 2011; Zhang et al. 2013).

kills and avian diseases (Figure 5.1). Today, wetlands surrounding the northern and southern shorelines where the Whitewater, New, and Alamo rivers drain into the Sea are potential habitats supporting remnant populations still able to take advantage of the area.

Heavy-metal poisoning of wildlife is a concern for existing and planned wetland habitat, however. Water in agricultural drains regularly test at toxic levels (Xu et al. 2016). If this water is used to supplement water destined for wetland habitat, the accumulation of toxic metals along the food chain (bioaccumulation) could adversely impact the health of fish and birds, especially those at high trophic levels. Investigation of groundwater and geothermal water in the southern portion of Salton Sea have been also found to contain high levels of arsenic and other heavy metals that may impact wildlife (Flores-Galvan et al. 2017).

Wetland ecosystems, at the interface between the Salton Sea and upland desert or agricultural lands, are key ecosystem components that interact strongly with the Sea. Riparian wetlands can have a role in the hydrologic dynamics, with greatly elevated evaporation rates and can be a water loss pathway that depends on both lake water and plant dynamics. At the same time, wetlands can influence nutrient dynamics through either plant uptake or biogeochemical transformation. Compared to native deserts or retreating shoreline, wetlands can stabilize the land surface and reduce

Figure 5.1 Schematic diagram of variables resulting in fish kills. The extent and severity of fish kills are the result of four interconnected variables: Algal blooms and phosphorus cycling from the Alamo River (dark green), algal blooms and phosphorous cycling from the New River (light green), algal blooms and total dissolved solids in the Salton Sea (orange/yellow), and seasonal temperatures (blue/orange). Credit: Kjelland et al. (2018).

dust emissions. Wetlands associated with the Salton Sea are also connected to key species conservation concerns. These wetlands are a key stop for migrating bird species spanning much of the western United States, Canada, and Mexico. They are also associated with aquatic habitat for the desert pupfish.

More information about ecosystem and conservation roles of Salton Sea wetlands are needed to assess and manage these ecosystems to achieve policy goals. The 2018 Salton Sea Management Plan describes building Species Conservation Habitats: diked ponds with water pumped from agricultural drains, groundwater, and the salty Salton Sea open waters. The ponds are projected to allow for the growth of endangered desert pupfish, tilapia, as well as important invertebrates for feeding wildlife. There is no guarantee that these

Threatened Food Webs

BOX 5B

ENDANGERED SPECIES LAWS and waterfowl protections will necessitate action as increasing salinity causes the die-off of all fish species in the Salton Sea within the next few years. More focus on wetlands that emerge naturally as the Sea recedes could provide critical new habitat with minimal taxpayer investment.

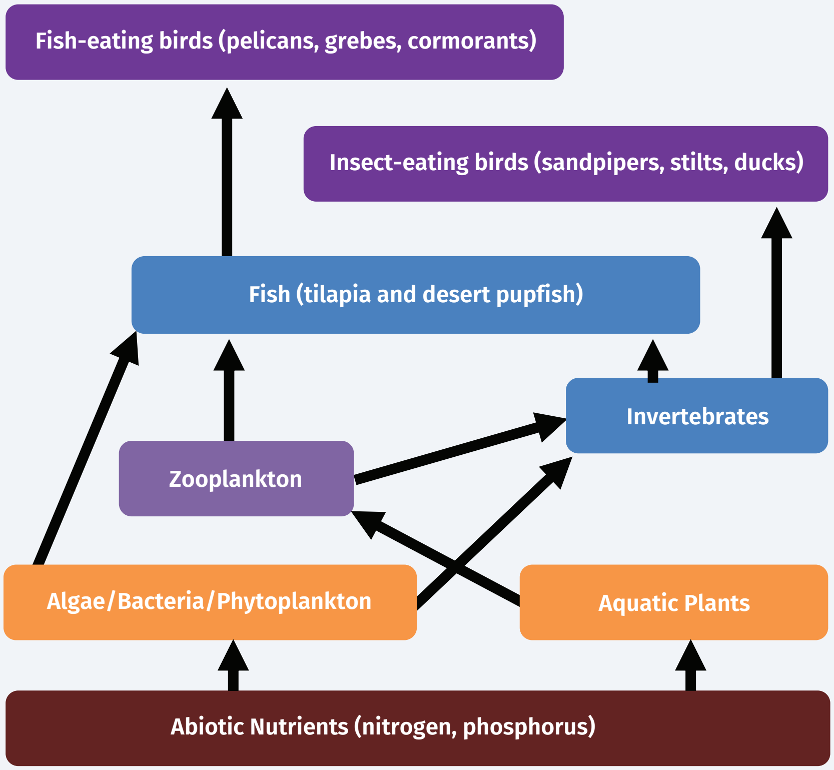

Figure 5.2 Simplified Salton Sea food web. CREDIT: Jonathan Nye.

Brown pelican. Jonathan Nye

Tilapia carcass. Dana Swarth

expensive. engineered habitats will prove sustainable in the short term or long term, however.

A more cost-effective strategy for developing bird habitat may be to cultivate the new wetlands that are emerging at drain outlets as the Sea recedes. According to U.S. Fish and Wildlife biologist T. Anderson (personal communication, July 9, 2021), these vegetated areas are “doing a fine job suppressing dust and producing entirely new thriving ecosystems at no cost to taxpayers” and can be improved and sustained with minimal modification or maintenance.

Aerobiology

MICROORGANISMS THAT LIVE in and around the Salton Sea, surrounding playa and wetlands, and nearby agricultural systems, have an impact on the air quality of the region. As the Sea recedes due to reduced water inputs in all scenarios, it exposes additional playa and increases atmospheric dust levels (Chapter 4). Similarly, in fallow agricultural fields and disturbed ecosystems nearby, topsoil can be transported into the air as dust. In addition, due to intense wind eddies that occur frequently over the Salton Sea, sea spray can be transported as well with the dust. Dust and sea spray from these diverse sources are composed of organic and inorganic materials, including adhering microbes, which can be transported locally or long distances, even between continents (Aciego et al. 2017). As these materials are picked up and transported, the entrained microorganisms on particles add to the biological diversity of the air, studied by an emerging field of research called aerobiology. The composition of this

ENDANGERED DESERT PUPFISH, **which inhabits shallow waters in and around the Salton Sea, can tolerate higher temperatures and salinities and lower oxygen levels than most fish.**
Copyright Minden Pictures

aeolian microbial community can have an impact on functioning of local and global ecosystems, potentially impacting human health.

Aquatic Food Webs

ANIMALS SUPPORTED BY THE SEA'S ECOSYSTEMS include fish and birds, supported by algae and arthropods. Fish in the sea today are restricted to tilapia (*Oreochromis mossambicus x O. urolepis*), by far the dominant species in the sea; desert pupfish (*Cyprinodon macularius*), an endangered species; sailfin mollies (*Poecilia latipinna*); and western mosquitofish (*Gambusia affinis*); with other introduced species of fish unable to cope with increasing salinity in recent years (Martin & Saiki, 2005). Tilapia were likely introduced by the escaping fish farms and through introduction by the California Department of Fish and Wildlife for control of noxious weeds and insects (Costa-Pierce, 1999), while desert pupfish are a native species to the American southwest. The primary constraints on the survival of these species include the temperature and salinity of the sea, both of which fluctuate wildly throughout the year due to seasonality associated with freshwater inflows. In general, annual average salinity is increasing beyond the physiological limits of these animals.

Tilapia venture to the bottom sediments to lay their eggs and are found in all parts of the sea in the winter. They migrate to nearshore and shallow waters in the spring and as hypoxia and sulfide levels increase, and return to the open, deeper waters in the winter as dissolved oxygen levels increase (Caskey et al. 2007). Tilapia are mixotrophic organisms feeding both on algae and other small animals, including small arthropods and smaller fish. In recent years the lower oxygen content has become too low for tilapia to survive resulting in massive fish die-offs (Cardona et al. 2008).

Desert pupfish are less commonly found in the Sea, as their primary habitats are in the fresher waters of the riparian zones and wetlands, though they travel through the sea between various breeding habitats (Figure 5.4). Tilapia and other non-native fish likely predate upon pupfish eggs, though the extent to which tilapia impact pupfish is unknown (Martin et al., 2009). Desert pupfish populations find refuge in channels and creeks around the sea, though can travel through the sea connecting populations (Riedel, 2016).

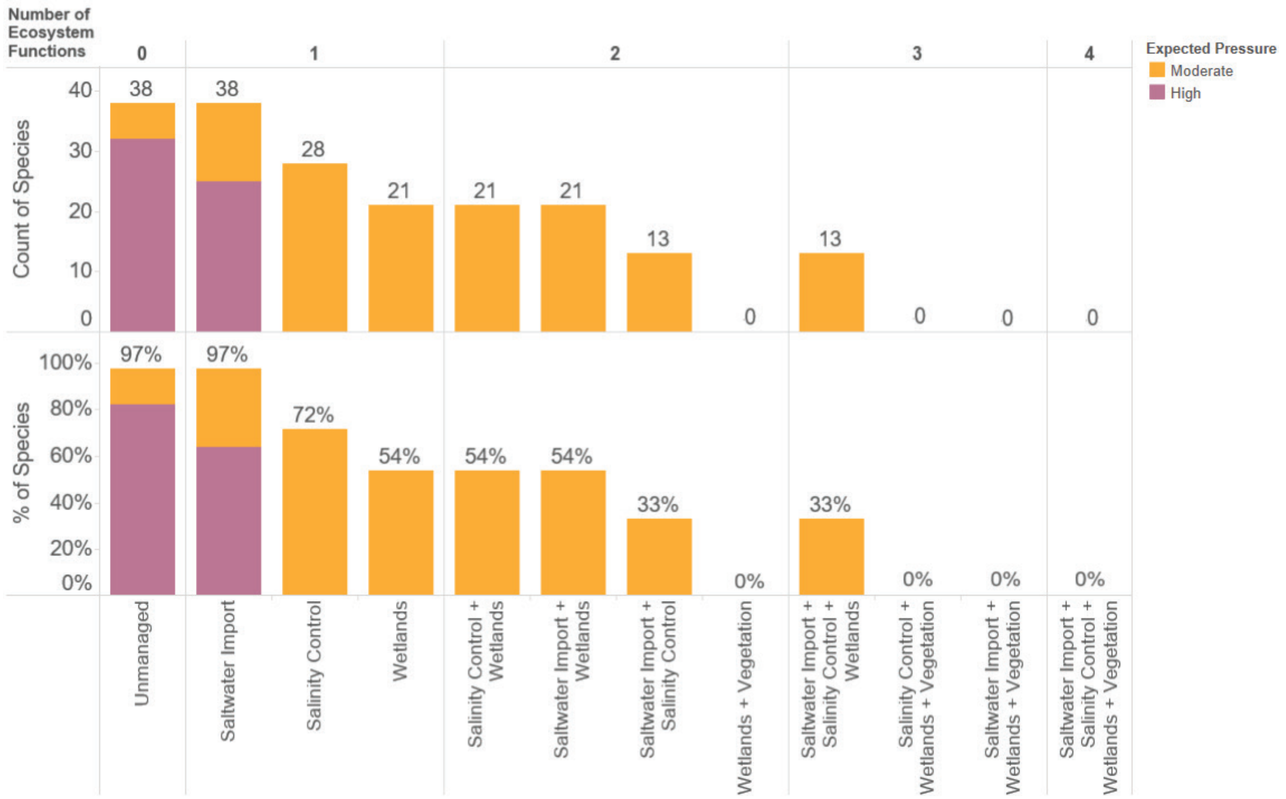

Figure 5.3 Calculation of expected pressures on ecosystem functioning of the Salton Sea. Different mitigation strategies have different expected pressures on species. Combining different mitigation strategies decreases the expected pressures on species. Credit: Forney (2018).

Conservation efforts have established more populations of pupfish beyond the native and historic habitat such as Salt Creek and the Trifolium Drain into various agricultural drains around the lake to stem long term declines in pupfish populations. However, these drains and creeks often only connect to the sea seasonally in the winter. Ultimately pupfish survive in agricultural drainage systems rather than the sea itself, partly due to predation pressures and ideal habitat and breeding space. (Martin & Saiki, 2005).

The Salton Sea can support as many as 350 different species of birds. Most bird species are migratory, occupying the sea in the winter months. The birds of the Salton Sea fall into two categories: invertebrate eating birds (insectivorous) and fish-eating birds (piscivorous). Insectivorous birds benefit more readily from the wetland habitat managed by the Fish and Wildlife Service in Sonny Bono Salton Sea National Wildlife Refuge. The insectivores feed largely in the wetlands and riparian zones while piscivores are largely subsisting on the tilapia in the littoral zone of the lake where their prey congregate.

Piscivorous birds are highly susceptible to fluctuations in populations of their prey, resulting in bird populations fluctuating as well (Hurlburt et al. 2009). Piscivores include pelicans, gulls, cormorants, terns and many others, typically migrating from coastal marine areas and other saline lakes (Lyons et al, 2018). Lyons et al.'s 2018 study of Caspian terns (*Hydroprogne caspia*) shows that these birds congregate near the margins of freshwater inputs to the Salton Sea in the north and the south, including the Whitewater, Alamo and New river deltas where fish are likely to congregate due to lower salinities and water temperatures. Ecosystem modeling of decreased freshwater inputs show that populations of piscivorous birds at the Salton Sea are very likely to be negatively impacted by reduced water availability from implemented QSA agreements (Kjelland & Swannack, 2018; Upadhay et al. 2018).

Research Needs

THE SALTON SEA FOOD WEB is currently on the threshold of ecosystem collapse. Without intervention, many higher-level organisms of the Salton Sea—fish and fish-eating birds—will almost certainly disappear. It is likely that the current levels of intervention will have the same result. Only with sustained effort can we maintain habitat suitable for birds, fish, and other organisms in the sea. The way to guarantee continued presence of these valued organisms is by controlling salinity, oxygen levels and temperatures. We may not be able to control rising temperatures and the increased frequency of heat waves due to climate change, but California can control the freshwater inputs into the Sea to maintain a healthy food web that benefits not only wildlife but also the people living nearby.

Connections among organisms and interspecies relationships are more complicated than the simplistic food web presented above (Box 5B). For example, certain species may have a larger impact than expected given their relative biomass on the ability of other organisms to survive, a concept known as keystone species or ecosystem engineers. While tilapia may not be the perfect model of a keystone species, it is likely that the food web will collapse with their disappearance. The Salton Sea represents a key stopping point for migratory bird species travelling along the Pacific Flyway, a migration route stretching from the Arctic to the tropics. The loss of this resource for migratory species would be potentially devastating in its impact to the sustainability of populations of these species.

Under any of conceivable future scenarios for Salton Sea management, naturally created wetlands may have greater potential for supporting wildlife than expensive, constructed habitats. To test this hypothesis, research must be funded to answer some key questions: What species are these wetlands supporting now? And what is their potential for long-term sustainable habitat? Can they be integrated into Salton Sea Management plans for deep water ponds? How much water is needed to maintain wetlands at a size that could significantly impact—and improve—migratory and resident bird habitat?

No matter how management of the Salton Sea develops over the coming decades, it is certain that there will be large—and possibly irreversible—changes to the ecosystem that pertains today. Everyone wants the beauty and majesty of the area to be enhanced, not degraded further than it has already. Partnering research with restoration efforts has the greatest potential to determine if the Salton Sea Management Program is heading in the right direction. An independent assessment of ecosystem functioning in its broadest sense is an important component for Salton Sea's future.

Three Possible Futures for Lake Ecology

We consider probable outcomes for Salton Sea ecology based on hypothetical scenarios for future lake levels:

Continued Decline

WITHOUT INTENTIONAL INTERVENTION, lake levels will continue to decline, even as wetlands are constructed on exposed lakebed.

If lake levels continue to decrease, the results will likely be devastating to most larger organisms living in and near the Sea. As the Sea shrinks, we know the salinity will increase to levels precluding the survival of fish species. With oxygen levels decreasing, hydrogen sulfide levels rising, increased salinity and high temperatures, the lake will become uninhabitable for tilapia. Although desert pupfish have specific adaptations for saline conditions, they are unable to survive for longer periods of time, rendering the Sea impossible to traverse for individuals traveling between breeding habitats.

It is also assumed that as the Sea shrinks in size, HABs will increase in prevalence. Furthermore, these conditions will also reshape the species composition of organisms at lower trophic levels with conditions more favorable to extremophile microorganisms and arthropods. Piscivorous birds will all but disappear in the absence of suitable prey. Insectivorous birds may survive in areas such as managed wetlands; however, changes in the insect community near the shoreline may result in a lack of suitable prey for these birds. Ultimately the biodiversity, productivity and functioning of the aquatic ecosystem in this scenario will collapse. Key questions:

- Will there be changes in the organisms at the base of the food chain? Will phytoplankton-produced toxins be enhanced?
- When will the endangered pupfish be extirpated? Will there be remnant populations in river outflow channels?
- We expect bird populations to decline, but will they disappear altogether? Will migratory birds lose a key stopover site?

BOX 5C

Stabilization

A CHANGE TO CURRENT water policy could intentionally direct a limited amount of Colorado River water to the Salton Sea.

If enough freshwater enters the lake to keep salinity levels in check, keeping tilapia populations stable, then perhaps piscivorous birds will remain. However, for tilapia to survive the Salton Sea would require higher inflows of freshwater rather than less, so it is likely that this scenario will result in the disappearance of fish and piscivorous birds. Microorganism and insect community composition, on the other hand, would likely reflect what occurs in other highly saline aquatic ecosystems, such as Mono Lake, where a prevalence of brine shrimp and flies support insectivorous birds. Key questions:

- How much water needs to be delivered to keep the ecosystem functional as it is today?
- Will created wetlands form suitable habitat for many of the important species?
- Can mitigation and conservation efforts be economically sustained?

Recovery

WITH LONG-RANGE PLANNING and significant capital investment, a significant new source of water could be pumped into the Salton Sea.

Water importation presents the best possible case for the survival and stability of fish and bird populations. However, the source of water will determine the Sea's community composition. Saltwater importation from the Gulf of Mexico may result in salinity too high for tilapia survival despite higher lake levels. Freshwater importation and wetland management is the best way to sustain the biodiversity, productivity and functioning of the Salton Sea ecosystem as we know it. Even with freshwater introduction, climate change may result in temperatures and oxygen availability incompatible with fish and birds. Key questions:

- What are the relative problems or opportunities that will originate from fresh or saltwater importation?
- How will food web structure change as lake volume and salinity change?

WETLAND near the Salton Sea. PHOTO CREDIT to Irfan Khan. Copyright ©2019. Los Angeles Times. Used with permission.

CHAPTER FIVE - REFERENCES

Aciego, S. M., Riebe, C. S., Hart, S. C., Blakowski, M. A., Carey, C. J., Aarons, S. M., Dove, N. C., Botthoff, J. K., Sims, K. W. W., & Aronson, E. L. (2017). Dust outpaces bedrock in nutrient supply to montane forest ecosystems. *Nature Communications*, *8*(1), 14800. https://doi.org/10.1038/ncomms14800

Anderson, T., Tiffany, M. A., & Hurlbert, S. H. (2007). Stratification, sulfide, worms, and decline of the Eared Grebe (*Podiceps nigricollis*) at the Salton Sea. *Lake and Reservoir Management*, *23*, 500–517. https://doi.org/10.1080/07438140709354034

Beman, J. M., Arrigo, K. R., & Matson, P. A. (2005). Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. *Nature*, *434*(7030), 211–214. https://doi.org/10.1038/nature03370

Carmichael, W. W., & Li, R. (2006). Cyanobacteria toxins in the Salton Sea. *Saline Systems*, *2*(1), 5. https://doi.org/10.1186/1746-1448-2-5

Caskey, L. L., Riedel, R. R., Costa-Pierce, B., Butler, J., & Hurlbert, S. H. (2007). Population dynamics, distribution, and growth rate of tilapia (*Oreochromis mossambicus*) in the Salton Sea, California, with notes on bairdiella (*Bairdiella icistia*) and orangemouth corvina (*Cynoscion xanthulus*). *Hydrobiologia*, *576*(1), 185–203. https://doi.org/10.1007/s10750-006-0301-2

Chaffin, J. D., & Bridgeman, T. B. (2014). Organic and inorganic nitrogen utilization by nitrogen-stressed cyanobacteria during bloom conditions. *Journal of Applied Phycology*, *26*(1), 299–309. https://doi.org/10.1007/s10811-013-0118-0

Chen, H., Wang, M., Wu, N., Wang, Y., Zhu, D., Gao, Y., & Peng, C. (2011). Nitrous oxide fluxes from the littoral zone of a lake on the Qinghai–Tibetan Plateau. *Environmental Monitoring and Assessment*, *182*(1–4), 545–553. https://doi.org/10.1007/s10661-011-1896-y

Costa-Pierce, B. (1999). *Final Synthesis Document: Fish and Fisheries of the Salton Sea*. Institute of Marine Science, University of Southern Mississippi, Ocean Springs, MS.

Flores-Galván, M., Arellano-García, E., Ruiz-Campos, G., & Daesslé, L. W. (2017). Genotoxic Assessment of Some Inorganic Compounds in Desert Pupfish (*Cyprinodon macularius*) in the Evaporation Pond from a Geothermal Plant. *Bulletin of Environmental Contamination and Toxicology*, *99*(2), 218–223. https://doi.org/10.1007/s00128-017-2114-6

Forney, D. (2018). *Ecological restoration potential of management strategies at the Salton Sea* [Report for the San Diego Wet Lab]. https://www.authorea.com/users/170258/articles/200338-ecological-restoration-potential-of-management-strategies-at-the-salton-sea

Hackett, J. D., Anderson, D. M., Erdner, D. L., & Bhattacharya, D. (2004). Dinoflagellates: a remarkable evolutionary experiment. *American Journal of Botany*, *91*(10), 1523–1534. https://doi.org/10.3732/ajb.91.10.1523

Heisler, J., Glibert, P.M., Burkholder, J.M., Anderson, D.M., Cochlan, W., Dennison, W.C., Dortch, Q., Gobler, C.J., Heil, C.A., Humphries, E., & Lewitus, A. (2008). Eutrophication and harmful algal blooms: a scientific consensus. *Harmful Algae*, *8*(1), 3–13. https://doi.org/10.1016/j.hal.2008.08.006

Hurlbert, A. H., Anderson, T. W., Sturm, K. K., & Hurlbert, S. H. (2007). Fish and fish-eating birds at the Salton Sea: a century of boom and bust. *Lake and Reservoir Management*, *23*(5), 469–499. https://doi.org/10.1080/07438140709354033

Kenefick, S. L., Hrudey, S. E., Peterson, H. G., & Prepas, E. E. (1993). Toxin Release from *Microcystis Aeruginosa* after Chemical Treatment. *Water Science & Technology*, *27*(3–4), 433–440. https://doi.org/10.2166/wst.1993.0387

Kjelland, M. E., & Swannack, T. M. (2018). Salton Sea days of future past: Modeling impacts of alternative water transfer scenarios on fish and bird population dynamics. *Ecological Informatics*, *43*, 124–145. https://doi.org/10.1016/j.ecoinf.2017.06.001

Liang L. L., Eberwein, J. R., Allsman, L., Grantz, D.A., & Jenerette, G. D. (2015). Regulation of CO_2 and N_2O fluxes by coupled carbon & nitrogen availability. *Environmental Research Letters*, *10*(3), art034008. https://iopscience.iop.org/article/10.1088/1748-9326/10/3/034008/pdf

Lu X., Liang, L. L., Wang, L., Jenerette, G. D., McCabe, M. F., & Grantz, D. A., (2017). Partitioning of Evapotranspiration Using a Stable Water Isotope Technique in an aArid and High Temperature Agricultural Production System. *Agricultural Water Management*, *179*, 103–109. https://doi.org/10.1016/j.agwat.2016.08.012

Lyons, D. E., Patterson, A. G. L., Tennyson, J., Lawes, T. J., & Roby, D. D. (2018). The Salton Sea: Critical Migratory Stopover Habitat for Caspian Terns (*Hydroprogne caspia*) in the North American Pacific Flyway. *Waterbirds*, *41*(2), 154–165. https://doi.org/10.1675/063.041.0206

Marti-Cardona, B., Steissberg, T. E., Schladow, S. G., & Hook, S. J. (2008). Relating fish kills to upwellings and wind patterns in the Salton Sea. *Hydrobiologia, 604*, 85–95. https://doi.org/10.1007/s10750-008-9315-2

Martin, B. A., & Saiki, M. K. (2005). Relation of desert pupfish abundance to selected environmental variables in natural and manmade habitats in the Salton Sea basin. *Environmental Biology of Fishes*, *73*(1), 97–107. https://doi.org/10.1007/s10641-004-5569-3

Martin, B. A., & Saiki, M. K. (2009). Trophic Relationships of Small Nonnative Fishes in a Natural Creek and Several Agricultural Drains Flowing into the Salton Sea, and Their Potential Effects on the Endangered Desert Pupfish. *The Southwestern Naturalist*, *54*(2), 156–165. https://doi.org/10.1894/GG-25.1

Moreau, M. F., Surico-Bennett, J., Vicario-Fisher, M., Crane, D., Gerads, R., Gersberg, R. M., & Hurlbert, S. H. (2007). Contaminants in tilapia (*Oreochromis mossambicus*) from the Salton Sea, California, in relation to human health, piscivorous birds and fish meal production. *Hydrobiologia*, *576*(1), 127–165. https://doi.org/10.1007/s10750-006-0299-5

Oikawa P.Y., Jenerette, G. D., & Grantz, D. A. (2015). Offsetting high water demands with high productivity: Sorghum as a biofuel crop in a high irradiance arid ecosystem. *Global Change Biology Bioenergy*, *7*, 974–983. https://doi.org/10.1111/gcbb.12190

Reifel, K. M., Swan, B. K., & Olivo, E. et al. (2007). Influence of river inflows on plankton distribution around the southern perimeter of the Salton Sea, California. *Hydrobiologia*, *576*, 167–183. https://doi.org/10.1007/s10750-006-0300-3

Reifel, K. M., McCoy, M. P., Tiffany, M. A., Rocke, T. E., Trees, C. C., Barlow, S. B., Faulkner, D. J., & Hurlbert, S. H. (2001). *Pleurochrysis pseudoroscoffensis* (Prymnesiophyceae) blooms on the surface of the Salton Sea, California. *Hydrobiologia*, *466*, 177–185. https://doi.org/10.1023/A:1014551804059

Riedel, R. (2016). Trends of Abundance of Salton Sea Fish: A Reversible Collapse or a Permanent Condition? *Natural Resources*, *7*(10), 535–543. http://doi.org/10.4236/nr.2016.710045

Sahagún, L. (2019, December 9). Amid the wasteland of the Salton Sea, a miraculous but challenging oasis is born. *Los Angeles Times*. https://www.latimes.com/environment/story/2019-12-09/a-new-dilemma-in-the-salton-sea-saga-unintended-marshlands

Salton Sea Management Program (SSMP). (2018). *Salton Sea Management Program Phase I: 10-Year Plan*, California Natural Resources Agency, California Department of Water Resources, and California Department of Fish and Wildlife. https://resources.ca.gov/CNRALegacyFiles/wp-content/uploads/2018/10/SSMP-Phase-1-10-Year-Plan.pdf

Salton Sea Management Program (SSMP). (2021). *2021 Annual Report on the Salton Sea Management Program*. California Natural Resources Agency, California Department of Water Resources, and California Department of Fish and Wildlife. https://saltonsea.ca.gov/wp-content/uploads/2021/03/2021-Annual-Report_3-5-21.pdf

Sapozhnikova, Y., Bawardi, O., & Schlenk, D. (2004). Pesticides and PCBs in sediments and fish from the Salton Sea, California, USA. *Chemosphere*, *55*(6), 797–809. https://doi.org/10.1016/j.chemosphere.2003.12.009

Tiffany, M. A., González, M. R., Swan, B. K., Reifel, K. M., Watts, J. M., & Hurlbert, S. H. (2007a). Phytoplankton dynamics in the Salton Sea, California, 1997–1999. *Lake and Reservoir Management*, *23*, 582–605. https://doi.org/10.1080/07438140709354039

Tiffany, M. A., Wolny, J., Garrett, M., KSteidinger, K., & Hurlbert, S. H. (2007b). Dramatic blooms of *Prymnesium sp.* (Prymnesiophyceae) and *Alexandrium margalefii* (Dinophyceae) in the Salton Sea, California*. Lake and Reservoir Management*, *23*, 620–629. https://doi.org/10.1080/07438140709354041

Upadhyay, R. K., Kumari, S., Kumari, S., & Rai, V. (2018). Salton Sea: An ecosystem in crisis. International *Journal of Biomathematics*, *11*(08), 1850114. https://doi.org/10.1142/S1793524518501140

Xu, E. G., Bui, C., Lamerdin, C., & Schlenk, D. (2016). Spatial and temporal assessment of environmental contaminants in water, sediments and fish of the Salton Sea and its two primary tributaries, California, USA, from 2002 to 2012. *Science of The Total Environment*, *559*, 130–140. https://doi.org/10.1016/j.scitotenv.2016.03.144

Zhang, S., Liu, F., Luo, P., Xiao, R., Zhu, H., & Wu, J. (2019). Nitrous oxide emissions from pilot scale three-stage constructed wetlands with variable nitrogen loading. *Bioresource Technology*, *289*, 121687. https://doi.org/10.1016/j.biortech.2019.121687