

Managing Lowland Wetlands in the Main Hawaiian Islands



Hulē'ia National Wildlife Refuge, Kauai. Photo by Adonia Henry.

By

Adonia R. Henry,

Wetland Ecologist, Scaup & Willet LLC

and

Leigh H. Fredrickson,

Senior Ecologist, Wetland Management and Educational Services, Inc.

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CHAPTER 1: PURPOSE

A Process-based Approach

This guide provides the foundation for a process-based approach to wetland management by incorporating the historical and current landscape setting into decision making. What is the landscape setting of a wetland? It is the surrounding area that influences the structures, processes, and patterns of abiotic and biotic components of a wetland through time. The landscape setting does not have a fixed boundary in time or space. As such, wetland management is inherently multi-disciplinary, requiring the integration of available information on formative processes, climate, hydrologic conditions, soils, geomorphic surfaces, biological processes, human-induced changes, and life-history requirements of key plants and wildlife. When changes within the landscape setting pre-date the written record, traditional ecological knowledge and archeological evidence are essential resources to inform the abiotic and biotic components.

Because process-based management is relatively young (compared to other disciplines), practitioners often lead the science by observing, documenting, experimenting, and adapting (Apostol 2006). The process-based approach presented in this guide encourages wetland managers and biologists to think critically, take a holistic approach to making informed decisions, implement and document on-the-ground actions, observe, and learn from the habitat and wildlife responses to those actions. Wetland management often requires creative solutions and is therefore as much an art as it is a science. This guide is not prescriptive and will not tell you what to do when. Rather, the intent is the following:

1. Provide a foundation for synthesizing processes, structures, and patterns of abiotic and biotic components of each wetland;
2. Integrate the concepts of ecological thresholds and disturbance dynamics into wetland management;
3. Identify mechanisms of a successful management approach;
4. Describe management strategies that have successfully been applied to wetlands in Hawai‘i; and
5. Provide examples of wetlands where practitioners have integrated multiple management strategies enabling native and other beneficial plants to outcompete invasive species.

Managers must develop an appreciation and curiosity for learning how abiotic and biotic components interact to determine dynamic wetland processes at multiple spatial and temporal scales and, in turn, influence waterbird use of wetlands.

Wetland management requires knowledge of ecosystem processes, plant and animal life histories, abiotic site conditions (past and present), and capabilities (Gray et al. 2013, Heitmeyer et al. 2013). Although the interest in wetland management in Hawai‘i often stems from recovery of endemic, endangered waterbirds, it’s the physical processes and abiotic conditions that drive plant and invertebrate response and hence, use of wetlands by endemic waterbirds. Understanding both biotic and abiotic components is a required upfront time commitment to increase effectiveness of management actions.

To achieve functional habitat conditions, managers must link formative processes, abiotic conditions, and resources required during different life-history stages of target species into their

thinking as a basis for scientifically informed decision making. Examples of poor wetland management and restoration designs that did not consider abiotic factors can be found across the U.S. and often resulted in increased long-term costs with reduced ecological benefits. Focusing management on just one life-history stage (e.g., nesting) of a species does not assure resources are available to meet the sequential needs of life-history stages necessary for maintaining sustainable populations of wetland-dependent wildlife. This is especially true for endemic waterbirds that rely on wetland habitats within Hawai‘i to support all life-history events.

Hawaii’s Unique Wetland Challenges

The Hawaiian Islands are the most remote island chain in the world, contributing to its high level of species endemism and lack of mammalian predators until settled by humans. The islands are formed by volcanic activity as the Pacific lithospheric plate drifts west-northwestward approximately 3.5 in/yr over a convective plume or “hotspot” in the mantle of the earth that has remained relatively fixed for the past 40 million years (Clague 1998). Plant and animal distribution patterns in time and space are related to geologic processes that have created about 107 separate shield volcanoes with diverse habitats in the Emperor Seamount Chain and younger Hawaiian Islands (Clague and Dalrymple 1987). The Hawaiian Archipelago currently includes 15 volcanoes across 8 main islands (Ni‘ihau, Kaua‘i, O‘ahu, Moloka‘i, Kaho‘olawe, Lāna‘i, Maui, and Hawai‘i), and numerous volcanoes, mostly submerged, older than 7 million years in the northwestern Hawaiian Islands. Wetlands historically occurred on all eight main islands and several of the northwestern Hawaiian Islands.

All of Hawai‘i’s extant, year-round resident waterfowl, rails, and shorebird species are endemic to the islands and are federally listed as endangered. They are considered conservation reliant because their threats need to be managed to ensure self-sustaining populations persist (Scott et al. 2010, Goble et al. 2012, Reed et al. 2012). The U.S. Fish and Wildlife Service (USFWS) identifies wetlands as biologically important (601 FW1) and essential to the downlisting of species of endangered waterbirds (USFWS 2011). Many of the wetlands in Hawai‘i, both large and small, require on-going management to maintain functional wetland habitats beneficial for endemic waterbirds.

Advances in wetland ecology are largely based on research and management of wetlands on continents, including Canada and the mainland U.S. in North America, Europe, and Australia. Although wetlands on islands, including those in Hawai‘i, have many unique characteristics, they also share similarities with wetland habitats around the world. For all wetlands, biotic and abiotic processes, particularly hydrologic disturbance dynamics, drive wetland function. Even though they are not well-studied within the islands, disturbance dynamics, flood pulses and drought, ecological thresholds, non-linear succession, metapopulation dynamics, and dispersal patterns are features of wetlands in Hawai‘i. The challenge lies in how to apply current knowledge to advance management of wetlands in Hawai‘i.

Cultural resources are a significant component of natural resource management in Hawai‘i, especially on floodplains and coastal plains where kalo lo‘i (taro fields) were constructed. Irrigated wetland agriculture pre-dates the written record going back about 3,000 years. Many projects in Hawai‘i aim to restore and manage both cultural and natural resources of wetlands.

Both provide a role in supporting endemic waterbirds; however, the resources they provide vary. Differences in species composition and vegetative structure contribute to differences in aquatic invertebrates (USFWS unpublished data). Koloa maoli use kalo lo‘i and managed herbaceous wetlands for different activities throughout their annual cycle (Malachowski and Dugger 2018). Both wetland types contribute to the recovery of endangered waterbirds and management of these systems can inform each other. For example, nutrient cycling in managed herbaceous wetlands can inform best management practices for fertilizing kalo lo‘i. Likewise, management actions that “re-set succession” in kalo lo‘i (e.g., wet tilling) can inform management of disturbance dynamics in seasonal herbaceous wetlands. Management of kalo lo‘i for waterbirds is outside the scope of this guide; however, other resources are available to enhance management of kalo lo‘i for endemic waterbirds (e.g., Uyehara 2004, NRCS 2009).



Kalo lo‘i with emergent wetland vegetation, Hanalei National Wildlife Refuge. Photo by Adonia Henry.

CHAPTER 2: GETTING STARTED

Disturbance Dynamics

Despite the significance of disturbance dynamics in wetland ecology, it has been adapted rather slowly by wetland practitioners. This is, in part, due to the historical lack of understanding about wetland functional dynamics, social and/or cultural misperceptions of natural systems as stable, and the desire to maximize a populations or reproductive success of a species every year (Middleton 1999). The same applies to habitat conditions – there is a desire to have consistent water every year. Managers have often attempted to maintain static water levels in wetlands, which has had a detrimental effect on wetlands world-wide (Keddy 2010). For example, wetlands with stabilized hydroperiods are dominated by one or a few species, have reduced decomposition rates, accumulated detritus, and/or form an anoxic zone (Keddy and Reznicek 1986, Magee 1993, van der Valk et al. 1994, Shay et al. 1999, Cronk and Fennessy 2001). Stabilized water levels have also contributed to long-term population declines in waterbird populations. Steen et al. (2006) suggest that North American species closely related to alau ula and alae keokoe are at high to moderate risk from stabilized water levels. Although mallard, which is the most closely related duck species to koloa maoli, was classified as low risk, four other species of dabbling ducks were classified as moderate. Stabilized water levels eliminate the dynamic patterns that allow a diversity of microhabitats and associated wetland-dependent birds to thrive (Steen et al 2006). These conditions lead to decreased long-term wetland productivity (Brinson et al. 1981, Wilcox and Meeker 1991, Wantzen et al. 2008).

Suggested Steps

Understanding key processes and disturbance dynamics that created and sustained natural wetlands is one of the most important components of developing wetland management strategies (Middleton 1999, Keddy 2010, Heitmeyer et al. 2013). Thus, the first step to developing a successful management program entails identifying abiotic components of the landscape setting for the wetland (Table 1). Abiotic components include geologic setting, soils, climate, hydrologic inputs, and geomorphic surfaces. These factors interact to determine the landforms that support wetland types across the islands. Anthropogenic modifications affect the structure, processes, and patterns of these abiotic components and should also be evaluated as part of this step.

Step 2 requires identifying the structures, processes, and patterns of the biotic components and associated changes through time. Traditional ecological knowledge, studies from paleoecology and archeology, and written historical records should be used to describe the historical biotic components. Life-history requirements of plants and animals should continually be updated as more information becomes available.

Mechanisms of physical and process-related change through time are determined based on scientific evidence and interpretation of the observer (e.g., Moss 2007). Combining reductionist and holistic approaches to wetland management allows creative and informed decision-making when knowledge about the complexity of the wetland system is incomplete. After the abiotic and biotic

*“There is no easy formula for success...beyond the need to develop a **plan**, frequently **monitor** plant and wildlife responses, and **keep detailed records** of natural conditions, management actions, and plant and wildlife responses.”
(Strader and Stinson 2005:3)*

components have been synthesized, you have the foundation to build a solid management approach (Step 3) and identify management strategies and actions (Step 4). Lastly, keeping detailed records of your management actions, evaluating habitat and wildlife responses, and sharing results from successes, unanticipated outcomes and failures are critical to advancing the effectiveness of wetland management and endangered waterbird recovery efforts. Wetland management encompasses a broad range of disciplines from biology to hydrology and soil science. Therefore, common terms used in the management of herbaceous wetlands are listed in Table 2.

Table 1. Steps for developing, implementing, and evaluating process-based wetland management.

Steps
<p>1. Identify abiotic components of the landscape setting.</p> <ul style="list-style-type: none"> a. Describe structure, processes, and patterns of abiotic components. b. Identify historical disturbance dynamics. c. Assess changes in physical structures. d. Assess changes in physical processes.
<p>2. Identify biotic components of the landscape setting.</p> <ul style="list-style-type: none"> a. Identify biotic drivers. b. Compile life-history requirements of plant and animal species. c. Assess changes in biota at multiple temporal and spatial scales.
<p>3. Define your management approach.</p> <ul style="list-style-type: none"> a. Engage people with different expertise and experiences. b. Identify available resources c. Develop habitat-based goals and objectives.
<p>4. Identify management strategies and actions.</p> <ul style="list-style-type: none"> a. Link abiotic factors to life-history requirements b. Restore or manage for disturbance dynamics c. Increase resiliency to adapt to future change
<p>5. Evaluate, adapt, learn, and share.</p> <ul style="list-style-type: none"> a. Identify an approach to gather scientific information and evaluate results of management actions. b. Keep detailed records of management actions. c. Assess plant, habitat, and wildlife responses to management actions. d. Adapt management strategy. e. Share results.

Table 2. Terminology commonly used in management of herbaceous wetlands.

Term	Definition
<i>Ecological</i>	
Aquatic invertebrates	For the purposes of this guide, this refers to macroinvertebrates (those big enough to see without a microscope) that spend at least part of their life in or are associated with water.
Beneficial plants	Native and naturalized plant species that are not invasive and provide forage (nutrients) and/or cover for resident, endemic, and migratory waterbirds. They also provide forage and substrate for aquatic invertebrates.
Decadent vegetation	Overgrowth of wetland vegetation that alters natural ecological processes.
Disturbance	Abiotic (e.g., flood scour) or biotic (e.g., herbivory) process that re-sets succession.
Organic matter	Carbon-based compounds from recently living organisms. In wetlands, organic matter often refers to dead or senesced portions of plants.
Seed bank	Natural storage of seeds, often dormant, in or on the soil.
Succession	Change in wetland vegetation over time driven by disturbances and the maturation of plant species
<i>Hydrological</i>	
Drawdown	Decreasing water depth and removal of surface water from a flooded wetland that exposes the substrate to air. This may occur naturally though evapotranspiration, flow through a natural swale or outlet, infiltration into the soil, and/or through active management of water through an outflow structure.
Flood-up, Reflood	Increasing water in a previously dry wetland. This may occur naturally by rainfall, groundwater discharge, overbank flooding, on-shore storm surge, and/or by active management of water through an inflow structure.
Groundwater discharge	Movement of groundwater from the subsurface to surface
Groundwater recharge	Movement of water from the surface to the subsurface
Hydrodynamics	Movement of ground and surface water to, through, and from a given wetland.
Hydroperiod	Temporal fluctuation in water on a wetland, including depth, duration, extent, and timing of water present.
Infiltration	The process by which water on the ground surface enters the soil.
Overbank flooding	Water that spreads into a river's floodplain when water inputs are higher than normal.
Sheetflow	Flow of water over land.
Storm surge	Change in water level generated by a storm with high winds over and above the predicted astronomical tide.
Storm tide	Combination of the storm surge and astronomical tide. Total water level rise during a storm, which is equal to the storm surge and astronomical tide
<i>Soil</i>	
Drying-rewetting cycle	Alternating presence of air and water in the soil pore space.
Mineral soil	Soil with <18% organic carbon and varying amounts of sand, silt, and clay. If a soil feels gritty or sticky, or resists compression, it is mineral soil.
Organic soil	Soil with >18% carbon. If a soil compresses easily (e.g., has almost no internal strength, or feels greasy when rubbed it may be an organic soil. Typically they are very black, porous, and light in weight.
Pore space	Voids in the soil that contain water and air.
Soil organic matter	Derived from carbon-based organic materials of plants, animals, and microorganisms.
Texture	The relative proportion of sand, silt and clay (soil particles < 2 mm) that make up the mineral fraction of soil.
Topsoil	The uppermost layer of soil where most of the biological soil processes occur.

CHAPTER 3: IDENTIFY THE ABIOTIC COMPONENTS

The value of abiotic conditions and the accessibility of long-term datasets and historical maps has increased substantially since wetland management at state and federal protected areas in Hawai'i began during the 1970s. Paleocological and archeological studies on the main Hawaiian Islands have provided evidence to characterize biological communities prior to human settlement that enables development of hypotheses about pre-historical conditions and how lowland ecosystems transformed through time. Synthesizing diverse historical records identifies the landscape setting that shaped ecosystem processes and increases our understanding of the dynamic nature of wetland landscapes (Swetnam et al. 1999). Understanding pre-historical and historical processes and ecosystem change through time better informs management actions resulting in a higher resiliency of wetland systems to adapt to future change.

Geologic Processes

Hawaii's volcanic origin and the porous nature of thin shield building lava flows combined with vertical dike lava formations along rift zones and calderas influences infiltration, which has profound effects on surface and subsurface water movements within the islands. Subsidence and other geologic processes, including slumping and landslides due to slope instability, chemical weathering, erosion, sedimentary deposition, and eustatic fluctuation of sea level, have shaped the current landforms on the Hawaiian Islands. The movement of water drives erosion and determines the distribution and depth of sediments that develop into soils from volcanic parent materials.

The rate of lava eruption and position of the volcano's summit relative to sea level determine the eruptive activity, composition, and morphology of each volcano (Clague 1998). The volcanoes on the older islands are more weathered with broad coastal plains and developed drainages that have relatively wide floodplains near the coast. The prominent mountains on Kaua'i, O'ahu, and Maui Nui are remnants of older shield volcanoes ranging in age from 5 million years on Kaua'i to about 1 million years on Maui. The oldest exposed lavas on the island of Hawai'i are 460,000 years old for Kohala and about 250,000 years old for Mauna Kea; Mauna Loa is nearing the end of its shield stage; whereas, Kilauea is in the explosive phase of shield building (Clague 1998). Younger post shield and rejuvenated-state lavas are present on all the islands. As shield volcanoes build, the Pacific plate warps under the weight of the multiple, massive lava flows causing the shield volcanoes to subside.

Volcanic basalt holds vast quantities of freshwater contributing to perennial stream flows. The broad coastal plains developed from alternating marine and alluvial deposits during fluctuating periods of eustatic sea level rise when either marine or terrestrial processes dominated. Decomposed or partly decomposed basalt beneath coastal plain sediments in some areas suggest that the basalt was deeply weathered before submergence and formed an effective cap rock (Stearns and Vaksvik 1935). These sedimentary deposits that form caprock aquifers confine freshwater basalt aquifers below them. Groundwater discharge from springs in the sedimentary deposits sustain wetlands on leeward coastal plains despite high evapotranspiration and low precipitation (see Hydrologic Drivers section).

Soils

Variable soil characteristics, including surface and subsurface soil texture, influence hydrodynamics – how water moves into, through, and out of wetlands. Soils on the main Hawaiian Islands are incredibly diverse given the islands relatively small land mass with soils described for 11 of the 12 soil orders (the highest soil taxonomic classification) and 232 soil groups (Gavenda et al. 1998, Lau and Mink 2006). Likewise, soil characteristics of wetlands in Hawai‘i are highly variable (Bantilan-Smith et al. 2009), which is expected given the variation of formative processes in Hawaii’s coastal lowlands. Forty wetland sites sampled by Bantilan-Smith et al. (2009) revealed 4 soil orders (plus lava) and 15 soil series. Soil formation is influenced by parent material (e.g., volcanic basalt, ash), local climate, slope and drainage conditions, surface and subsurface movement of water, nature of organic material added to or removed from the soil, and time the substrate exposed to weathering.

The earliest known soil survey for the main Hawaiian Islands was conducted during 1939 and published following World War II (Cline 1955). Because it was completed primarily for agricultural purposes, soils in some areas were described from comprehensive field work based on soil survey transects between 1/8 and 1/2 mile apart. Thus, in some areas such as the north shore of O‘ahu, historical soil survey interpretations were more detailed than later mapping efforts. This historical data can be used to inform native soil distribution prior to land use changes that modified soils and generate hypotheses about historical wetland communities (Henry and Fredrickson 2013). Soils were mapped again during the 1970s based on 1965 field work and interpretations of aerial photographs using updated soil taxonomy (Foote et al. 1972). Soil data continue to be updated by Natural Resources Conservation Service and area available on-line (<https://websoilsurvey.sc.egov.usda.gov>).

Climatic Drivers

Climatic conditions determine the amount, type, and pattern of seasonal, annual and long-term water inputs into wetlands. They also influence rates of drying from wind, temperature, humidity, and evapotranspiration. Hawaii’s subtropical climate has two seasons that are described by the ancient Hawaiians as *kauwela* (hot season) and *ho‘oilohou* (causing to sprout). During summer, trade winds occur over 80% of the days. The warm, dry season is generally from May through September and the cooler, wet season is from October through April. At any given elevation near sea level, temperatures have relatively low variability with a 10–15°F diurnal range and annual variation of only 9°F (Giambelluca and Schroeder 1998). Given the mild climate, Hawai‘i has a year-long growing season. Although this makes control of invasive plants challenging, it also provides year-round opportunities for managing native and other beneficial plants.

In contrast to temperature, precipitation is highly variable. Due to the orographic effects of mountain ranges and wind patterns in Hawai‘i, rainfall patterns vary greatly over relatively short distances and short temporal scales. For example, median annual rainfall increases more than 100 inches over 4 miles from the town of Kahuku (40 inches) to the headwaters of the watershed in the Ko‘olau Mountains (150 inches) on O‘ahu (Liao 2003). Extremes in precipitation are important drivers in wetland systems. These extremes cause flood pulses and drought, which are important components of long-term water-level fluctuations and drivers of wetland function and

structure (Middleton 1999, Wantzen et al. 2008). Annual precipitation can range from about 50% to more than 200% of the long-term average. Daily extremes in rainfall can range from about 4 inches (occurs every 2 years) to more than 12 inches (every 100 years) on the Kahuku coastal plain (Liao 2003).

Interannual and interdecadal variation in precipitation results from the El Niño-Southern Oscillation (ENSO) cycle and the Pacific decadal oscillation (PDO). During El Niño events, rainfall tends to be below average, where drought can last for two seasons during winter and spring (Chu and Chen 2005, Chu 1995). In Hawai‘i, El Niño events coincided with the 10 driest years from 1890-1980 (Schroeder 1993). Low winter rainfall also occurs when the PDO is positive with approximate 30-year cycles between wet (1946-1977) and dry periods (1974-2001) (Chu and Chen 2005). Rainfall patterns also reflect the interaction of ENSO and PDO cycles. The driest winters occur during El Niño events and a positive PDO phase while the wettest winters occur during La Niña and a negative PDO phase (Chu and Chen 2005).

Wetlands on the windward side of the Hawaiian Islands typically receive more precipitation compared to those on the leeward side. Cold fronts, which are responsible for Hawaii’s trade winds, pick up a large amount of moisture as they move across the warm Pacific Ocean. As these air masses move up the mountain slopes, temperatures cool and the air can no longer hold as much moisture and orographic rainfall occurs. The trade wind-associated temperature inversion prevents air flow from going over tall mountains such as Haleakā on Maui. As a result, air is forced to move around Haleakalā through the isthmus where the Keālia plain experiences very high winds. In contrast, air masses go over the lower elevation Mount Wai‘ale‘ale resulting in lower wind speeds on the Mānā coastal plain on the leeward side of Kaua‘i. Kona winds can bring heavy rainfall to leeward sides of the islands as low pressure areas develop northwest of the main islands, move eastward, and then bring warm air masses from the south. The number of Kona storms is highly variable each year; whereas, cold fronts that produce trade winds and orographic rainfall are much more common.

Hydrologic Drivers

Of the complex processes in wetlands, the pattern of water-level fluctuation is the dominant physical process that influences primary productivity, decomposition, nutrient cycling, chemistry (e.g., salinity), species richness, and the distribution of plants and animals (Mitsch and Gosselink 2000, Jackson 2006, Mendelsohn et al. 2014). This pattern of water-level fluctuation, which is commonly referred to as hydroperiod, includes the depth, duration, extent, and frequency of flooding. The variability of hydrologic conditions within a wetland and across wetland types creates disturbances (e.g., flooding, drought) that provide opportunities for regeneration, non-linear succession, and maintenance of biota (Keough et al. 1999, Middleton 1999). For example, flood tolerance is the primary constraint on diverse wetland plant communities because plants must be able to adapt to low oxygen levels in the soil (Keddy 2010). In contrast, drought is a primary driver of competition among wetland plants (Merlin et al. 2015).

Hydrologic conditions, which are driven by precipitation, surface water flows, and groundwater, interact soils to create diverse and dynamic wetlands across multiple landforms and geomorphic surfaces. When precipitation falls on porous volcanic substrates, water infiltrates and moves

through subsurface strata. On the island of O‘ahu, it is estimated that 16% of precipitation returns to the ocean as surface runoff, 44% evaporates (or is transpired), and 40% infiltrates to recharge the basal aquifer at a rate of 1,229 ft³/s (792 Mgal/d; Nichols et al. 1996, Zeigler 2002).

Surface Water

Surface water, including overland flow, streamflow and ocean water, is responsible for most of the erosion on Hawaii’s volcanic basalt. Drainage basins that have eroded down to intersect dike-impounded groundwater and/or receive groundwater from high or low elevation springs generally have perennial flows to the ocean. Streambeds above the water table can lose water creating intermittent or ephemeral non-perennial flow conditions. Streamflow in streams is highly variable due to the spatial and temporal patterns of rainfall across the main Hawaiian Islands. As erosional surfaces progress, relatively broad floodplains form at the low elevation depositional zone of perennial streams. Although perennial streams are distributed across most of the island of Kaua‘i, they are concentrated on windward sides of O‘ahu, Maui, Moloka‘i, and Hawai‘i islands.

Streamflow through coastal floodplains results in diverse substrates characteristic of fluvial systems, which are underlain by fluvial and marine deposits from rising and falling sea levels. For example, fluvial sands, silts, and muds of the Hanalei River bury marine sands in the backshore and across the coastal plain (Calhoun and Fletcher 1996). Rates of fluvial sediment deposition across the floodplain vary, generally decreasing from with distance from the river bank (Calhoun and Fletcher 1999). Meandering streamflow and associated sediment transport across even small floodplains create crevasse splays, point-bars, back swamps, and abandoned channels. Varying particle size, soil texture, thickness of deposits, and origin of subsurface deposits influence water holding capacity of floodplain soils and the types of wetlands they support.

Where rivers empty into the ocean, sand berms or “sand plugs” may close the river channel completely forming a bay-mouth bar. River mouths with high wave exposure and small inlet surface areas are prone to sand plugs. In Hawai‘i, this typically occurs on leeward shorelines (e.g., Nishimura and Lau 1978), such as on the Keālia coastal plain. If a sand plug is present during periods of high streamflow, adjacent low-lying coastal areas will likely flood when water flows exceed the rate at which it flows through the sand plug. Under certain high flows, the channel will open to the ocean. This is further evidence of wetland potential on leeward sides of islands where natural flooding and drawdown conditions occurred because of streamflow and the presence/absence of sand plugs.

Groundwater

Freshwater basal aquifers are the most abundant groundwater resource in the main Hawaiian Islands (Mink and Bauer 1998). Due to the density difference between sea water and freshwater, basal groundwater extends 40 feet below sea level for every foot of freshwater above sea level. Sedimentary deposits (alluvium and marine sediments) on the coastal plains of older islands form caprock aquifers that confine basal groundwater. Unconfined groundwater in these sedimentary deposits tends to be slightly brackish. Fresh, basal groundwater discharges through springs in overlying sedimentary caprock or as submarine discharge into the ocean. Caprock and coral formations on coastal plains substantially restricts discharge in western Kaua‘i, southern and northern O‘ahu, and the western half of Maui where basal heads exceed 10 feet (Mink and Bauer 1998). This groundwater discharge historically supported vast coastal wetlands on the otherwise dry, leeward sides of these islands (e.g., Figure 1). In contrast, most basal groundwater on the Kona coast of the island of Hawai‘i discharges as spatially and temporally variable submarine groundwater discharge (Peterson et al. 2009).

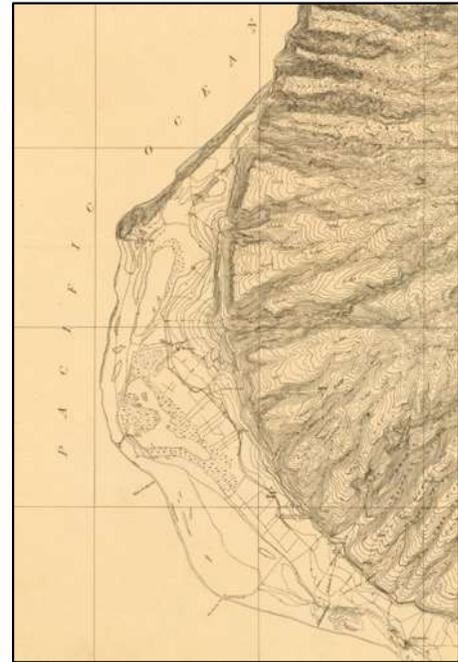


Figure 1. Wetlands on the Mānā coastal plain on the leeward side of Kaua‘i circa 1910 (USGS 1910).

In addition to basal aquifers, groundwater occurs in volcanic dike complexes, lowland sedimentary deposits/caprock aquifers, perched water tables, and stream alluvium (Lau and Mink 2006). Volcanic dike complexes, which are comprised of dense, poorly permeable, and nearly vertical sheets of basalt in calderas and volcanic rift zones, impound groundwater at high elevations. This dike-impounded groundwater discharges through fractures at high-elevation springs, and/or stream valleys that have eroded through a volcanic dike. Recent geophysical surveys suggest that volcanic dikes, perched water tables and confining strata of variable permeability occur over extensive areas outside of calderas and rift zones, where they contribute to increased groundwater storage not been accounted for in conventional groundwater models (Izuka and Gingerich 2003, Thomas et al. 2017). This likely has yet undescribed effects on some lowland wetlands.

Anthropogenic Modifications of Abiotic Components

Anthropogenic changes to wetlands and other lowland habitats in Hawai‘i date back to the arrival of Polynesians, expanded and intensified throughout European contact, and culminated with the draining and filling of many wetlands during the 20th century. The transformation of Hawaii’s native lowland habitats date back to between 800 and 1200 AD (some estimates as early as 500 AD) when Polynesians began settling the Hawaiian Islands (Kirch 2011). Land management practices of Polynesians integrated seasonal patterns of abiotic conditions (e.g., rain, wind) and spiritual connections of the land and its inhabitants (e.g., people, animals) in agricultural and natural settings (Gon 2003). A growing human population was maintained by large, intensive, and evolving agricultural systems for the next 1,000 years, resulting in various ecological changes to lowland wetlands throughout the islands (Kirch 1985, Vitousek and Beamer 2013). Geologic changes throughout the Holocene also influenced the abiotic conditions and human settlement patterns. For example, a rapid cooling temperature and sea level decline around 1300 AD influenced Pacific settlement patterns and shifted some coastal communities inland, changed subsistence patterns, and ended long-distance cross ocean interaction in the Pacific Basin (Nunn 2007).

Kalo was one of the most important food sources brought to Hawai‘i by Polynesian settlers. Traditional ecological knowledge suggests that kalo grown in wet lowland valleys was self-sustaining and it is described as a semi-wild ecosystem (Gon 2003). Fish and vegetation were incorporated into wetland soils as a natural fertilizer to enhance kalo growth (Handy and Handy 1991). Archeological evidence also attributed soil erosion from intensive agriculture in wet, windward valleys of the main islands as the cause of sedimentation in valley floors and coastal lagoons prior to European contact. Sedimentation rates at Ukoa Marsh increased during the Polynesian period possibly from clearing lands for agriculture and/or natural geologic changes during the Holocene (Athens and Ward 1993).

As the Native Hawaiian population grew, kalo cultivation expanded across lowland areas and to dry, leeward habitats. Estimates of kalo lo‘i during peak production range from 25,000 to nearly 300,000 acres (see Muller et al. 2010). Expansion of kalo agriculture likely increased the amount and/or availability of ‘wet’ habitats, as well as the constancy or predictability of water in these habitats. But, it also diverted water from streams, which likely modified downstream hydrology of riverine, palustrine, and estuarine wetlands. Dryland kalo cultivation was more intensive requiring burning of vegetation to clear and fertilize land, terraces to retain soil, and intricate irrigation systems to deliver water from streams and overland flow (Handy and Handy 1991). Burned vegetation (ash) and rotten kukui trees were used as fertilizer land for dryland kalo. Because slash and burn cultivation methods in drier areas removed native vegetation it’s hypothesized that it decreased infiltration of water, increased surface runoff, and accelerated erosion of forest soils (Yen et al. 1972, Beggerly 1990).

Following the arrival of Europeans in 1778, alteration of native habitats drastically increased with many introductions of non-native species (see next section) and more land-altering activities. When combined with a for-profit, commodity approach to agriculture and industrial advancements, the cumulative effects of European modifications to abiotic components were much greater than Polynesian modifications. Current conservation efforts continue to address

loss of abiotic processes and structures, as well as the loss of traditional ecological knowledge and cultural resources.

In contrast to re-routing water within a watershed as often done during Polynesian times, European settlers diverted water from streams and transported it to agricultural areas far from its original watershed (Culliney 2006). Vast groundwater resources were exploited after a well drilled on the Ewa coastal plain during 1878 discovered fresh artesian water. The head of basal groundwater on the Ewa plain historically was 42 feet, which is now reduced by about one-half due to extraction of groundwater (Mink and Bauer 1998).

Natural wetlands, *kalo lo‘i*, and rice fields were filled, ditched and/or drained throughout the 1900s to grow sugarcane and other agricultural crops. Crops were irrigated by stream flow diverted into reservoirs. From 1922 to 1931, 2,000 to 3,235 acres of wetlands were drained on the Mānā Plain (University of Hawai‘i 2004). This was likely the largest lowland wetland complex on the main Hawaiian Islands. Pumping stations were eventually installed on the Mānā Plain to prevent flooding and maintain artificially low groundwater levels. Military facilities expanded during World War II further modifying Hawaii’s coastal plains. During the 1950s, wetland loss on O‘ahu, including an attempt to drain 210 acres of Kaelepulu Pond, continued to occur at an accelerated rate (Medeiros 1958). As tourism and the resident population increased, wetlands were filled for hotels, condominiums, and housing developments. Roads further changed hydrologic conditions of wetlands by blocking overland sheet flow, modifying outlets to the ocean by channeling streams through bridges and/or culverts, and reducing or blocking tidal flows from estuarine wetlands.

CHAPTER 4: IDENTIFY THE BIOTIC COMPONENTS

Biotic Drivers and Disturbance Dynamics

Biological processes in wetlands are complex, ranging from biochemical processing of elements and nutrient flux to herbivory, competition, and animals modifying the physical environment. These biotic drivers influence the abundance and distribution of plants and, in turn, other wetland-dependent wildlife. Biotic drivers range from birds, mammals, and fish to invertebrates and plants. The influence of biotic drivers varies temporally depending on natural population cycles and anthropogenic changes to biological communities. The full impact of biological drivers in Hawaii's lowland wetlands will likely never be known due to the extinction of native, endemic species, such as large flightless geese and flightless rails, prior to European contact. These and other extinct species likely performed critical ecological functions such as pollination, seed dispersal and scarification, and herbivory, (e.g., Olson 1990, James 1995, Young et al. 1996). Slikas (2003) describes the loss of biodiversity and ignorance about the ecology of oceanic islands as 'sobering' because hypotheses about ecology based on only extant and historically recorded species are likely wrong.

"The assumption that the historically known biota of a prehistorically inhabited island contains an intact complement of species in a natural state of equilibrium is invalid for the Hawaiian Islands"
(Olson and James 1982a:635)

Wildlife has an important role in wetland nutrient cycling by making nutrients available to primary producers via excretory processes and translocating nutrients between ecosystems. They also indirectly affect nutrient cycling by altering prey abundance and/or species composition and by modifying the physical environment (Vanni 2002). Litter decomposition by invertebrates in a Hawaiian rainforest released more nitrogen than estimates of nitrogen input from rainfall, dry deposition, volcanic sources, atmospheric dust, and nitrogen fixation (Meyer et al. 2011); it likely has similar importance in Hawaiian wetlands. Bioturbation, the physical disturbance of sediments by invertebrates or other organisms, can significantly affect nutrient exchange between sediments and the overlying water. Bioturbation by oligochaetes stimulates organic matter processing and bacterial growth (e.g., Mermillod-Blondin 2020). Burrowing organisms are one of the primary agents of soil aeration in wetlands and oxygenated wetland soils increase aerobic respiration of aquatic plants, which contributes to the development of redoximorphic features (Craft 2001).

Herbivory is an important biotic driver that shapes the structure, composition, and distribution of habitats available for use by waterbirds and other wetland-dependent wildlife. Herbivory by invertebrates and waterbirds, can remove up to 100% of plant biomass, but experimental evidence suggests 30-60% removal is most common (Lodge 1991). Herbivory by geese creates short cover habitats, which when combined with seasonally variable hydrology, results in a wide suite of invertebrates available for shorebirds and other waterbirds (e.g., Gustafson 2006). At least five species of extinct large flightless waterfowl are hypothesized to have performed a significant role as herbivores in a wide range of habitats in Hawai'i (Olson and James 1991, James and Burney 1997). The large-bodied extinct moa-nalos (vanished fowl) were comparable in size to large swans, which can consume 10 to 20 pounds (wet weight) of food per day (Mitchell and Eichholz 2019).

Ecosystem engineers are commonly viewed as obvious biological drivers of wetlands in North America and other continents (e.g., beavers, muskrats, spawning salmon, etc). However, ecosystem engineers occur in virtually all ecosystems and can be any organism that modifies the physical environment and associated habitats, directly or indirectly influencing the availability of resources to other organisms (Jones et al. 1997). The effects of ecosystem engineers are a function of their behavior, size, and population density that are modulated by the abiotic conditions (Moore 2006).

The historical and current role of native ecosystem engineers in Hawaii's lowland wetlands, historically and currently, is unknown. However, macrophytes, burrowing invertebrates, and filter feeders are examples organisms that can cause structural change in the physical environment (Gutiérrez et al. 2011). All of these occur in Hawaii's lowland coastal wetlands and likely have important ecological roles. Macrophytes create pores in sediment via root growth; submerged aquatic vegetation alters water depth, flow rates, and sediment deposition; and invertebrates dislodge fine sediments or may anchor sediments decreasing the probability of scour in low flood events (Zanetell and Peckarsky 1996, Champion and Tanner 2000, Schulz et al. 2003, Cardinale et al. 2004, Moore 2006, Gutiérrez et al. 2011). Some plants have extensive root systems that anchor sediments and reduce erosion during flood events.

Anthropogenic Modifications to Biotic Components

The Polynesian environmental ethic expected nature to provide to for humans, but required a reciprocal relationship where humans were responsible for stewardship and conserving resources for the future (e.g., Kamakau 1964, Pukui et al. 1972, Pogue 1978, and Pukui 1983 as cited in Gon 2003). This important aspect of Polynesian culture preserved many natural resources even during periods of relatively high human populations. Unfortunately, this ethic was not practiced by all Polynesian settlers as the custom of bird catchers was to collect feathers and then eat the birds, rather than let the birds go to provide for future generations. Large birds were likely also hunted as a protein source by Polynesians (Moniz 1997, van Riper and Scott 2001). Polynesian rats (*Rattus exulans*) caused substantial changes to lowland habitats and reduced reproductive success of native birds (Kirsch 1985, van Riper and Scott 2001, Athens et al. 2002). Dogs (*Canis familiaris*) were another mammalian predator introduced by Polynesians. At least 45 species of endemic birds, known from fossil evidence, went extinct prior to the historical period (Olson and James 1982ab, 1984, 1991, James 1991). These include 10 or 11 species of geese, 3 species of flightless ibis, 8 species of flightless rails, and several species of avian predators. Given the patterns of avifaunal extinction, Polynesian settlement, land-use modifications for agriculture these extinctions were human-caused (Olson and James 1984).

On some coastal plains, the decline of lowland dry forest species due to Polynesian rats occurred prior to human occupation of that site (Athens et al. 2002). Loulu palms (*Pritchardia* sp.) and other trees in lowland forests declined following arrival of Polynesians (Allen 1997, Athens 1997). Fossil evidence also suggests that extinct and currently extant species of forest birds occurred in lowland forests (Olson and James 1984). Fossil remains of geese (*Branta* sp.) from lowland habitats on Moloka'i, Kaua'i, and O'ahu suggest this genus was not restricted to the

high altitudes inhabited by nene (*Branta sandvicensis*) during the historical period prior to re-introduction efforts (Olson and James 1982b).

When Europeans arrived in the Hawaiian Islands, accounts from the 1770s refer to abundant resources on the windward coasts. For example, the Kahuku coastal plain on O‘ahu was described as “exceedingly fine and fertile...with many large villages and extensive plantations” (Captain Charles Clerke, H.M.S. Resolution, as quoted in Beaglehole 1967:I:572). By 1883, many of the kalo loi in the Kahuku area were abandoned due to the rapid population decline (Hall 1839 as cited in Handy and Handy 1972), likely resulting from introduced contagious diseases.

Europeans drastically changed the biota of the Hawaiian Islands by more introducing more mammalian predators, livestock that invaded remaining in-tact forests, and foreign plants. Three plant species brought to Hawai‘i by Polynesians became invasive: kukui (*Aleurites moluccanus*), hau (*Talipariti tiliaceum*), and ‘awapuhi (shampoo ginger, *Zingiber zerumbet*; Culliney 2006). Seventy-six species of invasive plants targeted by the Hawai‘i Invasive Species Council (HISC 2022) were introduced by Europeans. In addition to non-native land mammals, 41 species of birds have been introduced to Hawai‘i (Pratt 1994).

At least 23 additional species of endemic birds have been extirpated since 1893 (Pratt 1994). Thirty three of the 44 remaining endemic species are federally listed as endangered or threatened under the Endangered Species Act. Declines in remaining populations of endemic bird species, including waterbirds, have been substantial. Relatively large populations of endemic Hawaiian waterbirds that maintained flight capabilities and predator avoidance strategies persisted despite introductions of non-native land mammals during Polynesian and early European settlement. Reductions in endemic waterbird populations appeared to be more drastic following draining and filling of large coastal wetland complexes from the 1920s to the 1960s. Continental waterfowl and shorebird migrants have also declined since the 1950s. The number of waterfowl wintering on O‘ahu, Maui, Moloka‘i, and Hawai‘i islands during the 1950s ranged from about 1,800 to over 10,000 based on January count data (Medeiros 1958). The maximum number of wintering waterfowl counted during January surveys from 1986 to 2019 was 1,326 individuals (DOFAW, unpublished data).

By the 1970s, remnant wetlands in the main Hawaiian Islands were dominated by invasive species (Shallenberger 1977). Modified hydroperiods, increased nutrients from agricultural lands, and lack of natural biocontrol contributed to the expansion of invasive plants in Hawaii’s wetlands. Invasive species such as California grass (*Urochloa mutica*), are still ubiquitous across multiple hydrologic conditions and wetland types in Hawai‘i, including isolated, floodplain, and estuarine, as well as natural and restored wetlands (Bantilan-Smith et al. 2009). Invasive plants also alter water flow, sediment transport, and other ecosystem processes (Catford 2017), creating feedback loops where altered hydrology further increases their competitive advantage (Galatowitsch et al. 1999, Chambers et al. 2003, Gaertner et al. 2014). As a result, most wetlands have crossed an ecological threshold where intensive management is now required to restore abiotic and biotic components.

Extant Wetland-Dependent Waterbirds

It can be a daunting task for a wetland manager to provide the diverse and constantly changing array of foods and cover necessary to meet all annual life-cycle needs for multiple endemic waterbird species on relatively small management areas. Several species may use the same wetland basin keying in on different wetland conditions within the basin ranging from open to closed vegetation, mudflats to shallow water, and short to long hydroperiods. Seasonal movements enable waterbirds to take advantage of newly flooded habitats and changing abiotic conditions. Linking these species-specific needs to abiotic conditions that drive wetland vegetation and invertebrate responses and overall function provide a foundation for successful management strategies that address the aforementioned challenges.

Waterbirds have evolved to thrive in constantly changing environments that characterize wetlands worldwide. This adaptability is likely the main reason flighted waterbird species have persisted throughout Polynesian and European settlement of the Hawaiian Islands, albeit at low population levels. This adaptation also makes conservation and management of almost any wetland habitat in Hawai‘i, regardless of size or location, beneficial for at least one endemic waterbird species for one life-history event.

Koloa Maoli (Hawaiian duck)

Life History

Koloa maoli, often referred to as koloa, breed year-round with nesting (egg-laying and incubation) peaks from January through April, with a 2nd annual peak during September and October (Swedburg 1967, Malachowski et al. 2018, 2019). Based on a 28-day incubation period and 65 days to fledge, brood-rearing then peaks February through July and October through December (Table 3). Nests occur in a variety of habitats on dry ground, including forests, seasonal wetlands, grasslands, taro loi, reservoir shorelines, bogs, and along streams, typically within 100 meters of water (Malachowski et al. 2018). Nests, including those in taro loi, are typically made from grasses and sedges and are well concealed in dense vegetation (Engilis et al. 2002, Malachowski et al. 2018).



*Koloa at edge of managed seasonal wetland.
Photo by A. Henry.*

Waterfowl breeding life history events are nutritionally demanding. High protein is required for hens to successfully lay eggs and for ducklings to molt from downy to juvenal plumage. Female koloa also require high energy to successfully lay eggs, likely similar to that reported for other dabbling ducks (168–212% basal metabolic rate; Alisauskas and Ankney 1992), and incubate their clutch for 28 days. Female mallards increase consumption of invertebrates up to 72% of their diet during egg-laying (Swanson et al. 1985); similar trends likely occur in female koloa. High availability of invertebrates is essential for duckling growth of all dabbling ducks (Sedinger 1992). For example, mallard and other dabbling duck ducklings consume more than 90%

*“Duckling growth is directly related to the availability of invertebrates.”
(Sedinger 1992)*

invertebrates during the first 2 weeks after hatch and many species retain about 50% invertebrates in their diet after 3 weeks, which is necessary to molt and grow rapidly (Chura 1961, Sugden 1973, Street 1978). No detailed food habit studies are available for koloa, but over half of the foods documented by Engilis et al. (2002) are animals, mostly invertebrates.

Invertebrate Taxa in Koloa Diets (Engilis et al. 2002)

Oligochaeta (earthworms)
Physidae (bladder/pouch snails)
Planorbidae (orb/ramshorn snails)
Hydrobiidae (mud snails)
Thiaridae (thiarid/trumpet snails)
Decapoda (crayfish)
Tendipidae (midges, blood worms)
Syphidae (flowerfly larvae)
Coenagrionidae (damsel fly larvae)
Large insects

Molt is the most understudied life history event of adult waterfowl, especially island species such as koloa. Although the seasonality of molt observed in North America dabbling ducks differs from island waterfowl species (Weller 1980), molt is a nutritional demanding life history event that requires abundant energy and protein resources. Without the constraints of long-distance migration and photoperiod cues at high latitudes, molt in koloa may be protracted compared to North American dabbling ducks, but energetics and nutrient requirements are likely similar. Adult dabbling ducks go through large compensatory changes in breast and leg muscles during molt (Hohman et al. 1992), but wing

molt may be delayed, or feathers may be shorter if protein resources are limited (e.g., Pehrsson 1987, Richardson and Kaminski 1992) suggesting that waterfowl use a mixed strategy of protein reserves and acquisition for feather synthesis.

Nutrient acquisition of adult dabbling ducks during molt is related to a complex interaction of factors, including environmental conditions, availability of food resources, timing of molt, body condition, and adaptive trade-offs (Hohman et al. 1992, Combs and Fredrickson 1996, Fox et al. 2013). Chronology of molt varies by sex and age; molt intensity tends to be higher during wet than dry periods (e.g., Miller 1986, Anderson et al. 2000); these observations are likely similar for koloa. Some studies show that dabbling ducks consume invertebrates in larger proportion than are available during molt; other studies show high energy plant foods are consumed in larger amounts than animal prey suggesting that both are necessary to maintain good body condition and successfully molt.

Plant Taxa in Koloa Diets
(Engilis et al. 2002)
Echinochloa crus-galli (barnyard grass seeds)
Paspalum urville (vasey grass seeds)
Filamentous green algae
Agricultural grains (rice, corn, wheat)

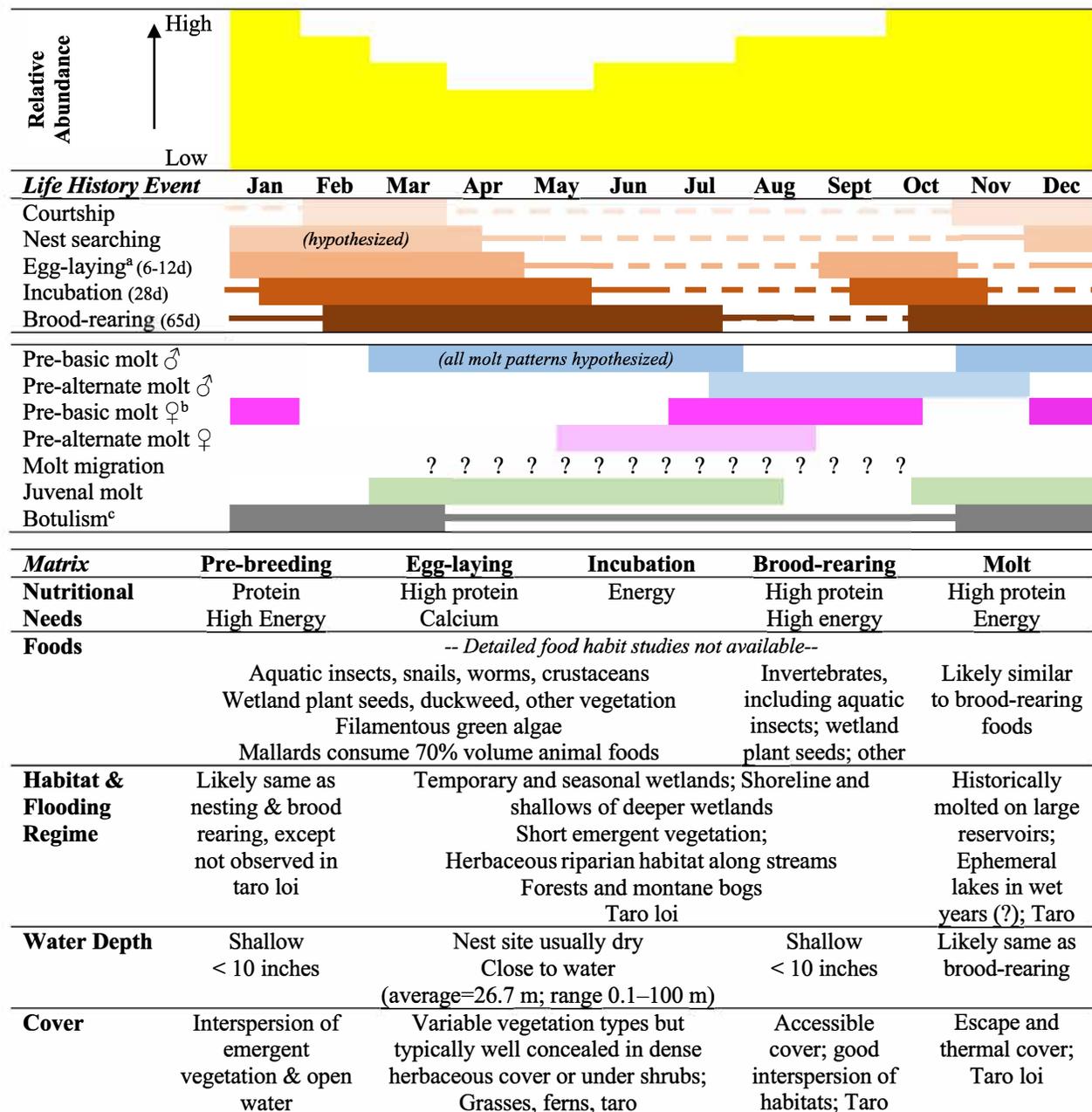
Evolving with endemic avian predators that were extant at the time of Polynesian settlement (Olson and James 1982b), koloa likely used wetlands with emergent vegetation cover during molt. Emergent wetlands also likely provided invertebrates, seeds, and other plant foods for koloa to maintain good body condition during molt. With the extinction of avian predators, introduction of mammalian predators, and anthropogenic changes to water resources, koloa adapted to use reservoirs during molt, likely providing increased protection from mammalian predators. Reservoir use by molting koloa has declined, likely due to increased human disturbance (Uyehara 2007).

Distribution and Population Trends

Prior to 1900, koloa were described as widespread and common on all the main Hawaiian Islands except Lāna‘i and Kaho‘olawe, occurring in habitats ranging from freshwater wetlands on the “hottest” coasts of the islands to streams up to 7,000 ft (Banko 1987). By the early 20th century, koloa populations had apparently declined quickly on all islands except Kaua‘i. Black (1901) and Henshaw (1903) stated koloa were becoming scarcer. About a decade later, Bryon (1915) described them as very rare on all islands but Kaua‘i. This decline coincided with the introduction (1883) and subsequent expansion of mongoose, extraction of groundwater from the coastal plains, and development of lands for sugarcane production. Alteration and drainage of coastal wetlands continued during the early 20th century when the Mānā Plain wetlands were drained beginning in 1923 resulting in a substantial decline of koloa from an estimated 400 to 5 birds per square mile in the remaining wetlands and ditches by the late 1940s (Schwartz and Schwartz 1953).

Given their secretive nature and use of many inaccessible habitats (e.g., high elevation riparian wetlands), koloa population status is and has been largely unknown. Winter counts during 2012–2016 on Kaua‘i ranged from 838 to 1,019 koloa with a 5-year modeled average population estimate of 947 birds (Paxton et al. *in press*). Because not all habitats are surveyed, these counts and population estimate likely represent minimum numbers. However, the recent population estimate is well below historical estimates of 400 birds per square mile in coastal wetlands on Kaua‘i (Schwartz and Schwartz 1953).

Table 3. Seasonal chronology of occurrence in lowland wetlands and life history requirements for koloa maoli (Hawaiian duck, *Anas wyvilliana*). Relative abundance based on monthly survey data at Hanalei National Wildlife from 2010 to 2016 (USFWS unpublished data). Life history information compiled from Munro (1944), Richardson and Bowles (1964), Swedberg (1967), Engilis et al. (2002), Uyehara (2007), Malachowski and Dugger (2018), Malachowski et al. (2018, 2019). Molt has not been studied in koloa; thus, it was hypothesized based on observations of flightless birds by USFWS staff and molt patterns for closely related North American mallard (*Anas platyrhynchos*).



^a Includes observations of nests (Swedberg 1967, Malachowski et al. 2018) and nest initiation dates back calculated based on age of ducklings (Malachowski et al. 2019).

^b Pre-basic molt of female mallards is disrupted with body molt occurring outside the breeding season and the wing molt occurring after brood rearing.

^c Based on number of dead carcasses and sick birds observed (USFWS unpublished data). Number of birds weighted by search effort does not vary by month (Reynolds et al 2021).

‘Alae ‘Ula (Hawaiian common gallinule)

Life History

‘Alae ‘ula is one of seven recognized subspecies of the common gallinule (*Gallinula galeata*), which was recently split from the Eurasian moorhen (*Gallinula chloropus*). ‘Alae ‘ula have shorter wings, larger facial shields, longer tarsi, and slightly greater body mass than their North American conspecifics (*G. g. cachinnans*; van Rees et al. 2020). These trends are characteristic of island waterbird species where reduced predation pressure and lack of long-distance seasonal migration selects for shorter wings and longer legs to traverse wetland and upland vegetation. van Rees et al. (2020) also proposed that increased inter- and intra-specific competition for limited wetland resources and subsequently increased agnostic behaviors are selection pressures for the larger body size and longer legs observed in ‘alae ‘ula.



‘Alae ‘ula. Photo by Gary Kramer, USFWS.

In Hawai‘i, ‘alae ‘ula breed year-round with peak nesting occurring from March or April through August (Shallenberger 1977, Byrd and Zeillemaker 1981). A second peak has also been observed during the fall at some locations in some years. Availability of nesting cover and protein for egg-production may determine when nesting occurs. ‘Alae ‘ula are cooperative breeders where older young will stay on the natal territories and help feed younger broods. Multiple brood family units are common in Hawai‘i and among other subspecies. Females and one or more daughters of other subspecies have been documented to share a nest site.

Male and female ‘alae ‘ula aggressively defend territories and nest sites from conspecifics and other waterbirds. Aggressive and courtship displays by ‘alae ‘ula are similar to those described for the American coot (*Fulica americana*). The size of actively defended nest territories likely varies based on habitat condition (cover) and resource available but has been documented to be greater than 25 ft from the nest site in Hawai‘i.

Nest building begins shortly before egg-laying. ‘Alae ‘ula build nests over water in a wide variety of relatively dense, marginal emergent vegetation (Berger 1972). Nests have also been observed in short emergent vegetation or floating-leaved vegetation with little or no cover provided (ARH personal observation). Interspersion of emergent and submerged aquatic (open water) habitats with a high amount of edge habitat is considered favorable for breeding (Chang 1990). Nests have been reported in both native and introduced species of emergent vegetation (Shallenberger 1977). Vegetation used for nest construction is likely dependent on surrounding vegetation. Only 64% of nests in taro lo‘i contained taro leaves (Byrd and Zeillemaker 1981), suggesting that ‘alae ‘ula prefer other wetland vegetation for nest construction. Of those nests in taro lo‘i, taro leaf fragments made up about one half of the nest material. Other vegetation used in nest construction includes leaves of sedges, millet, climbing dayflower, and California grass (Byrd and Zeillemaker 1981). Water depths at nests at Hanalei National Wildlife Refuge averaged 2.5 inches, which is shallower than depths reported from other locations (11–80 inches; Byrd and Zeillemaker 1981).

‘Alae ‘ula lay 1 egg per day and have an average clutch size of 5.6 eggs (Relton 1972, Krauth 1972, Byrd and Zeillemaker 1981). The incubation period is 19–22 days with slightly asynchronous hatching, suggesting that incubation may begin before the last egg is laid. Young are fed by their parents (and older siblings); they start to feed independently at 21–25 days. Brood rearing continues for a total of 40–50 days and juveniles disperse from natal territory around 72 days (range 52 to 99 days).

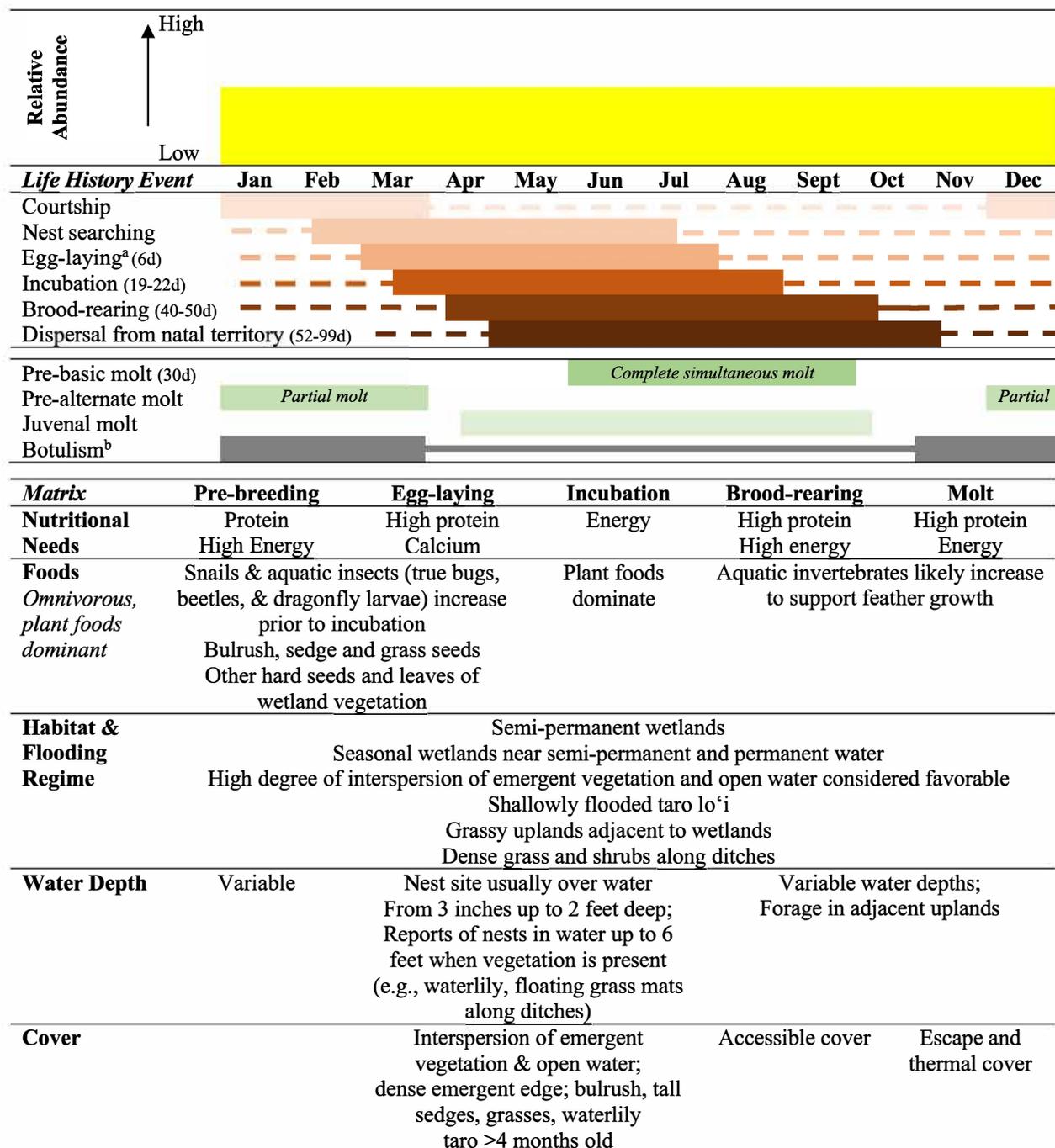
At higher taxonomic levels (e.g., genus, family), foods of ‘alae ‘ula are generally similar to that of the North American subspecies (Bannor and Kiviat 2002, DesRochers et al. 2009b). Although often considered herbivorous, ‘alae ‘ula are omnivorous, consuming predominantly plant foods with animal prey likely increasing prior to breeding. The proportions of plant and animal foods in ‘alae ‘ula diets are unknown but plant foods could range from 35 to >80% of their diet as has been reported for other subspecies, depending on life-history requirements and prey availability.

‘Alae ‘ula are gleaners (pick individual seeds and aquatic invertebrates from vegetation or water) and grazers (cut leaves and stems of live vegetation). Small, hard food items, such as seeds of grasses (Poaceae), sedges (Cyperaceae) and smartweeds (Polygonaceae), and pondweeds (Potamogetonaceae) and snails (Gastropoda) are considered important foods of ‘alae ‘ula. They also commonly graze on vegetative material and recent observations suggest leaves and stems may be more prevalent in their diet than seeds (DesRochers et al. 2009, LHF personal observation). Aquatic arthropods, including beetles (Coleoptera), true bugs (Hemiptera), ants and wasps (Hymenoptera), true flies (Diptera), spiders (Araneida), crustaceans (Crustacea), and dragonflies and damselflies (Odonata) are common in gallinule diets (see summaries in Bannor and Kiviat 2002, Gutscher-Chutz 2011).

Invertebrate Taxa in ‘Alae ‘Ula Diets (Hawai‘i-specific)
 Lymnaeidae (pond snail)
 Physidae (bladder/pouch snail)
 Planorbidae (orb/ramshorn snail)
 Thiaridae (thiarid/trumpet snail)
 Arachnida (spider)
 Orthoptera (grasshopper)

Plant Taxa in ‘Alae ‘Ula Diets (Hawai‘i-specific)
Cyperaceae (Sedges & Rushes)
Bolboschoenus maritimus (kaluha seeds & seed stalks)
Cyperus javanicus (ahuawa seed stalks)
C. polystachyos (manyspike flatsedge seed stalks & shoots)
Eleocharis geniculata (bent spikerush seed stalks)
Schoenoplectus spp. (akaakai seeds)
Poaceae (Grasses)
Cynodon dactylon (Bermuda grass seed stalks)
Echinochloa spp. (millet seed stalks)
Urochloa mutica (California grass leaves <4 inches)
Eleusine indica (Indian goosegrass)
Setaria pumila (yellow foxtail seed)
Other
Typha spp. (cattail male flowers)
Egeria densa (waterweed stems & leaves)
Batis maritima (pickleweed leaves; low nutrient value)
 Filamentous green algae

Table 4. Chronology of life history events for ‘alaie ‘ula (Hawaiian common gallinule, *Gallinula galeata sandvicensis*). Relative abundance based on relatively consistent count numbers between summer and winter surveys (Paxton et al. *in press*). Life history information compiled from Shallenberger (1977), Chang (1990), Bannor and Kiviak (2002), DesRochers et al. (2009ab). Development of young birds, body mass, and breeding ecology are similar to the North American subspecies (*G. g. cachinnans*; Bannor & Kiviak 2002, DesRochers et al. 2010).



^a Lay 1 egg/day; average clutch size 5.6 eggs.

^b Based on number of dead carcasses and sick birds observed (USFWS unpublished data). Number of birds weighted by search effort does not vary by month (Reynolds et al 2021).

'Alae Ke'oke'o (Hawaiian coot)

Life History

'Alae ke'oke'o (*Fulica alai*), one of the least studied endemic species in the Hawaiian Islands, is closely related to the American coot. Most morphological measurements between the species overlap, with the exception of longer bill lengths of 'alae ke'oke'o. Similar to 'alae 'ula, 'alae ke'oke'o breed year round, with nesting peaking May–July (Morin 1998). Byrd et al. (1985) and Engilis and Pratt (1993) suggest nesting may be opportunistic, dependent on rainfall. Availability of protein resources likely also influences timing of breeding. Aggressive and courtship displays by 'alae ke'oke'o are similar to those described for the American coot, but territoriality is not well studied. Non-breeding 'alae ke'oke'o may form large flocks.



'Alae ke'oke'o swimming near sparse emergent vegetation. Photo by John Mosesso, USGS.

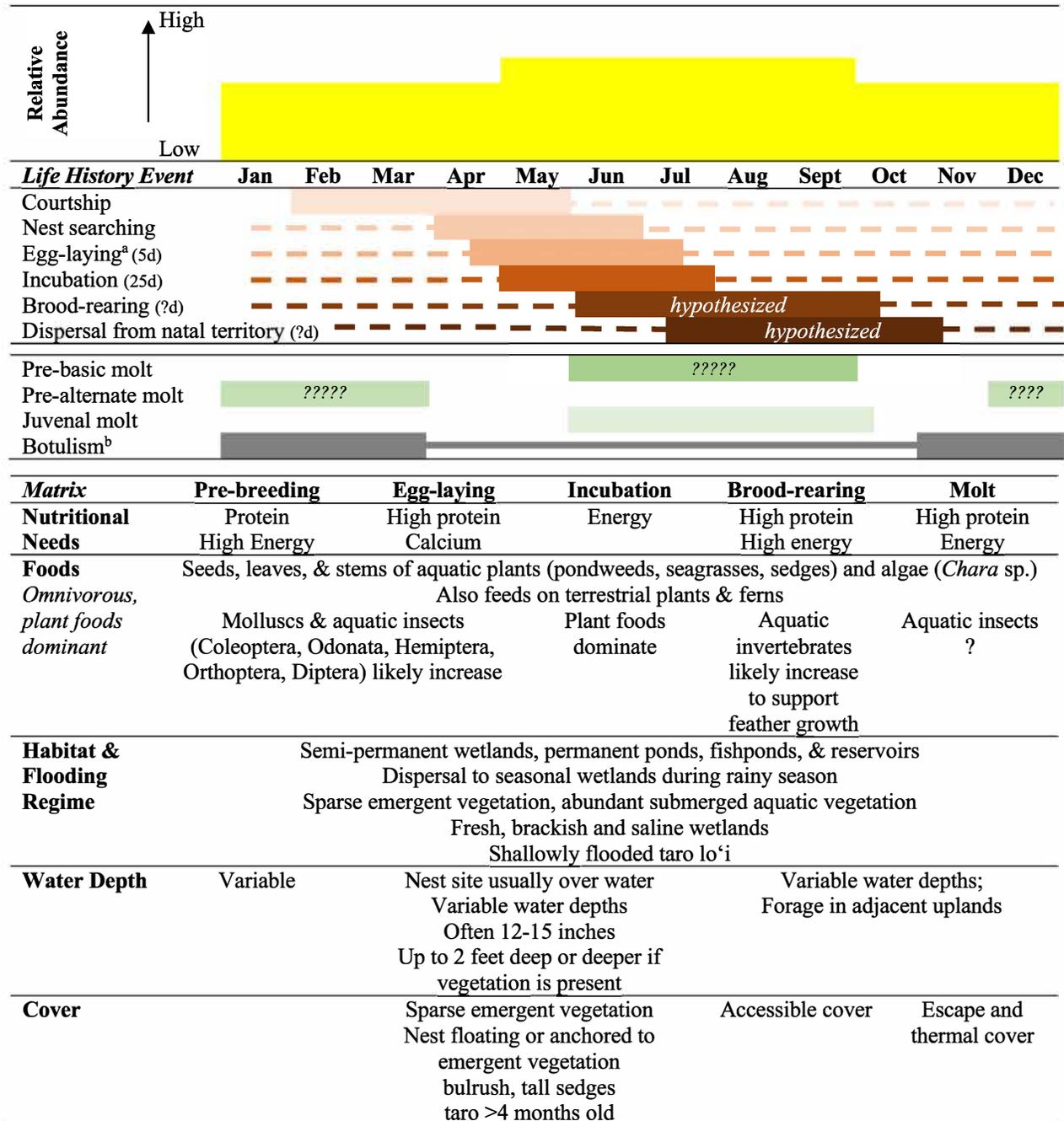
Nest platforms are large, either floating or anchored to sparse emergent vegetation (see summary in Pratt and Brisbin 2002). Nests can be as close as 20 feet but are more typically spaced 80 feet apart (Byrd et al. 1985). Females lay an average of 5 eggs, which is smaller than that reported for American coots, and incubate eggs for about 25 days (Shallenberger 1977, Byrd et al. 1985, Morin 1998). Although nest success is relatively high, chick mortality during the first 2 weeks of brood-rearing is also high (Byrd et al. 1985). Re-nesting and double-brooding have been reported, but no information is available on brood-rearing.

In wetlands, 'alae ke'oke'o forage by pecking, dabbling on the water surface, immersing head and neck, and/or diving. Feeding method is primarily related to depth of food underwater (Brisbin and Mowbray 2002). 'Alae ke'oke'o are omnivorous, with plant material likely dominant, similar to American coots. Leaves, seeds, and stems of aquatic plants and mollusks are reported as food items by Munro (1960). Otherwise, very little information is available specific to foods consumed by 'alae ke'oke'o. American coots primarily feed on pondweeds, sedges, and algae. Aquatic invertebrates, although less common, are likely an important part of their diet during breeding, particularly for egg-laying and growing young (Jones 1940, Desrochers and Ankney 1986, Driver 1988). Post-breeding dispersal is widespread (Pratt and Brisbin 2002).

Population Trends

Statewide biannual count data show large annual fluctuations in number of 'alae ke'oke'o. Pratt and Engilis (1993) attribute this to climatic and associated wetland conditions as high numbers follow years of high rainfall. Interisland movements, including dispersal to Ni'ihau and Hawai'i islands during the rainy season (Udvardy 1960, Mike Mitchell, USFWS [retired], personal communication), may also influence counts. Long-term trends in 'alae ke'oke'o count data suggest the population has increased since the 1986 (Paxton et al. *in press*). In contrast, data from 2006 to 2016 show weak evidence for population declines on 4 of the 6 main islands; trends are inconclusive for the statewide estimates (Paxton et al. *in press*).

Table 5. Chronology of life history events for ‘alaie ke‘oke‘o (Hawaiian coot, *Fulica alai*). Relative abundance based on count numbers that tend to be higher during summer surveys (Paxton et al. *in press*). ‘Alaie ke‘oke‘o likely disperse to newly flooded habitat during the rainy season. Life history information compiled from Shallenberger (1977), Byrd et al. (1985), Morin (1998), and Pratt and Brisbin (2002). Includes diet items specific to Hawai‘i (Munro 1960) and for closely-related American coots (*Fulica americana*; Brisbin and Mowbray 2002).



^a Assumes 1 egg/day; average clutch size=5 eggs; mode=6.

^b Based on number of dead carcasses and sick birds observed (USFWS unpublished data). Number of birds weighted by search effort does not vary by month (Reynolds et al 2021).

Ae'o (Hawaiian stilt)

Ae'o is one of three recognized subspecies of the black-necked stilt (*Himantopus mexicanus*) and is most closely related to the North American subspecies (*H. mexicanus mexicanus*). Ae'o use a variety of upland and wetland habitats with salinities ranging from fresh to hypersaline. Native plants characteristic of wetlands used by ae'o include 'ae'ae (*Bacopa monnieri*), 'akulikuli, makaloa, and other native sedges.

Ae'o forage on aquatic invertebrates and fish while wading in water up to 4–5 inches deep (Telfer 1973, 1976) and commonly use wetlands with water < 9 inches deep (DOFAW 2015). Three visual feeding methods have been described for black-necked stilts: pecking prey on mud or the water surface, plunging their head to capture food in the water column, and snatching flying insects from the air (Hamilton 1975). They also use scythe-like sweeps where they swipe their head and bill through water or soft mud. Scythe-like sweeps and plunging have been reported for ae'o (see summary in Robinson et al. 1999).

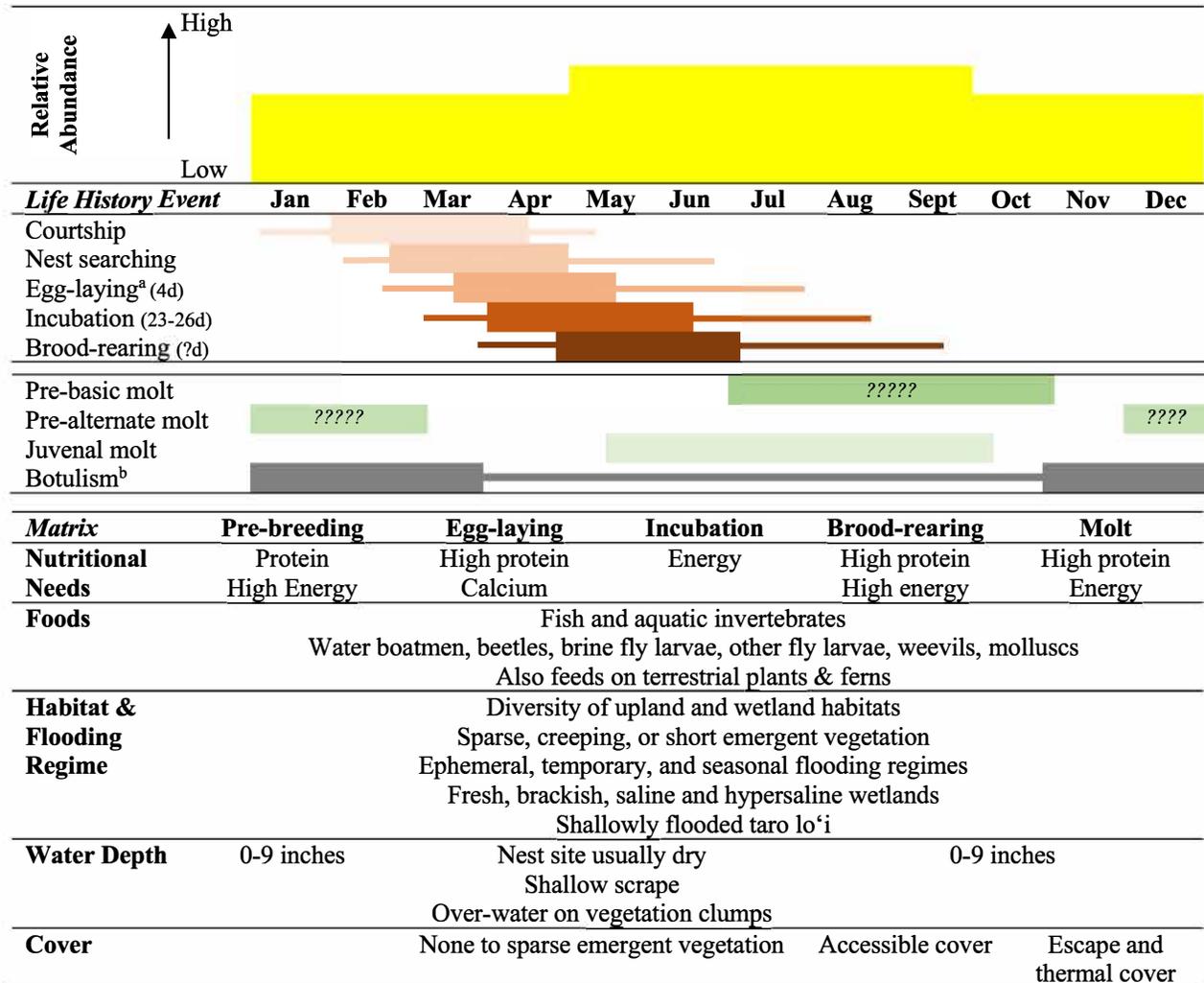
Telfer (1975, 1976) reported ae'o spent 70% of foraging time pursuing fish, sometimes trapping them in shallow water, and suggested vertebrate prey are an important part of their diet. Ae'o also consume water boatmen, beetles, and brine fly larvae. Invertebrates prey consumed by black-necked stilts in North America, including weevils, other fly larvae, and snails, may also be present in ae'o diets. Small quantities of seeds and other vegetative matter (<2% by weight) have been recorded from stomachs of black-necked stilts (Wetmore 1925).

Ae'o appear to be paired year-round but frequency of pairs is less during the winter (Coleman 1981). Ae'o exhibit seasonal breeding patterns with peak nesting following the rainy season. Egg-laying begins during mid-February with incubation peaks during April–May (Coleman 1981). Ae'o make a shallow scrape on coastal flats with no or limited low-growing vegetation or mudflats with very sparse emergent vegetation. They may also nest on high spots, small islands, or vegetation clumps over water and will build up nests if water rises (Telfer 1975, Coleman 1981). Nests on edges of taro lo'i and managed wetland impoundments are common if vegetation is kept short. Nest lining varies with most vegetation added during incubation.

Clutch size averages 4 eggs; nests with more eggs likely have eggs from >1 female. Males and females share incubation for 23–26 days after which eggs usually hatch within 24 hours (Coleman 1981). Nest success tends to be relatively high, but the number of eggs that hatch is significantly lower than the number laid (Christenson et al. 2021). Nest success decreases later in the breeding season and increases with height of vegetation (Harmon et al. 2020). Chicks can leave the nest within 1-2 hours of hatching. Adults may brood chicks for up to 2 weeks but feeding of young has not been observed in the wild (Coleman 1981). Family groups may remain together for up to a year.

Ae'o are strongly territorial but territories may be aggregated in suitable habitats with adults jointly defending the area around nests from conspecifics, other birds, and predators. Adults with newly hatched young are very aggressive toward unrelated young and have been observed attacking chicks not their own (Robinson et al. 1999). As adult densities increase, nest success rate decrease, suggesting the territoriality may influence reproductive success at higher population levels (van Rees et al. 2020).

Table 6. Chronology of life history events for ae'ō (Hawaiian stilt, *Himantopus mexicanus knuseni*). Relative abundance based on count numbers that tend to be higher during summer surveys (Paxton et al. *in press*). Ae'ō likely disperse to newly flooded habitats during the rainy season. Life history information compiled from Coleman (1981), Chang (1990), and Robinson et al. (1999). Includes diet items specific to Hawai'i (Telfer 1975, 1976) and for closely-related North American black-necked stilt (*H. mexicanus mexicanus*; Robinson et al. 1999).



^a Assumes 1 egg/day; average clutch size=3.6 eggs.

^b Based on number of dead carcasses and sick birds observed (USFWS unpublished data). Number of birds weighted by search effort does not vary by month (Reynolds et al 2021).



Ae'ō. Photo by Adonia Henry.

Wetland Invertebrates

Invertebrates found in wetlands provide a critical protein resource for all waterbirds. Even primarily herbivorous species of waterbirds, consume invertebrates to meet the necessary protein and amino acid requirements to lay eggs and molt. Although this is most well documented for dabbling and diving ducks (Alisauskas and Ankney 1992, Krapu and Reinecke 1992), it also occurs in species of Rallidae (Bannor and Kiviat 2002, Brisbin and Mowbray 2002). Aquatic invertebrates are recognized as the major link between primary producers and wetland-dependent wildlife, but there is a paucity of information about the roles functional feeding groups have in energy flow and nutrient cycling of wetlands (Wissinger 1999).

Invertebrates with aquatic, semi-aquatic, and terrestrial life cycles are found in lowland wetlands throughout Hawai'i and are probably the least well-studied biotic component of these wetlands. Of the taxa commonly found in diets of waterbirds, an estimated 12,000 species of annelids, crustaceans, molluscs, and insects (including near relatives) occur in Hawai'i (Eldridge and Miller 1997). More than half of those species have been introduced. Impacts of non-native invertebrates vary by island, elevation, watershed, and stream reach. Non-native invertebrates predate and compete with native invertebrates for food. That being said, introduced fish have likely had the biggest impact on native aquatic invertebrates and they are implicated in the range constriction and reduced abundance of native damselflies (see summary in Polhemus & Asquith 1996).

When part of wetland ecological studies, invertebrates in wetlands are often identified to family, so the full complement of species in Hawai'i's wetland is unknown. Even when efforts are made to identify species, identification of all individuals may not be possible. Invertebrates from about 28 orders and 86 families of annelids, crustaceans, molluscs, and insects (including near relatives) have been identified from lowland wetland and stream reaches (Appendix B). Species of insects from aquatic orders in which almost all species have aquatic larvae are included when reported (Appendix B – Table 23). Invertebrates are often categorized by functional feeding groups based on the type of food consumed and their feeding mechanism (see summaries in Wissinger 1999, Voshell 2002).

Native and Other Beneficial Plants

Endemic waterbirds in Hawai‘i evolved to utilize wetland and uplands habitats with native plants and aquatic invertebrates. Following Polynesian settlement and European contact, many introduced species became naturalized and are now part of Hawaii’s wetland flora. Naturalized species that do not have aggressive growth characteristics that degrade wetland habitats can be beneficial for waterbirds. Native and naturalized species are used for food, cover, and/or nesting material (e.g., Engilis et al. 2002, DesRochers et al. 2009b). Thus, beneficial plants include native and naturalized species that meet life-history requirements of endemic waterbirds and do not degrade wetland habitats (e.g., form monocultures, alter hydrology).

To assess negative and positive attributes of vegetation in managed wetlands, a rating system was developed based on observations of plant growth and waterbird use at Hanalei and Hulē‘ia NWRs (Chadd Smith, USFWS, personal communication). The rating system includes six positive attributes and three negative attributes (Table 7). Species receives a score of +1 for each positive attribute they provide and -1 for each negative attribute. Scores are added together for a maximum of 6 (very beneficial) to -3 points (not beneficial and degrade habitat).

When naturalized species with high scores germinate in managed wetland units at Hanalei and Hulē‘ia NWRs, they are managed to provide resources for endemic waterbirds. Control and eradication efforts can then focus on species with low scores that degrade wetland habitats and limit waterbird use. Ratings can be adjusted based on site specific observations and/or management objectives at other wetland sites as needed. Attributes can also be expanded to include other aspects of waterbird use (e.g., leaves as a food resource) or habitat condition. This rating system provides a semi-quantitative method to evaluate wetland condition and is more detailed than previous classification efforts (e.g., Erickson and Puttock 2006).



Table 7. Positive and negative attributes of select native and naturalized wetland plant species in relation to general life-history requirements of endemic waterbirds and plant growth characteristics. Rating system developed for habitat management at Hanalei and Hulē‘ia National Wildlife Refuges (Chadd Smith, USWFS, personal communication).

Species Scientific name, Hawaiian or English common name	Positive Attributes (+1)						Negative Attributes (-1)			Total Score
	Seed Production	Structure for Nest	Nest Material	Cover	Roost Habitat	Decomposes Easily	Aggressive Growth	Flood tolerant	High Maintenance	
<u>Native</u>										
<i>Cyperus javanicus</i> , ‘ahu‘awa	1	1	1	1	1	1				6
<i>Cyperus laevigatus</i> , makaloa	1	1	1	1	1	1				6
<i>Cyperus odoratus</i> , pu‘uka‘a	1	1	1	1	1	1				6
<i>Cyperus polystachyos</i> , Manyspike flatsedge	1	1	1	1	1	1				6
<i>Cyperus trachysanthos</i> , pu‘uka‘a	1	1	1	1	1	1				6
<i>Eleocharis obtusa</i> , blunt spikerush	1	1	1		1	1		-1		4
<i>Fimbristylis cymosa</i> , mau‘u ‘aki‘aki	1		1			1				3
<i>Fimbristylis dichotoma</i> , forked fimbry	1	1	1	1	1	1				6
<i>Schoenoplectus juncooides</i> , kaluha	1	1	1	1	1	1		-1		5
<i>Schoenoplectus tabernaemontani</i> , ‘aka‘akai	1	1		1	1			-1		4
<i>Sporobolus virginicus</i> , ‘aki‘aki	1	1	1			1		-1		3
<i>Bacopa monnieri</i> , ‘ae‘ae		1	1					-1	-1	0
<u>Naturalized</u>										
<i>Cyperus meyanianus</i> , Meyen’s flatsedge	1	1	1	1	1	1				6
<i>Cyperus papyrus</i> , papyrus		1		1				-1	-1	-1
<i>Cyperus pilosus</i> , fuzzy flatsedge	1	1	1	1	1	1				6
<i>Eleocharis geniculata</i> , bent spikerush	1	1	1		1	1		-1		4
<i>Eleocharis radicans</i> , rooted spikerush	1		1			1		-1		2
<i>Fimbristylis aestivalis</i> , Summer fimbry	1	1	1		1	1				5
<i>Fimbristylis ferruginea</i> , West Indian fimbry	1	1	1	1	1	1		?	-1	?
<i>Fimbristylis miliacea</i> , grass-like fimbry	1	1	1	1	1	1			-1	5
<i>Kyllinga nemoralis</i> , shortleaf spikesedge			1			1		?		?
<i>Rhynchospora caduca</i> , anglestem beakrush	1	1	1	1	1			-1	-1	?
<i>Schoenoplectus californicus</i> ,	1	1		1	1			-1	-1	-1
<i>Cyndon dactylon</i> , Bermuda grass	1		1					-1		1
<i>Echinochloa colona</i> , jungle rice	1	1	1	1	1	1				6
<i>Echinochloa crus-galli</i> , millet	1	1	1	1	1	1				6
<i>Leptochloa fusca</i> , sprangletop	1	1	1	1	1	1				6
<i>Panicum maximum</i> , Guinea grass	1	1	1	1				-1		-1
<i>Paspalum conjugatum</i> , Hilo grass	1		1					-1		-1
<i>Paspalum scrobiculatum</i> , ditch millet ???										
<i>Paspalum vaginatum</i> , seashore paspalum	1	1	1					-1	-1	-1
<i>Bracharia mutica</i> , California grass	1	1	1					-1	-1	-1
Ludwigia	1	1		1	1	1		-1	-1	3
<i>Ammannia coccinea</i> , scarlet toothcup	1	1	1			1		-1		3

Invasive Plants

The prolific vegetative reproduction found in Hawaii's highly invasive wetland plants, combined with high photosynthetic efficiency and rapid nutrient uptake are typical of invasive wetland plants worldwide (Cronk and Fennessy 2001). Forty-four species of introduced plants that occur in Hawaii's wetlands are considered highly invasive; 86% of those are perennial (Erickson and Puttock 2006). Of those, 13 species are often the focus of control efforts at state and federally managed wetland management areas (ARH and LHF, personal observations) and are frequently observed in Hawaii's lowland wetlands (Bantilan-Smith et al. 2009; see text box).

Other species, such as water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*) are less frequently observed, but highly invasive. Many wetland plant species invasive to Hawai'i are described as having vigorous growth rates and/or high biomass production (Table 8, Table 9, and Table 10).

Invasive Plants Common in Hawaii's Lowland Wetlands

California grass (*Urochloa mutica*)
Pickleweed (*Batis maritima*)
Seashore paspalum (*Paspalum vaginatum*)
Marsh fleabane (*Pluchea indica*)
Climbing dayflower (*Commelina diffusa*)
California bulrush (*Schoenoplectus californicus*)
Haole koa (*Leucaena leucocephala*)
Wedelia (*Sphagneticola trilobata*)
Guinea grass (*Panicum maximum*)
Cattail (*Typha latifolia* & *T. domingensis*)
Red mangrove (*Rhizophora mangle*)
Hau (*Talipariti tiliaceum*)
Kiawe (*Prosopis pallida*)

Table 8. Factors associated with “invasiveness” of introduced and highly invasive herbaceous and woody shrub species (Erickson and Puttock 2006) that are widespread with a high frequency of occurrence in lowland wetlands in the main Hawaiian Islands (Bantilan-Smith et al. 2009).

Scientific Name	Common Name	Seed Structure	Growth Form	Sexual Reproduction	Asexual Reproduction	Inundation tolerance	Photosynthetic efficiency/Productivity	High Nutrient Uptake	PIER risk score
<i>Urochloa mutica</i> (syn. <i>Brachiaria mutica</i>)	California grass	M	P	Irregular, low seed production	Stolons; roots at stem nodes & from fragments; adventitious roots	High	C ₄ ; high biomass	Very efficient uptake of N & P	12
<i>Batis maritima</i>	Pickleweed	D	P	High seed bearing, but not well-studied; high germination in wide range of conditions	Roots at stem nodes & stem fragments; continuous re-sprout from root crowns	Medium	C ₃ ;		9
<i>Paspalum vaginatum</i>	Seashore paspalum	M	P	Yes, but rarely produces viable seeds	Rhizomes, stolons, & adventitious roots; forms dense rhizomatous mats	High; also drought tolerant	C ₄ ; vigorous growth in fresh to hypersaline; maintains high photosynthesis	Increased K increases root & shoot growth	7
<i>Pluchea</i> spp. <i>P. indica</i> ¹ <i>P. carolinensis</i>	Indian fleabane Cure-for-all	D	P	Prolific seed producers; 500 flowers/panicle head; seeds likely have short viability	Re-sprout from roots and root crown	Low			11 15
<i>Commelina diffusa</i>	Climbing dayflower	M	P ³	1,600 seeds/plant in closely related species; produces more seeds in disturbed areas	Roots at stem nodes & stem fragments; heavy branching	Medium?	C ₃ ; vigorous growth habit	Yes, but high N may reduce growth	23
<i>Schoenoplectus californicus</i> ²	California bulrush	M	P	Yes, but germination is relatively rare	Spreads by rhizomes, rhizome fragments	High		Yes	n/a

¹ Occurs more frequently in lowland wetlands than *P. carolinensis*.

² Reported as *Schoenoplectus* sp. in Bantilan-Smith et al. (2006).

³ Perennial in the tropics; annual in temperate regions.

Table 9. Factors associated with “invasiveness” of introduced and highly invasive herbaceous plant (Erickson and Puttock 2006) that can have locally prolific occurrences but are less frequently observed in lowland wetlands in the main Hawaiian Islands (Bantilan-Smith et al. 2009).

Scientific Name	Common Name	D/M	A/P	Sexual Reproduction	Asexual Reproduction	Inundation tolerance	Photosynthetic efficiency/Productivity	High Nutrient Uptake	PIER risk score
<i>Sphagnetocola trilobata</i> ^a	Wedelia, creeping oxeye	D	P	>4,000 seeds/m ² in seed bank	Roots at stem nodes and stem fragments	Medium? Dry/mesic habitats	Can spread >100 miles/yr; allelopathic	Not in tropics	13
<i>Ipomoea alba</i>	White morning glory	D	P	Seeds can be spread by water	Fragments; climbing vine that forms dense mats & shades out other species	Medium? Moist habitats		Yes	n/a
<i>Typha latifolia</i>	Broad-leaf cattail	M	P	222,000 seeds/spike; viable for 100 years	Rhizomes (can occupy >538 ft ² two years after germinating with total rhizome length of 480 m)	High		Yes	26
<i>Eichhornia crassipes</i> ^a	Water hyacinth	M	P	3,000 seeds/flower viable for >28 years	Stolons (most common mode for spreading)	High	Has one of the highest photosynthetic rates in plants	Yes	26
<i>Pistia stratiotes</i>	Water lettuce	M	P	>4,000 seeds/m ² in seed bank and >80% viability; long-lived	Stolons are primary mechanism of spread	High		Yes	18
<i>Megathyrsus maximus</i> (syn. <i>Panicum maximum</i>)	Guinea grass	M	P	Prolific seed producer	Rhizomes, tillers	Very low	39-94% higher maximum photosynthetic rates than native species		17
<i>Cynodon dactylon</i>	Bermuda grass	M		Prolific seed producer, viable >2 years	Stolons & rooted runners; fragments increase buds	High; also drought tolerant	C ₄ -fast-growing; biomass >7,000 lbs/acre	Yes	22

^a Listed as one of the 100 worst invasive species by the IUCN (Lowe et al. 2000).

Table 10. Factors associated with “invasiveness” of introduced and highly invasive tree species (Erickson and Puttock 2006) that are of management concern and can have locally prolific occurrences lowland wetlands in the main Hawaiian Islands (Bantilan-Smith et al. 2006).

Scientific Name	Common Name	D/M	A/P	Sexual Reproduction	Asexual Reproduction	Inundation tolerance	Photosynthetic efficiency/Productivity	High Nutrient Uptake	PIER risk score
<i>Rhizophora mangle</i>	Red mangrove	D	P	1 seed per fruit that germinates in fruit (viviparous); seedling propagules abundant and viable for 1 year	Aerial roots anchor to substrate and form below & above ground laterals	Roots in mud have 50% air space; reduced growth w/ sea level rise	Fast growth under wide range of environmental conditions; high degree of plasticity	Yes, P & NPK nutrients	13
<i>Talipariti tiliaceum</i> (syn. <i>Hibiscus tiliaceu</i>)	Hau	D	P	Seeds viable for <2 years	Roots from bent or prostrate branches	Medium	Very fast growing when young		n/a
<i>Leucaena leucocephala</i> subsp. <i>leucocephala</i> .	Koa haole	D	P	Prolific seed producer; grows easily from seeds	Regrows from cut stumps and cuttings; basal shoots rapidly regenerate after fire	Low	17 tons/ac/yr, possibly up to 42 tons/ac/yr	Nitrogen fixer	11-21
<i>Prosopis pallida</i>	Kiawe, mesquite	D	P	Low fruiting efficiency but 10-40 seeds/fruit and up to 142,000 seeds/tree per year with long viability; High germination rates in wide variety of substrates	Regrowth from dormant buds below soil surface on stem/trunk	Low	Fast root growth; two flowering seasons/year	Nitrogen fixer	n/a
<i>Thespesia populnea</i>	Milo, Portia tree	D	P	Large fruit crops; regenerates rapidly from seeds that have long viability	Regrowth from cut stems	Low	Moderate (2-3 ft/yr) growth rate ; shifts to C4 under salt stress		9

CHAPTER 5: DEFINE YOUR MANAGEMENT APPROACH

Engage People with Different Expertise and Experiences

Interest in wetlands stems from different perspectives, including interest in a specific species of taxonomic group or exposure to a specific site or location, but often does not include an interest in abiotic conditions or hands-on manipulation of soil and water to enhance wetland habitats. To be successful, wetland managers need to embrace a suite of skills and intellects including visual-spatial, naturalistic, logical-mathematical, linguistic, kinesesthetic, interpersonal, and intrapersonal (see Gardner 2011). Although verbal (linguistic) math (logical) intellects are embraced in academic settings, other skillsets are also essential for effective wetland management. For example, practitioners with spatial intellects may be very good at interpreting data or spatial patterns of management results. A practitioner with logical intelligence has excellent problem-solving abilities. A person with kinesthetic intelligence is very good at fixing equipment. By comparison, a manager with good linguistic and interpersonal abilities may be more likely to acquire funding for long-term management through well-written grants or persuasive speeches. Thus, the most effective wetland management is often achieved through collaboration with individuals from multiple disciplines who have had different experiences and demonstrate strengths in different intellects.



Interdisciplinary team of biologists, equipment operators, soil scientists, botanists, planners, and ecologists helping to sample soils and discuss restoration designs and management options at Mānā Plain Wetland Restoration.

Identify Available Resources

The amount of effort required per acre of wetland varies based on species present, equipment used, staffing capacity, and accessibility. Although no hard and fast rule exists for this relationship; general observations suggest that the equivalent of one full time land management position (FTE) is required to successfully manage 30 acres of wetlands in Hawai‘i. Whether the FTE is one staff person dedicated to wetland management, or a part-time staff person who organizes monthly volunteer workdays, it is essential to have a plan for treating re-growth of invasive species after initial removal efforts. Otherwise, invasive species are likely to recolonize, creating conditions where efforts are constantly focused on invasive species control rather than providing resources that meet life-history requirements of endemic waterbirds. Management strategies outlined in Chapter 6 can be implemented using a variety of gear ranging from hand tools to heavy equipment.

Develop Habitat-Based Goals and Objectives

Habitat-based goals should describe a desired future condition that contributes to a larger mission or vision of the organization or partnership (Table 11). Goals should also contain an action (e.g., enhance), attribute (e.g., area), and target (e.g., quantity). Goals may be lofty and difficult to achieve taking several years to successfully accomplish them. Objectives, strategies, and actions are then identified as step downsto attain goals.

Historically, the focus of management objectives was often on wildlife populations, not habitats. This was, in part, because habitats are complex with constantly changing. In addition, the emphasis on management of rare species, including endangered Hawaiian waterbirds, is often linked to meeting population objectives. Historical management objectives were poorly tied to life-cycle events of wildlife species and were also vague or lofty and were more like goals or even visions (LHF personal observation). Recovery objectives for Hawaiian waterbirds include specific, measurable attributes for population numbers (stable or increasing minimum population of 2,000 birds for each species), but habitat objectives are broad: “establish and protect...both core and supporting wetlands that are managed as habitat suitable for waterbirds...” (USFWS 2011:121). Habitat objectives are refined by recovery criteria which identify the percentage of core and supporting wetlands that need to be protected and managed.

All management objectives, whether habitat or population-based, should be quantifiable and are commonly referred to as ‘*SMART*’ objectives: *S*pecific, *M*easurable, *A*chievable, *R*esults-oriented, and *T*ime-specific (Elzing et al. 2001, Schroeder 2006, USFWS 2013, Bjerke and Renger 2017). By clearly articulating a measurable attribute, threshold value, direction of change (or trend), and time-frame, quantifiable objectives provide a foundation for determining evaluating the response of plants and wildlife to management strategies (Elzinga et al. 2001). Examples of quantifiable habitat objectives for actively managed wetlands include the following:

- Shallowly flood 50% of seed-producing wetland vegetation during early October to make seeds and aquatic invertebrates available to ‘alae ‘ula prior to the peak season.
- Slowly drawdown water levels on 5 acres beginning in March to concentrate seed and invertebrate resources for koloa ducklings and stimulate germination of beneficial wetland plants on exposed substrates.

Table 11. Examples of habitat-based goals for wetland habitats in Hawai‘i.

Organization	Example of Habitat-based Goal	Mission or Vision of Organization
Mālama Hulē‘ia	Remove 23 acres of red mangrove within the Hulē‘ia River Watershed.	A free-flowing, healthy and productive Hulē‘ia ecosystem perpetuating community pride.
DOFAW	Restore native vegetation to 30 acres of aquatic, wetland, and upland habitats at Kawai‘ele Waterbird Sanctuary.	Responsibly manage and protect watersheds, native ecosystems, and cultural resources and provide outdoor recreation and sustainable forest products opportunities, while facilitating partnerships, community involvement and education.
USFWS	Protect, maintain, and enhance seasonal wetland habitats at Kealia Pond NWR to meet the life history needs of endangered Hawaiian waterbirds.	Work with others to conserve, protect, and enhance fish, wildlife, plants, and their habitats for the continuing benefit of the American people.

CHAPTER 6: DEVELOP MANAGEMENT STRATEGIES

Establish Native and Other Beneficial Plants, Naturally!

Creating conditions to promote the germination and growth of native and other beneficial plants is critical to achieve habitat management objectives that are directly tied to restoration and management actions. Natural germination is a cost-effective method, particularly over a large area, to maximize food and cover resources for endemic waterbirds. Planting and seeding of rare species that incorporates traditional ecological knowledge on growing patterns (e.g., Gon 2003) can supplement natural germination and increase species diversity.

Managers can create conditions for germination because wetland seed banks are persistent. Seeds of wetland plants can survive multiple periods of drought and re-wetting conditions; some species are known to be viable for hundreds of years (Keddy and Reznicek 1982, Leck and Brock 2000, Leck and Schultz 2005, Brock 2011, Cross et al. 2015). In addition, the density of wetland seed banks can be extremely high, reaching more than 700,000 seeds/m² for a single species (Bissels et al. 2005). Seeds typically germinate from the upper 3 cm of soil. Seeds also persist buried deep in the soil profile until a disturbance, such as a flood, swell, or mechanical management action, scours the substrate, brings seeds up from deep burial, and provides a niche for seeds to germinate. Species richness of seed banks is generally higher than that of above-ground vegetation due to abiotic varying conditions under which different species germinate (e.g., Keddy and Reznicek 1982, Mulhouse et al. 2005). Seed dispersal by water, animals, and wind, replenish depleted seed banks and can further increase species richness compared to richness of the above ground vegetation.

The specific requirements for breaking seed dormancy and, in turn, germination of wetland plants are poorly documented and understood, especially for native wetland species in Hawai'i. However, general principles and knowledge of genera or family-level germination characteristics can be successfully applied to managed wetlands in Hawai'i. For seeds from the seed bank to germinate, they need to break dormancy and be exposed to conditions adequate to complete all stages of germination (Figure 2). Except for some species of submerged aquatic vegetation, all seeds of wetland plants need water and oxygen for the embryo to grow. But soil that is too wet can reduce the amount of oxygen available in the soil pore space and prevent germination. Dormancy patterns, soil moisture, temperature, and light requirements vary by species (e.g., Schütz 2000, Chauhan and Johnson 2009). Many wetland plants also require light for germination (Grime 1981) and therefore germinate best on bare topsoil. Scarification appears to stimulate germination of a wide range of wetland and upland species (e.g., Scowcroft 1978, Baskin et al. 2004, Leck and Schütz 2005, Mueller-Dombois 2005). Because many wetland plant species have seeds with hard and/or thick seed coats, scarification breaks down the hard seed coat common in wetland plants allowing the seed to absorb water and oxygen from the soil. Receding water and decreasing soil moisture after flood events likely created optimal soil moisture and temperature conditions suitable for germination on newly disturbed soil surfaces.

Management strategies that promote germination can be mimicked in managed wetlands equipment, ranging from tractors with discs to hand tools (Table 12). The disturbance required for successful germination of beneficial species will depend on existing habitat conditions. Regardless of wetland type, invasive vegetation needs to be removed before germination of

beneficial plants is possible. Accumulated organic matter and litter, which are common in wetlands with a history of dense stands of invasive species, prevent sunlight from reaching the soil surface, reduce soil temperature, increase soil moisture, and may reduce germination potential of beneficial wetland plants. Note that plant response to the same management action implemented during a wet or dry period of the wetland cycle will likely be very different due to differences in abiotic conditions.

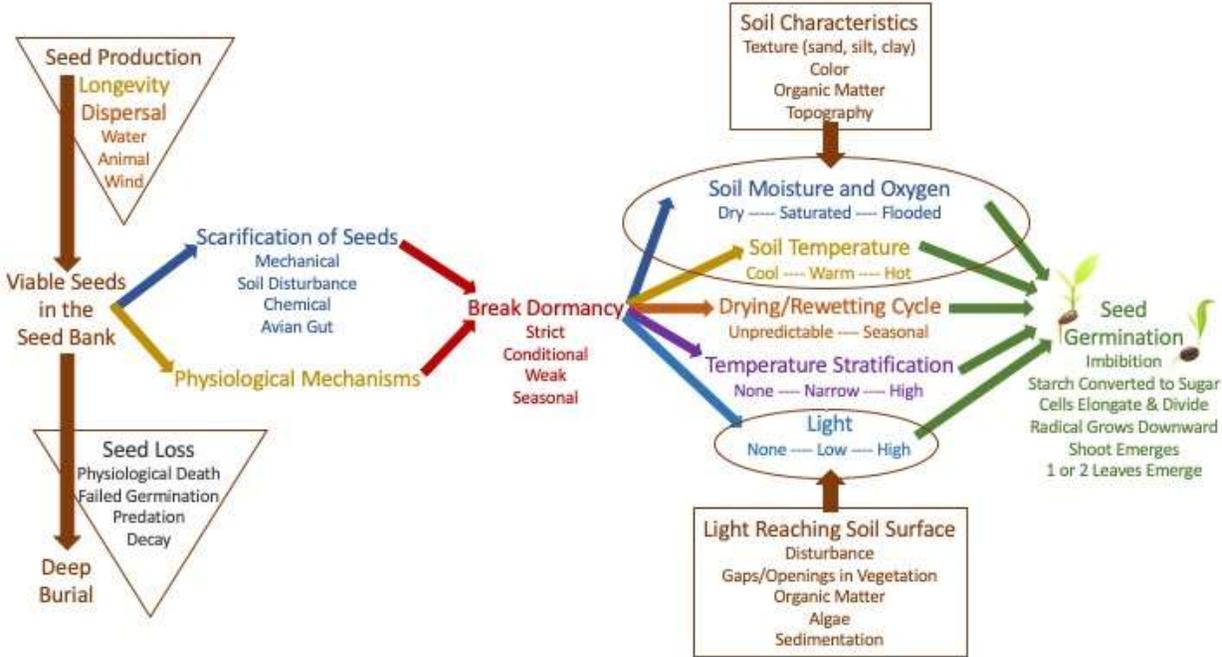


Figure 2. Conceptual model of seed germination from wetland seed banks.

Table 12. Management strategies, equipment, and actions that stimulate germination of beneficial wetland plant species.

Management Strategies	Management Equipment and Actions by Wetland Size		
	Large	Medium	Small
Break Down and Remove Accumulated Organic Matter (dead and undesirable vegetation)^{1,2,3}	Backhoe Tractor (120-130 hp) with implements <ul style="list-style-type: none"> • Mower/Brush Cutter <ul style="list-style-type: none"> • Cut vegetation into smaller pieces to increase decomposition rates • Grinder/Masticator <ul style="list-style-type: none"> • Break up root crown to stress plant and reduce regrowth • Further breaks down organic matter • 	Tracked skid steer (105-110 hp) with attachments described for tractors	Small equipment (e.g., brush cutter, rototiller)
			Hand tools <ul style="list-style-type: none"> • Shovels <ul style="list-style-type: none"> • Remove above and below ground biomass • Reel lawn mower <ul style="list-style-type: none"> • Won't be effective on dense vegetation • Weed wacker /String trimmer • Pull by hand
Disturb/Scarify Soil	Tractor (120-130 hp) with implements <ul style="list-style-type: none"> • Disc (10' tandem pull behind with cookie cutter & smooth discs) <ul style="list-style-type: none"> • Incorporate organic matter into soil • Break up rhizomes • Bring buried seeds to soil surface • Surface soil clod size dependent on depth & disc size • • Rototiller <ul style="list-style-type: none"> • Smooth soil surface 	Tracked skid steer (105-110 hp) with attachments described for tractors	Small equipment (e.g., rototiller)
			Hand tools <ul style="list-style-type: none"> • Garden rake <ul style="list-style-type: none"> • Shallow disturbance • Shovels <ul style="list-style-type: none"> • Patchy soil disturbance when used to remove vegetation
Increase Soil Moisture	All Wetland Sizes		
	Active Water Management	No Water Control	
	<ul style="list-style-type: none"> • Shallow flooding followed by drawdown⁴ • Drawdown after flood event • Rainfall • Seasonal groundwater dynamics • Slow inflow of water to increase soil water content 	<ul style="list-style-type: none"> • Drawdown after flood event • Rainfall • Seasonal groundwater dynamics 	

¹ See Table 18 and Table 19 for specific invasive species control methods.

² The amount and type of accumulated organic matter should be considered when selecting equipment to ensure efficient removal techniques.

³ Vegetation may need to be removed off-site to a suitable upland area following State and Federal regulations.

⁴ Drawdown is the gradual removal of surface water that exposes the wetland substrate.

Produce Aquatic Invertebrates

Producing abundant aquatic invertebrates is essential for functional wetland systems and meeting important life-history needs of endemic waterbirds (see summaries in Chapter 4). All four species of endemic waterbirds consume invertebrates during at least one life-history event. Aquatic invertebrates are incredibly diverse occupying six functional feeding groups: shredders, scrapers/grazers, collectors, plant piercers, predators, and parasites. As a result, they are major components of the food web that are responsible for moving energy and nutrients to higher trophic levels. Although aquatic invertebrates have distinct responses to environmental conditions, inconsistent patterns and complex interactions make it difficult to predict their specific response to management actions (Batzer 2013). That said, management actions should target the biotic and abiotic factors shown to have the greatest influences on aquatic invertebrate abundance and diversity, including hydroperiod and plants (Batzer 2013, Bischof et al. 2013) while also considering other environmental factors. Hypotheses for cause-and-effect relationships among biotic and abiotic factors and aquatic invertebrates in fresh and brackish water wetlands in Hawai‘i are shown in Figure 3 (modified from Hentges & Stewart 2010).

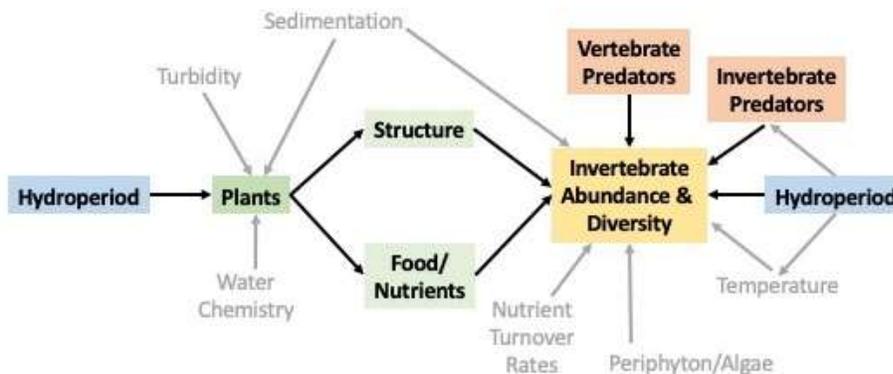


Figure 3. Hypotheses for cause and effect relationships among biotic and abiotic factors and aquatic invertebrates in fresh and brackish water wetland in Hawai‘i (modified from Hentges & Stewart 2010). Main controls on invertebrate populations (Batzer 2013) are highlighted and in black.

Invertebrates have evolved to inhabit diverse wetland, streams, and other aquatic habitats. They have adapted to variable hydroperiods characteristic of wetlands (Figure 4). They survive periods of drought by aestivating as eggs, larvae, and/or adults. Invertebrate species capable of flight disperse between seasonal wetlands and permanently flooded water bodies during dry periods.

The highest diversity and abundance of invertebrates in wetlands occurs in habitats with diverse and abundant structure that provides food (direct or indirectly), attachment sites, and cover from predators (Voshell 2002). In wetlands and other lentic water bodies, this occurs in vegetated areas with complex living and dead plant structure. Temporary and seasonal wetlands typically have more available oxygen and higher nutrient turnover rates than deeper permanently flooded wetlands, further contributing to abundant invertebrate populations. Vegetation litter on mudflats also provides important nutrients and habitat for benthic invertebrates (e.g., Wrubleski et al. 1997). Plant species with complex and/or finely divided leaf structure and increased surface area generally support larger invertebrate assemblages than species with simple leaf structure (Krull 1970, Fredrickson and Reed 1988, Thomaz et al. 2008). Thus, plants with complex leaves or long narrow leaves will provide more structure compared with broad-leaved plants (Table 13).

Interspersion of vegetation types, mud flats, and open water also increases invertebrate abundance and diversity because invertebrate taxa response different to environmental conditions and plant structure (Voigts 1976, Hornung and Foote 2006, De Szalay and Resh 2008). Complex living and dead plant communities can be achieved by creating conditions for a diversity of plant species (see previous section). Management strategies that support abundant and diverse aquatic invertebrate communities, and associated management actions and wetland characteristics are summarized in Table 14.

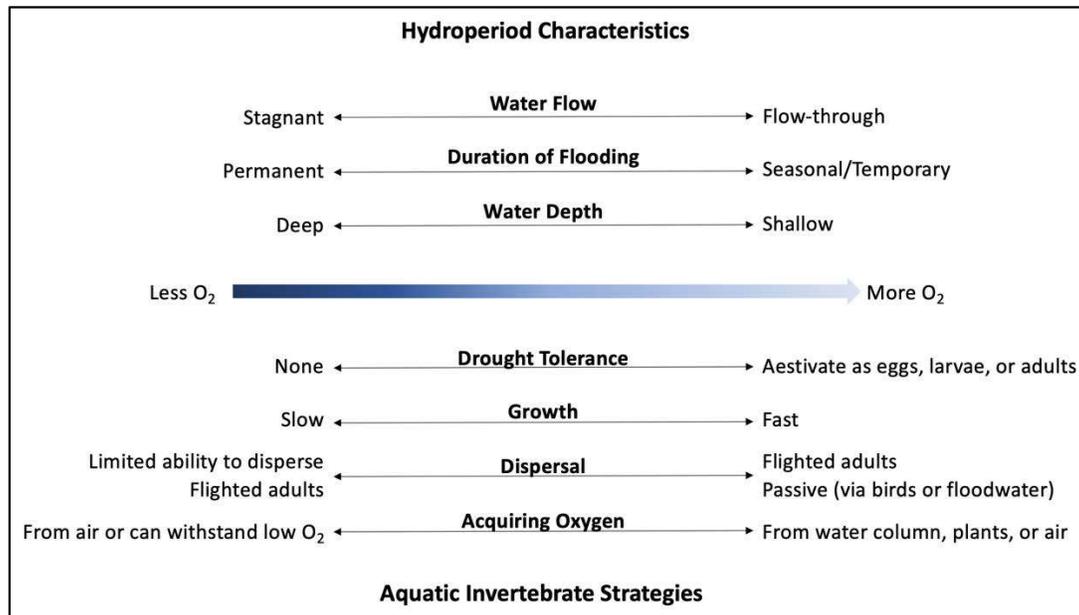


Figure 4. Aquatic macro-invertebrate strategies in wetlands with different hydroperiod condition.

Table 13. General relationship between plant structure and aquatic invertebrate abundance.

Aquatic Invertebrate Abundance	Plant Structure	Description	Examples
High ↓ Low	Complex leaf	Whorled, dense, finely dissected, or strongly branched leaves	<i>Ruppia, Stuckenia</i>
	Floating leaf	Floating leaves, not rooted to a substrate, roots suspended in water	<i>Lemna</i>
	Long, narrow leaf	Long, thin leaves and stems with little or no branching	<i>Fimbristylis, Cyperus</i>
	Short, broad leaf	Short oval or round leaves	<i>Bacopa, Ludwigia</i>
	Robust, long broad leaf	Robust structure and/or long broad leaves and stems with little or no branching	<i>Nymphaea, Typha</i>
Low	Shrub or tree	Shrubs or trees with woody stems and/or trunks	<i>Hibiscus</i>

Table 14. Management strategies, associated management actions, and wetland characteristics that support abundant and diverse aquatic invertebrates.

Management Strategies	Management Actions	Wetland Characteristics
Complex Vegetation Structure	<ul style="list-style-type: none"> • Reduce or eliminate aggressive invasive vegetation that form monocultures and typically has low structure value (e.g., cattail, California bulrush). • Mow < ½ of beneficial vegetation prior to re-flooding. • <i>See actions for diverse vegetation</i> 	<ul style="list-style-type: none"> • Diversity of native and beneficial plants, including herbaceous monocots and dicots and shrubs. • Plant material in different stages of decomposition as food resource for invertebrates.
Diverse Vegetation	<ul style="list-style-type: none"> • Seasonal or temporary flooding regime for emergent vegetation. • Semi-permanent flooding for submerged aquatic vegetation. • Tidally influenced emergent and submerged aquatic vegetation. 	<ul style="list-style-type: none"> • Multiple soil types the support different vegetation. • Microtopography that results in germination of different species during drawdown conditions. • Variable hydroperiod characteristics that create dynamic patterns of diverse microhabitats.
Interspersion of Habitat Types	<ul style="list-style-type: none"> • Restore or manage multiple wetland basins or management units with different habitat types. • Mow openings in existing vegetation before re-flooding occurs. 	<ul style="list-style-type: none"> • Diverse vegetation with diverse structure. • Plant material in different stages of decomposition. • Interspersion of standing emergent vegetation, submerged aquatic vegetation, and/or open water in mowed areas.
Enhance Nutrient Turnover	<ul style="list-style-type: none"> • Mow areas of vegetation prior to re-flooding to increase coarse particulate organic matter available as food for aquatic invertebrates and increase decomposition rates. 	<ul style="list-style-type: none"> • Increase coarse particulate organic matter available as food for aquatic invertebrates • Organic matter in different stages of decomposition. • Temporary and seasonal wetlands with dynamic wet/dry cycles
High O ₂ Availability	<ul style="list-style-type: none"> • Shallow flooding. • Increase flow-through conditions to prevent stagnant water. • Remove above ground biomass of invasive vegetation. 	<ul style="list-style-type: none"> • Shallow water depth. • Reduce large quantities of organic matter (e.g., decadent vegetation) that can deplete O₂ when wetland is re-flooded.
Allow Invertebrate Response to Changing Conditions	<ul style="list-style-type: none"> • Gradual drawdown of water and re-flooding in managed units 	<ul style="list-style-type: none"> • Gradual slope increases edge habitat that concentrates seeds and invertebrates. • Invertebrates prepare to aestivate during dry periods.

Make Resources Available

After beneficial plants and invertebrates colonize, grow, and, in the case of plants, produce seeds, management actions should then focus on making those resources available. Food and cover resources required by waterbirds vary depending on life cycle needs (Appendix C). Breeding is the most energetically demanding period for waterfowl and other waterbirds requiring protein, lipids, and minerals in high abundance to successfully reproduce. Breeding encompasses seven life-history events: courtship, pair formation, nest-searching, pre-laying, egg-laying, incubation, and brood rearing. Each requires nutrients in different proportions to successfully complete. If food resources (especially protein) are limited during breeding, waterbirds may delay breeding, fail to breed, or have reduced clutch size and/or egg mass (Krapu and Reinecke 1992). Although endemic waterbirds can breed year-round in Hawai‘i, each species has a peak breeding season. Very little is known about molt in Hawaiian waterbirds, but it can likely occur year-round as well.

The primary management strategy for ensuring food resources are available for waterbirds is manipulating water levels to provide optimum water depths for foraging (Table 15). Water depths <12 inches provide foraging conditions for all species of endemic waterbirds as well as most migratory waterfowl and shorebirds. Although water depths 12 to 24 inches can increase diversity of available wetland habitats, deeper water is more likely to hinder management of dynamic flooding; thus, encouraging growth of undesirable invasive plants adapted to anoxic conditions (e.g., cattail, bulrush, etc). In addition, aquatic habitats >12 inches are not limited in the main Hawaiian Islands because they are readily found as reservoirs, stock ponds, golf course ponds, and canals with vegetated edges.

Along with water depth, duration and timing of wetland inundation are other hydroperiod characteristics important to consider when making resources available (Table 16). Waterbirds are adept at exploiting spatially and temporally variable food resources, where they respond opportunistically to weather-related changes in food availability. Therefore, managed hydroperiods (depth, duration, and timing of flooding) should be variable from year to year to maintain long-term wetland function and prevent a monoculture of species adapted to static conditions. Wetland basins without active management are subject to natural seasonal flooding conditions based on groundwater, surface water, and precipitation inputs. Water flow from groundwater discharge or surface water sources should be managed to prevent stagnant, anoxic conditions and reduce the probability of a botulism outbreak.

Table 15. Water depths used by endemic waterbirds and migratory waterfowl and shorebirds for foraging (shaded) and nesting (--N--). U=upland; M=mudflat.

Species	Water Depth (inches)														13-24	25-36	37-48+
	U	M	1	2	3	4	5	6	7	8	9	10	11	12			
Koloa maoli	N																
Aeo		N															
Alae keokeo																	
Alae ula																	
Northern shoveler																	
Northern pintail																	
Gadwall																	
American widgeon																	
Canvasback																	
Ring-necked duck																	
Lesser scaup																	
Bufflehead																	
Pacific golden plover																	
Ruddy turnstone																	
Wandering tattler																	
Sanderling																	
Bristle-thighed curlew																	

Table 16. Management strategies that maximize resources available for endangered waterbirds and promote long-term wetland function.

Management Strategy	Management Actions
Shallow water	<ul style="list-style-type: none"> • Target water levels <12 inches to provide foraging habitat for endemic waterbirds. • Target water levels 12-24 inches to provide additional habitats only where it does not compromise long-term management of dynamic seasonal flooding. • Install low-water crossings to allow high water from heavy rains or floods to spread out across landscape. • DO NOT excavate deep, steep-sided basins. • Incorporate gradual slopes and broad contours into restoration designs.
Seasonal flooding	<ul style="list-style-type: none"> • Monitor ground and surface water inputs to determine elevation of restored wetland basin that maximizes seasonal flooding given naturally occurring variation in ground and surface water inputs. • For actively managed basins, install water control structures at appropriate elevations to ensure all surface water can be effectively removed. • Flood wetland basins for only part of the year.
Variable duration of flooding	<ul style="list-style-type: none"> • Mimic variability in wet and dry season conditions while providing predictable resources for waterbirds. • Vary duration of flooding among years from 2 to 8 months. • Rotate flooding among basins with water management capabilities. • Restore wetland basins with variable hydroperiods
Variable timing of flooding	<ul style="list-style-type: none"> • Initiate flood-up on different dates during the year. • Incorporate early, average, and late flood-up dates into management plans and allow for flexibility given changing weather condition. • Initiate drawdown on different dates during the year. • Incorporate early, average, and late drawdown dates into management plans and allow for flexibility given changing weather condition (e.g., do not try to have a drawdown during a 50-year rainfall event). • These conditions occur naturally in areas where hydroperiod is driven by rain or overbank flooding.
Prevent stagnant water	<ul style="list-style-type: none"> • Protect groundwater springs and areas of groundwater discharge. • Remove barriers to surface water flow. • Create flow-through conditions across a wetland basin.
Provide resources for different species and life-history events that occur year-round.	<ul style="list-style-type: none"> • Manage wetland basins in different successional stages, water depths, timing and duration of flooding. • Coordinate among federal, state, and privately managed wetland areas within watersheds, ahupuaa, moku, and island-wide to provide adequate resources across multiple spatial scales.

Control Invasive Plants

Similar to establishing native plants, controlling invasive plant species requires an understanding of life-history strategies. The most effective control strategies target one or more life-history stages that reduces the viability of the invasive species. Wetlands dominated by invasive species have crossed ecological thresholds where intensive management is required to restore and manage the abiotic processes and structures that maintain wetland function. Intensive management enables a site to cross back to the dynamic reference condition where native and other beneficial species outcompete invasive species. This can be achieved by 1) selecting an area that can be effectively treated (and re-treated) given available staff, volunteers, and funding; 2) implementing management actions that target above and below-ground biomass; 3) managing for or restoring hydrological disturbance dynamics; 4) monitoring for re-growth; 5) re-treating the area, as needed; and 6) creating conditions for germination and growth of native and other beneficial species that can eventually out-compete the invasive specie(s).

Emergent angiosperms account for most of the invasive species in Hawaii’s wetlands (Erickson and Puttock 2006) and are the focus of this section. Management of these invasive plants should consider growth points (types of meristematic tissue), growth form (annual or perennial), above and below-ground biomass, and seed structure (monocot or dicot) because resource allocation (e.g., energy, nutrients) and growth strategy vary among different vegetation types (Table 17).

Table 17. Characteristics of emergent wetland monocot and dicot species.

Characteristic	Emergent Monocots		Emergent Dicots	
	Annual	Perennial	Annual	Perennial
Meristematic tissue (growth point)	Apical	Apical	Apical	Apical
Vegetative spread	+	+++++	+	+++++
Below-ground biomass	+	+++++	+	+++++
Seed Production	+++++	Varies	+++++	Varies
Dominant energy allocation after growth	Seeds	Roots/rhizomes/ re-sprouting	Seeds	Roots/rhizomes/ re-sprouting
Anoxia tolerance	Low	High	Low	Varies

Because most of the highly invasive plants in Hawaii’s wetlands are perennial, management strategies must target both above (Table 18) and below-ground biomass (Table 19). Removing only above-ground biomass is not sufficient for control because nutrients and energy stored in the roots and rhizomes enables fast and prolific re-growth.

Above-ground biomass of monocots and dicots have different growth points or meristems. Meristems are comprised of cells capable of continued cell division responsible for plant growth. Thus, management actions implemented will vary based on the presence of invasive monocots or dicots. Basal meristems are found only in monocots at the base of nodes and leaf blades, allowing rapid regrowth after leaves are damaged (e.g., from herbivory or mowing). Apical meristems occur in both monocots and dicots at the tips of stems and roots. Hence, mowing will effectively remove most apical growth points in herbaceous dicots but will not removal basal growth points of monocots. Although the invasive dicots lack basal meristems, many species

exhibit prolific re-sprouting by root apical meristems from the root crown (e.g., pickleweed), which will limit effectiveness of mowing.

Annual and perennial species have different resource allocation strategies related to meristem growth. At some point, as determined by environmental conditions and genetics, the shoot apical meristem of dicots and monocots transforms to produce flowers or flowering shoots. In annual plants this process is irreversible, which, in simplified terms, results in resource allocation first to growth, followed by all meristems becoming reproductive. In contrast, most perennial plants utilize varying strategies of resource allocation to repeatedly go from vegetative to sexual reproductive development throughout the year (Albani and Coupland 2010). Perennial plants also allocate more resources to below-ground biomass than annual plants. Thus, for perennial species, managers need to implement control techniques that target: 1) vegetative and sexual reproduction occurring year-round after plants are established; 2) apical and basal (in monocots) meristems; and 3) below-ground biomass (Table 18 and Table 19).

Invasive species can re-establish from very low densities if control efforts are not maintained (e.g., Reinhardt Adams and Galatowitsch 2008). The likelihood of invasion, growth, and re-invasion of invasive species in wetlands increases in areas with hydrologic modifications (Cronk and Fennessy 2001). Managing for or restoring historical disturbance dynamics reduces competitiveness of many invasive species and can limit growth and re-invasion following control efforts.

Table 18. Management strategies and actions to control above-ground biomass in invasive plants.

Management Strategy	Management Action	Considerations	Examples
Remove basal meristems (monocots)	<ul style="list-style-type: none"> • Mulch/Grind • Mow multiple times 	<ul style="list-style-type: none"> • More effective than mowing because it destroys the root crown (see Table 19) • Doesn't remove basal meristem near base of plant, so re-growth occurs. 	<ul style="list-style-type: none"> • California grass and guinea grass at Hanalei NWR, Kaua'i • Initial strategy to open-up wetlands at Hanalei & Hulē'ia NWRs, Kaua'i
Remove shoot apical meristems (dicots & monocots)	<ul style="list-style-type: none"> • Mow • Prescribed burn 	<ul style="list-style-type: none"> • More effective on dicots than monocots. • Large nutrient flux into wetland following burn which can increase biomass the following year. 	<ul style="list-style-type: none"> • California grass at Hanalei NWR, Kaua'i • California bulrush at James Campbell NWR, O'ahu
Prevent seed production	<ul style="list-style-type: none"> • Mechanical treatments (mow, disk) 	<ul style="list-style-type: none"> • Most effective when used in combination with other strategies. • Disking can stimulate re-growth from root fragments in some species. 	

Table 19. Management strategies and actions to control below-ground biomass in invasive plants.

Management Strategy	Management Action	Considerations	Examples
Remove root apical meristems	<ul style="list-style-type: none"> • Hand pull • Excavate • Disk multiple times 	<ul style="list-style-type: none"> • Labor intensive; more efficient with large volunteer groups and repeat applications. • Costly; requires time to dewater if material is wet; large quantity of material; requires repeat removal to reduce re-growth • Regrowth often occurs from root fragments; disking can stimulate growth in some species. 	<ul style="list-style-type: none"> • Marsh fleabane at Kawai‘ele Waterbird Sanctuary, Kaua‘i and Waie‘e Coastal Wetland Refuge, Maui • Short-term success (<3 years) before re-growth of California bulrush at Punamanō, James Campbell NWR, O‘ahu
Kill root apical meristems	<ul style="list-style-type: none"> • Directed heat/spot burn • Herbicide • Flood • Directed heat & flood or roller chop & flood • Other multiple management actions 	<ul style="list-style-type: none"> • Effective on seedlings and new re-sprouts of woody growth; heat is usually sufficient to damage root and prevent re-growth. • Application rates & timing species specific; may have non-target effects on invertebrate forage. • Effective on species with low anoxia tolerance. • Depth and duration of flooding must be sufficient to limit oxygen. • Multiple management actions likely to increase control 	<ul style="list-style-type: none"> • Pickleweed at Kaloko-Honokōhau NHP, Hawai‘i • California grass at Hanalei NWR, Kaua‘i; California bulrush at James Campbell NWR, O‘ahu • Natural flooding killed marsh fleabane and haole koa at Manā Plain Wetland Restoration, Kaua‘i • Experimental success in lab with California grass (Chaudhari et al. 2012) • California grass at Hanalei NWR, Kaua‘i
Reduce rhizome energy reserves	<ul style="list-style-type: none"> • Mow multiple times • Mow before seeds mature 	<ul style="list-style-type: none"> • Monocots will regrow after mowing, depleting energy and nutrient reserves. 	
Destroy root crown	<ul style="list-style-type: none"> • Mulch/Grind 	<ul style="list-style-type: none"> • Effective at limiting re-growth of grasses 	<ul style="list-style-type: none"> • California grass and Guinea grass at Hanalei NWR, Kaua‘i

Control Non-native Vertebrates

Introduced vertebrates kill adult and young waterbirds, predate nests, and degrade wetland habitats thereby negatively impacting recovery of endemic waterbirds, re-establishment of migratory bird pathways, and wetland habitat condition. Non-native predators, particularly mammals, reduce reproductive success of endemic waterbirds (Underwood et al. 2014, Christensen et al. 2021). However, the relative impacts of overall and species-specific predation, habitat loss, wetland condition, and other threats on population-level dynamics of endemic waterbirds are unknown. Relatively large populations of endemic Hawaiian waterbirds that maintained flight capabilities persisted through Polynesian and early European introductions of non-native mammals. Habitat loss, fragmentation, and other anthropogenic modifications likely had biggest direct impact on endemic waterbird populations. These factors are also known to increase predation rates on waterbirds. Thus, non-native vertebrate control is an integral aspect of managing wetland habitats and increasing reproductive success of waterbirds in Hawai‘i. Non-native vertebrate control efforts are summarized for Federal and State management areas (Table 20). Resources on species-specific control methods are available in the digital Hawai‘i Wetlands Library maintained by the Pacific Birds Habitat Joint Venture (https://pacificbirds.org/hawaii_wetlands/predators/).

Table 20. Control efforts for non-native vertebrates at Federal and State management areas on the main Hawaiian Islands.

Management Area	Exclusion Fence		Control/Removal Efforts							
	Predator Proof	Hog or Deer	Ungulates	Feral cat	Mongoose	Rodent	Cattle egret	Barn owl	Bull frog	Non-native fish
Kaua‘i										
Hanalei National Wildlife Refuge		X		X				X		
Hulē‘ia National Wildlife Refuge		X								
Kawai‘ele, Mānā Plains Forest Reserve			X	X			X	X		
O‘ahu										
Ki‘i Unit, James Campbell NWR				X	X	X				X
Punamanō Unit, James Campbell NWR										
Honouliuli Unit, Pearl Harbor NWR	X									
Waiawa Unit, Pearl Harbor NWR		X								
Pouhala Marsh Wildlife Sanctuary										
Kawainui Marsh Wildlife Sanctuary		X								
Hāmākua Marsh Wildlife Sanctuary										
Maui										
Keālia National Wildlife Refuge		X								
Kanahā Pond Wildlife Sanctuary		X					X			
Moloka‘i										
Kakahai‘a National Wildlife Refuge										
Hawai‘i										
Kaloko Fishpond, KHNHP										
‘Aimakapā Fishpond, KHNHP										

Reduce Probability of Avian Botulism

Life-history of Clostridium botulinum

Avian botulism is caused by the bacterium *Clostridium botulinum*, which produces seven different types of botulinum neurotoxins when infected by a virus (bacteriophage). The type C botulinum neurotoxin affects more than 100 species of waterbirds, including endemic waterbirds in Hawai'i. *C. botulinum* are commonly found in wetland sediments as part of a zone of high biological activity at the sediment-water interface where large concentrations of bacteria and other microorganisms are major components of the food web. Bacteria and other microorganisms break down organic matter and, in turn, provide forage for protozoa and benthic macroinvertebrates.

For a botulism outbreak to negatively affect waterbird health, the following processes need to occur: germination of bacterial spores; infection by a virus that carries the gene to encode for the neurotoxin; vegetative growth and replication (cell division) on a high protein substrate; autolysis (cell destruction) which releases the neurotoxin; and a pathway for neurotoxin transfer to birds (Rocke and Bollinger 2007). Increased bacterial growth and production of botulinum neurotoxins are typically produced under low oxygen conditions on a high protein substrate (Mitchell and Rosendahl 1987, Barres and Kadlec 2000). Decaying carcasses are optimal growth medium for *C. botulinum*. Other factors influencing bacterial growth and toxin production are temperature, pH, redox potential, and water vapor pressure (Rocke and Bollinger 2007). Interactions among abiotic factors and competition among benthic bacteria also influence if a botulism outbreak occurs. *C. botulinum* persists under extreme environmental conditions by producing dormant spores and can remain viable for years until conditions for bacterial growth and toxin production are suitable. Once ingested by birds, the toxin binds to nerve endings, where it interferes with muscle movement causing eventual paralysis.

Dabbling ducks, such as koloa, which sift through sediments to feed, and filter feeders, including northern shovelers, are especially likely to encounter and consume dead or live invertebrates that contain sufficient levels of toxin to cause botulism. Once large enough quantities of toxin are ingested by birds to cause death, the 'carcass-maggot cycle' creates a positive feedback loop. Decomposing carcasses in wetlands provide an anaerobic environment with a rich protein source and may also generate high internal temperatures, further aiding growth of *C. botulinum* and toxin development. Fly larvae (maggots) which forage on decaying carcasses effectively concentrate the toxin (Rocke and Bollinger 2007). Waterbirds can easily ingest invertebrate larvae that fall off carcasses and continue the cycle of toxin infection.

Management Strategies

Outbreaks of avian botulism are unpredictable due to the complex factors regulating bacterial growth, presence of the virus, and transfer to birds. Except for carcass removal, management recommendations made prior to the mid 1970s have not been effective in reducing botulism (Reed and Rocke 1992). Due to a lack of understanding of general wetland ecology and conditions that promoted outbreaks, some recommendations, such as stabilizing water levels and creating steep banks, were detrimental and further contributed to compromised wetland function (LHF personal observation).

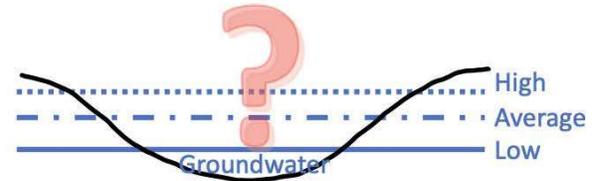
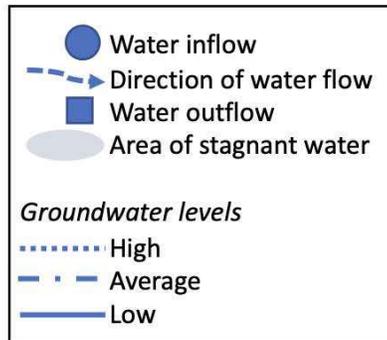
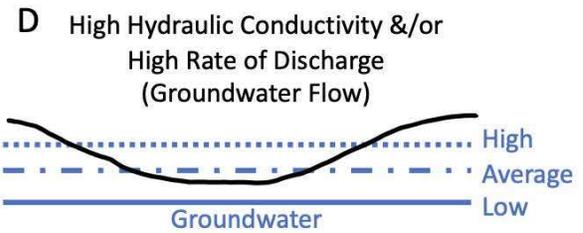
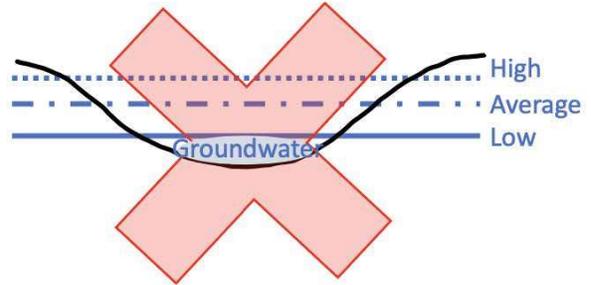
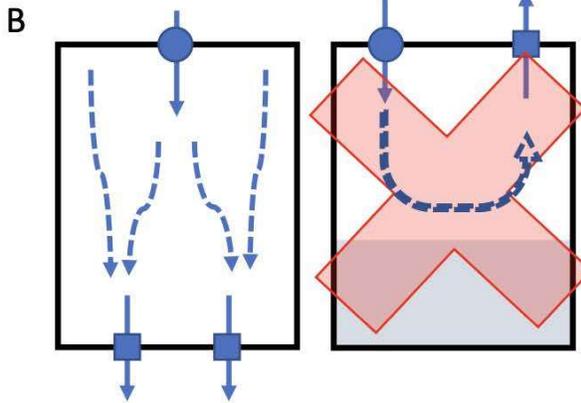
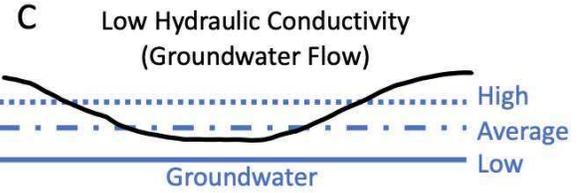
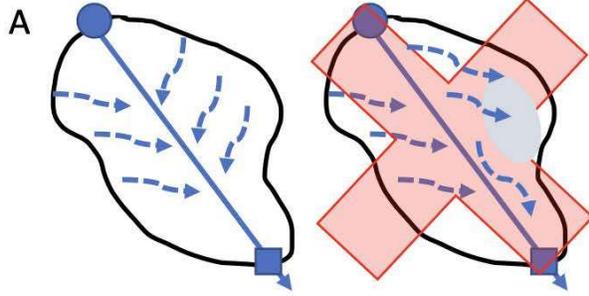
The most important management strategy to reduce the probability of an avian botulism outbreak is to maintain, create, and/or restore water flow through conditions to reduce anaerobic conditions associated with stagnant water (Figure 5). Design and placement of water inflows and outflows should allow water circulation throughout the entire unit. For wetlands without active water management, managers should consider the relationship of basin topography to groundwater levels, tidal inputs, and/or stream flows.

Table 21. Management strategies and actions that reduce the probability of occurrence of avian botulism.

Management Strategy	Management Action
Reduce stagnant water and anaerobic conditions	<ul style="list-style-type: none"> • Increase water in-flows and out-flows. • Grade wetland basin to remove depressions that hold water following managed and natural drawdowns.
Limit organic matter in newly flooded habitats	<ul style="list-style-type: none"> • Mow < ½ of beneficial vegetation unit prior to flooding. • Remove or reduce above ground biomass of invasive vegetation prior to flooding.
Limit protein substrates	<ul style="list-style-type: none"> • Remove and rehabilitate sick birds. • Remove dead and decaying carcasses of fish and birds.

CONNECTED WETLAND OR MANAGED WETLAND UNIT

DEPRESSIONAL WETLAND



***NOTE:** The bottom design is hypothesized based on observations of depressional wetlands on coastal plains of Kaua'i and O'ahu. More data are needed to validate this assumption. Permanently flooded groundwater fed basins may not be desirable for other reasons.

Figure 5. Wetland designs that increase surface water flow (A and B) and seasonal water fluctuations in depressional basins (C and D) to reduce stagnant water and anoxic conditions that can contribute to botulism outbreaks.

CHAPTER 7: EVALUATE, ADAPT, AND SHARE

Management decisions are often made with incomplete information due to lack of data and/or incomplete understanding of the biotic and abiotic components of wetland habitats. Multiple types of information are used to inform wetland management, including inventories of biotic and abiotic conditions, implementation tracking (what was done, where, and when), habitat and wildlife responses to management actions, and effectiveness of management actions. The latter require monitoring to make observations, collect data, and analyze key attributes. Dratch et al. (2017) summarizes the USFWS framework for inventory and monitoring designed to link to management issues on a refuge or the broader landscape (USFWS policy 701 FW2).

Inevitably management actions may result in unexpected responses of plants and/or wildlife due to the variability inherent in natural systems. When that happens, we should have the necessary information to determine why those responses occurred or to at least develop plausible hypotheses. We also need to adapt management actions. How do we embrace unexpected but beneficial outcomes? And vice versa – how do we adapt management strategies to prevent future undesirable outcomes?

Allocation of resources to monitoring is challenging due to limited staff and funding. Efforts to prioritize information needs can reduce the competing needs of on-the-ground actions and monitoring. Salzar and Salafsky (2006) illustrate a decision tree where resources are allocated among on-the-ground-actions and different types of monitoring for conservation areas with substantial threats. Nichols and Williams (2006) suggest that the effectiveness of conservation actions can be increased by focusing monitoring on crucial information needs, including observational monitoring based on management-oriented hypotheses.

Reynolds et al. (2016) state that successful monitoring programs have explicit objectives and a conceptual ecological model that includes ecological processes, drivers, stressors, and system responses. Monitoring based on conceptual ecological models is more likely to identify key processes and indicators and therefore contribute significantly to management (Gross 2003, Ogden et al. 2005).

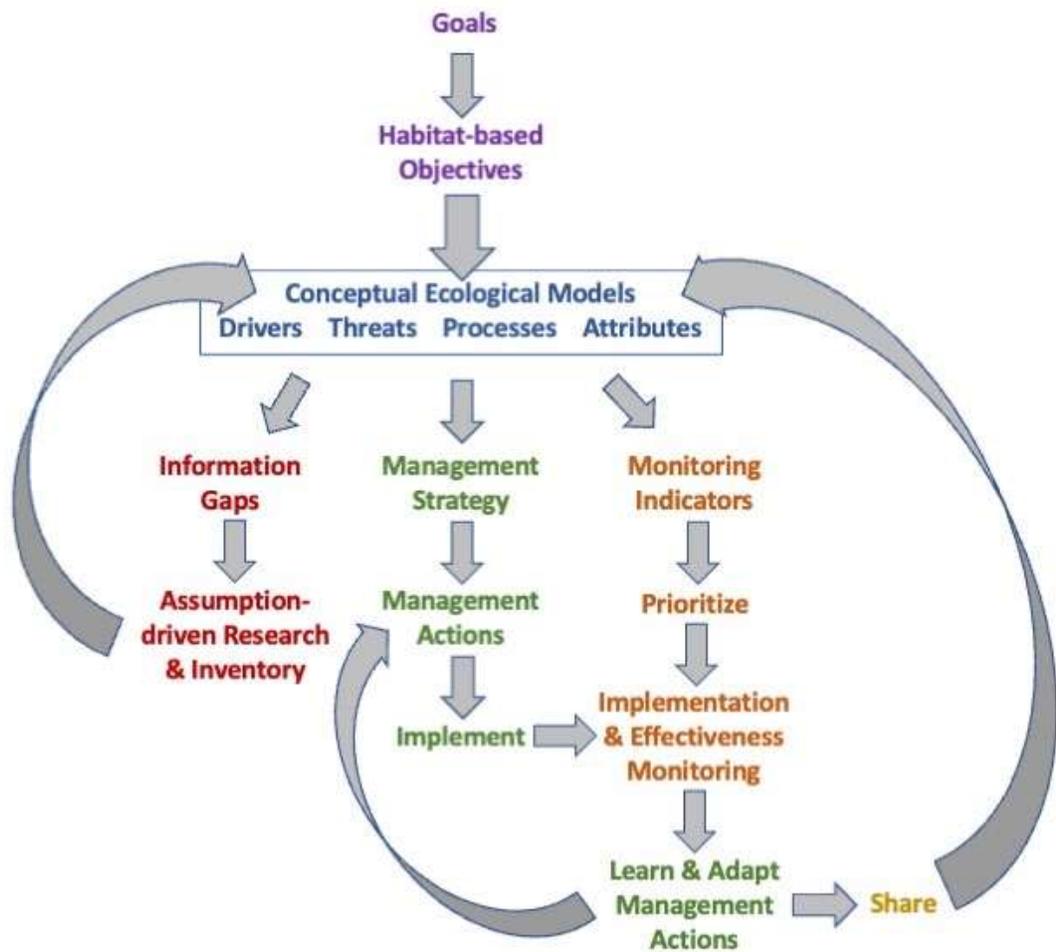


Figure 6. Strategy for developing, monitoring, and increasing efficacy of management actions in wetland habitats. Modified from Gross (2003), Ogden et al. (2005), NEAT (2006), and CMP 2020.

CHAPTER 8: INTEGRATING MANAGEMENT STRATEGIES

Moist-soil Management in a Highly Modified Floodplain

Rational and Infrastructure Improvements

Moist-soil management techniques, originally developed on the continental U.S., were adapted to Hawai‘i-specific conditions and refined based on observations of plant and waterbird responses at Hanalei National Wildlife Refuge. Moist-soil management techniques are beneficial in highly modified systems where natural processes are unable to be restored (Fredrickson and Taylor 1982). In addition, these techniques can increase the availability, abundance, and nutritional quality of plants and aquatic invertebrates consumed by waterbirds (Fredrickson 1996, Brasher et al. 2007, Kross et al. 2008, Farley et al. 2022). This case history encompasses more than 15 years of adaptively managing wetland habitats to provide foraging, pre-breeding, nesting, brood-rearing, and loafing/roosting habitats for endangered waterbirds at Hanalei National Wildlife Refuge.

Wetland units at Hanalei National Wildlife Refuge not in active taro cultivation were dominated by invasive grasses when the refuge was established. Initial efforts to provide habitat for endangered waterbirds in these areas entailed mowing and flooding the invasive grasses (USFWS 2021). As a result, wetlands were characterized by uniform structure, limited seed production, and low species diversity. In addition, California grass, *paspalum*, and other highly invasive species grew quickly forming dense mats of vegetation that make the units unsuitable habitat for waterbirds.

Existing floodplain modifications, including water delivery infrastructure and impoundments, made wetland units at Hanalei National Wildlife Refuge well-suited to begin implementing moist-soil management techniques in the Hawaiian Islands. Beginning around 2004, moist-soil management techniques were applied wetland units to mimic natural dynamics of seasonally flooded wetlands by actively manipulating soils, hydrologic conditions, and vegetation (Fredrickson and Taylor 1982). The goal of using moist-soil management techniques was to reduce invasive species and create conditions for the germination, growth, and seed production of beneficial plants. Initially, it was challenging to accomplish this goal because 1) equipment and staffing resources were not adequate to manage all of the wetland areas, 2) landscape position and soils were not considered when impoundments were constructed, and 3) limited information or observations were available on the life history of native and other beneficial plants.

Two of the 3 limitations were addressed over a 5 to 10-year period: equipment was upgraded as funding resources allowed and soil sampling identified abiotic factors that limited efficacy of water management. Soil sampling identified 1) buried beach ridges below floodplain deposits and 2) gradually increasing soil texture toward the Hanalei River (University of Missouri, unpublished data; Figure 7). Buried beach ridges are consistent variable sea levels throughout the Holocene; coarser textured soils are often found closer to rivers as a result of more frequent flooding and faster water velocities compared to areas of the floodplain farther from the river. Thus, wetland units were re-designed to reduce water loss through infiltration to buried beach ridges and/or coarser textured soils (Figure 8).

Staffing for on-the-ground habitat management was limited to one equipment operator for Hulē‘ia and Hanalei NWRs from 2004 until 2018. Two additional habitat management staff were hired during 2018. Although duties also increased at that time, additional staff enabled more wetland units to be managed for endangered waterbirds (e.g., Kuna units). Information on the life history of beneficial wetlands plants in Hawai‘i is still limited, but observations of vegetation response and waterbird use at managed wetland units linked endangered waterbird life-history requirements to vegetation conditions.

Management strategies that focused on removing above and below-ground biomass of invasive plants were implemented first. The area treated was initially limited to the ABC units to ensure staff had time to follow-up as needed to ensure that re-growth of invasive vegetation was treated before plants spread and set seed. The number and duration of management actions varied depending on specific unit conditions (e.g., soil type), observed vegetation response, and weather (e.g., rainfall, flooding, etc.). The intensity and frequency of management actions were highest during initial efforts to remove invasive vegetation (Figure 9). Once cover of invasive vegetation was substantially reduced such that spot spraying effectively kept cover at less than about 10%, an ecological threshold was crossed where native and other beneficial plants outcompeted aggressive invasive species (Figure 9). With less management efforts needed to control invasive plants, options for management actions that target waterbird life history requirements increase.

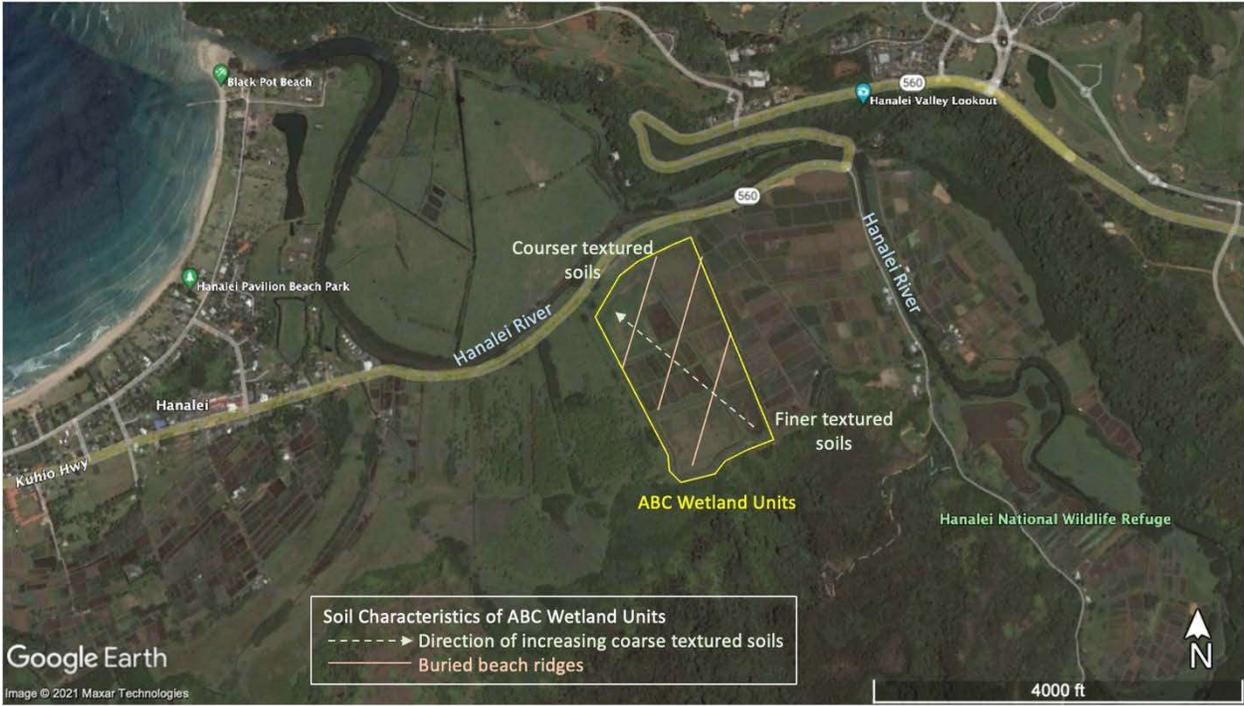


Figure 7. Soil characteristics of ABC managed wetland units Hanalei National Wildlife Refuge, Kaua‘i, in relation to the current Hanalei River and beach. Base image from Google Earth, © 2021 Maxar Technologies, dated April 2003. Soil data collected by the University of Missouri-Columbia.



Figure 8. ABC managed wetland units at Hanalei National Wildlife Refuge, Kaua‘i, during 2003 (left) compared to subsequent years (2009, 2013, and 2017) after impoundment boundaries were re-designed to reduce water loss through infiltration to buried beach ridges and/or courser textured soils. Images from Google Earth © 2021 Maxar Technologies.



Moist-soil Management Techniques at Hanalei NWR

Drawdown.— One of the most important steps in moist-soil management is to slowly drawdown or remove water from a wetland unit. The benefits of a drawdown are multi-faceted, including the following:

- Mimic natural seasonal drying that followed the wet or “” season.
- Reduce anoxic and hypoxic conditions.
- Increase oxygen in soil pore space, which increases oxidation.
- Increase nutrient turnover rates.
- Create conditions for germination of a wide variety of native and other beneficial plant species.
- Increase plant competition, which reduces monocultures of flood-tolerant species.
- Concentrate aquatic invertebrates.
- Allow access to the area to manipulate vegetation and soils.
- Provide suitable substrate for germination.

Soil Manipulations that Mimic Ecological Disturbance. —

Discing wetland soils mimics soil disturbance that occurs after a large flood or on-shore storm surge. It also scarifies the soil, breaks up root systems, incorporates organic matter into wetland soils, and brings up seeds from deep burial to within 1 inch of soil surface where germination takes place. The goal of discing as a moist-soil management tool is to re-set a wetland unit to an early succession phase dominated by seed-producing plants. Discing can also be beneficial to control invasive species that have colonized a wetland unit (see Table 18 and Table 19).

Large discs needed to break up well-established invasive vegetation create large clumps of soil, making the soil surface uneven. Finish discs and tillers create a finer, smoother soil surface that mimics sedimentation of receding flood waters after high velocity scouring. Wet tilling is a common practice in taro cultivation and can be done as part of moist-soil management. Prior to tilling, flood the unit with water 3 to 6 inches deep. Wet tilling accomplishes a finer break up of soil and root systems while saturating the soil compared to discing. The resulting fine, smooth soil surface germination of native flatsedges, which outcompete California grass and aggressive species of *Paspalum*.

A mulcher or masticator is another tool used to scarify the soil. A mulcher is very effective at grinding meristematic tissue in the root crown of invasive plants, and therefore is effective at controlling invasive plants.



Increase Soil Moisture.— Once a suitable substrate for germination is present, rainfall or a slow drawdown of shallow water provides soil moisture to stimulate growth of native wetland plants.

Germination.— Natural germination of wetland plants in Hawai‘i has been observed during the spring when water levels recede following the wet season and during the fall when precipitation saturates exposed wetland soils (Chadd Smith, personal communication). Due to the year-round growing season, germination conditions can be managed for any time of the year if a unit has water management capabilities. However, a managed drawdown during the wet season may be impacted by flooding or rainfall that prevents removal of all surface water from a wetland unit or basin. A gradual drawdown saturates the soil surface and exposes wetland soils to sunlight. Surface soil characteristics (e.g., lumpy vs smooth), moisture, temperature and other abiotic factors determine which species germinate from the seed bank (see Figure 2).



The exact vegetation response will depend on timing of the management action, weather, and associated abiotic conditions. The unit should be observed daily once germination begins to identify the species that are germinating. Nutsedges, fimbry, millet are beneficial species that germinate at Hanalei NWR. Following a discing/tilling disturbance, these species will be able outcompete the highly invasive monocots. If California grass or other aggressive invasive species germinate, it is easier to control them when they are young compared to mature plants with well-established root systems and seeds. Undesirable species may also grow from vegetation fragments. Those should be spot sprayed, mowed, and/or grubbed depending on amount of regrowth

Growth and Seed Production.— Following germination, growth of native and other beneficial plants takes 1 to 3 months before seed production starts to occur. Shallow reflooding from rainfall or managed water inputs can increase growth of some species, including *INSERT FLATSEGE NAMES and millet. Other food-producing plant species such as ‘aki‘aki are less tolerant to flooding while growing. When moist-soil management techniques are initiated on a wetland unit, it is likely that California grass and other invasive species will regrow from vegetative fragments. These areas should be spot sprayed with approved herbicides. This reduces their chance of spreading and forming monocultures while giving a competitive advantage to native plants.

Plant Breakdown for Aquatic Invertebrates.— Dense areas of plant growth can be mowed to physically break down stems and leaves, which in turn provides coarse particulate organic for aquatic invertebrates. This habitat mosaic maximizes invertebrate response because mowed

wetlands have higher abundance and biomass of invertebrates, whereas non-mowed areas are colonized by a higher diversity of invertebrates (De Szalay and Resh 2000). A high abundance and diversity of aquatic invertebrates increases the range of proteins and essential amino acids available to waterbirds. Mowing also increases the interspersion of “open water” and emergent vegetation within a wetland unit and creates openings for waterbirds to land and forage when the wetland is flooded.



Shallow Flooding to Make Resources Available.— Once food and cover resources are produced, water levels between 3 and 12 inches will provide resources for 4 species of endangered waterbirds. Aquatic invertebrates, including water boatmen and diptera are observed within 3 days of flooding (Chadd Smith, USFWS, personal communication).

Get the Birds to Work for You!— Wetlands with abundant plant and invertebrate food resources will attract large numbers of endemic and, during the winter, migrant waterfowl. Movement and foraging by waterbirds in flooded wetlands further breaks up and knocks down emergent vegetation creating more openings and increasing decomposition and nutrients available for aquatic invertebrates. This breakdown will reduce the management effort required in subsequent years. For example, mowing, grinding, and/or discing may not be needed a frequently when natural openings occur and provide suitable germinate substrate during subsequent drawdowns.



Linking Management to Waterbird Life Histories

This section summarizes information about habitat condition, invertebrate response, and waterbirds based on observations in managed wetlands at Hanalei and Hulēia NWRs.

Early Succession Wetlands for Pre-breeding

Waterbirds have high nutrient demands prior to breeding. Food resources available to pre-breeding and breeding waterfowl (and likely other waterbirds) influence reproductive success in several ways. Limited food resources can reduce breeding attempts when birds are not in good condition (Krapu and Reinecke 1992). In addition, body condition is often correlated with increased survival. Visual isolation from conspecifics and other breeding pairs is another habitat characteristic that influences pair formation and signal behaviors.

Habitat Characteristics for Pre-breeding Waterbirds

- Abundant protein and high energy food resources.
- Visual isolation from conspecifics for courtship and pair formation.

Recent, shallowly flooded (3 to 9 inches) wetlands with 50% emergent vegetation and 50% open water or submerged aquatic vegetation provide abundant aquatic invertebrates and seeds, visual isolation, open areas for stilt foraging. Benthic and water column aquatic invertebrates that colonize newly flooded habitats within 24 hours. Herbivores, detritivores, and gatherers are some of the earliest colonizers of newly flooded habitats (Wiggins et al. 1980, Mackay 1992, Bischof et al. 2013). Koloa, alae keokeo, alae ulu, and aeo all utilize shallowly flooded, early succession wetlands for foraging.



Mid-succession Wetlands for Nesting

Mid-succession wetland units with 50 to 70% emergent vegetation cover that are shallowly flooded for 2 to 3 months provide structure for nest sites of alae ula and ale keokeo. These wetlands also provide abundant invertebrates and seeds for adult birds during incubation breaks, including koloa, which nest in adjacent uplands or along the edge of managed wetland units. Temporal shifts in aquatic invertebrate populations likely parallel patterns found in other seasonal wetlands where grazers increase as periphyton develops and predators, scavengers, and shredders tend to increase as time since flooding increases (Wiggins et al. 1980, Mackay 1992, Bischof et al. 2013).



Mid succession wetlands are typically utilized by koloa, alae ula, and alae keokeo. To successfully lay and incubate eggs all waterbirds need high protein resources (e.g., Alisauskas and Ankney 1992, Colwell 2010). Clutch size, synthesis of egg protein, and occurrence of re-nesting may be reduced if protein is limited (see Krapu and Reinecke 1992). Incubation is an energetically demanding life-history stage for female waterbirds.

Late Succession Wetlands for Nesting and Brood-rearing

Brood rearing is another energetically demanding life history event, where dabbling ducks (and likely other waterbirds) have high protein requirements immediately after hatching for feather development. As hatchlings grow, diets shift to a more omnivorous or herbaceous diet where increased energy resources are required for body growth.

Late-succession wetland units have had >6 months of vegetative growth, resulting in high cover (50-70%) of emergent vegetation >2 feet tall. This continues to provide adequate structure for nesting, as well as foraging habitat for recently hatched broods. Tall emergent vegetation provides thermal cover, protection from inclement weather and escape cover from predators. Water depths from 6 to 12 inches provide a diversity of foraging habitat for all 4 species of endemic waterbirds, although high vegetative cover limits use by aeo to more open areas of the wetland unit. Aquatic invertebrate communities are diverse with taxa occupying a broad range of functional feeding groups.



Rotational Management to provide Year-round Resources

Wetland units are managed on a staggered rotational basis that matches wetland condition with life-history needs of endangered waterbirds (Figure 10). By staggering the phase or stage of wetland units, all successional phases are available year-round. This provides annually consistent habitats and resources will incorporating the necessary variability in wetland.

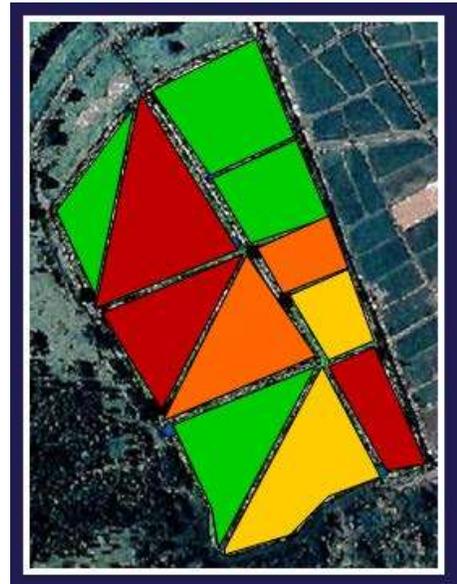


Figure 10. Example of rotational management in ABC units at Hanalei National Wildlife Refuge. Varying flood-up dates, water levels, and vegetation structure and annually provides resources for endangered waterbirds. From Chadd Smith, USFWS.

Managing Emergent and Submerged Aquatic Vegetation in a Created Wetland

Rational

Kawai‘ele Waterbird Sanctuary was created after sand was mined on the Mānā Plain during the 1980s. Flooded by brackish groundwater, aquatic habitats were historically dominated by wigeongrass (*Ruppia maritima*; Thomas Kaiakapu, DOFAW, personal communication). Wigeongrass is a submerged aquatic seagrass with worldwide distribution that can grow in estuarine, palustrine, and lacustrine wetlands ranging from fresh to hypersaline and temporary to permanently flooded water 0 to 12 feet deep (Kantrud 1991). It has physiological adaptations that enable plants to adjust to changing salinity (Murphy et al. 2003). Perennial and annual growth forms produce seeds (also referred to as drupelets) capable of surviving drought and year-round growth occurs in wetlands at subtropical and tropical latitudes. Although highly adaptable to varying abiotic conditions, wigeongrass is limited by high turbidity, wave action, and wind fetch.

Wigeongrass supports abundant and diverse aquatic invertebrate assemblages. Both vegetation and associated invertebrates are an important food source for waterfowl, coots and rails (Rallidae), and shorebirds (see review in Kantrud 1991). Although native fish use wigeongrass habitats extensively for cover and foraging on invertebrate prey, they seldom consume large amounts of wigeongrass itself. In contrast, introduced fish species substantially reduce and can eliminate entire stands of wigeongrass and other submerged aquatic vegetation by direct herbivory and increasing turbidity (Sidorkewicz et al. 1998, Peyton 2009).

Following the introduction of tilapia (*Oreochromis* spp.) at Kawai‘ele, wigeongrass stands were quickly eliminated resulting in open water with no submerged aquatic vegetation (Thomas Kaiakapu, DOFAW, personal communication). Although turbidity likely increased, bottom substrates were still visible in up to 6 feet of water. Therefore, direct consumption of wigeongrass by tilapia was hypothesized to be the factor that resulted in its complete removal from aquatic habitats at Kawai‘ele. This hypothesis was confirmed with field cage experiments during 2007. Wigeongrass only grew in cages where wigeongrass was transplanted and large tilapia were excluded and reached 100% aerial cover in 2 cages after four months (Peyton 2009). Tilapia were observed grazing on wigeongrass <24 hours after it was transplanted in cages with fish present. Muskgrass (*Chara* sp.), a plant-like green alga, was observed growing with wigeongrass in one cage.

The emergent wetland vegetation zone at Kawai‘ele was extremely narrow due to steep slopes between uplands and permanently flooded aquatic habitats following sand removal. The uplands were dominated by invasive shrubs, primarily marsh fleabane and koa haole, and invasive grasses. Wetland enhancement efforts at Kawai‘ele have the following goals:

- Restore native vegetation to 30 acres of aquatic, wetland, and upland habitats.
- Increase the area of seasonally-flooded wetland habitats (including mudflats) that support emergent vegetation.
- Eradicate tilapia and other non-native fish to restore wigeongrass and other submerged aquatic vegetation to aquatic habitats.

Increasing Emergent Wetland Habitats

Water levels were monitored for 3 years to estimate short-term temporal variability in water depths in existing aquatic habitats. This monitoring identified the elevation range of wetlands that would have temporary to seasonal flooding regimes. Heavy equipment was used to remove invasive vegetation on upland berms and re-contour existing habitats. Steep slopes greater than 3:1 (horizontal:vertical distance) were reduced to 5:1 and 10:1 where possible. This increased the transition zone between uplands and aquatic habitats. These gradual slopes now support emergent wetland vegetation. Water levels fluctuate based on precipitation (e.g., rain during kona storms) and evapotranspiration creating shallowly flooded habitats for foraging waterbirds and varying soil moisture conditions for germination of native plants.



Photo courtesy of Jason Vercelli, DOFAW.

For the next phases of sand removal, ArcGIS 3D Analyst was used to design shallowly flooded wetland basins with target elevations that create natural wetting and drying conditions to support seasonally flooded wetlands surrounded by upland habitats (Figure 11). Following creation of one wetland basin in Parcel 4, water levels fluctuate naturally creating shallowly flooded areas where ae‘o, ‘alae ‘ula, ‘alae ke‘oke‘o, and koloa regularly forage. Aquatic invertebrates were observed within a week of natural flooding and wigeongrass colonized the wetland within the first year.

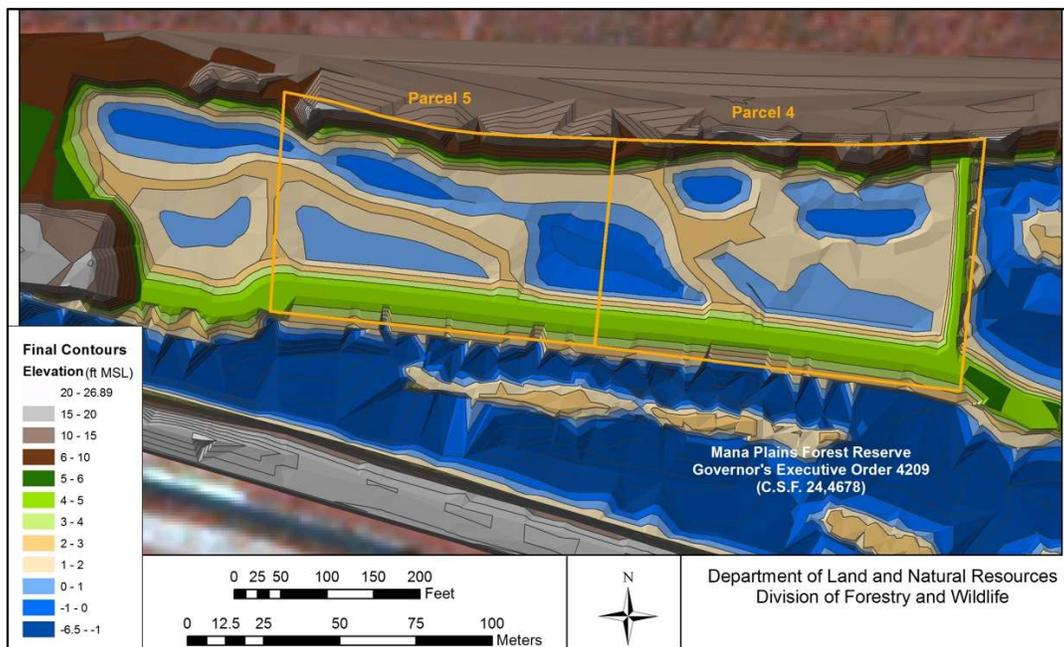


Figure 11. Proposed contours and target elevations (ft msl) for seasonally flooded wetland basins at Kawai‘ele Waterbird Sanctuary, part of the Mānā Plains Forest Reserve. Map courtesy of DOFAW.

Establishing Native Vegetation and Controlling Invasive Plants

Three management strategies were utilized to re-establish native vegetation:

1. Soil scarification to promote natural germination.
2. Broadcasting seeds.
3. Planting rare species and other wetland plants to increase diversity.

Soil disturbance from the heavy equipment used to re-contour wetland and upland habitats scarified the soil resulting in germination of native shrubs, forbs, and grasses. Germination increased after precipitation from kona storms (Jason Vercelli, DOFAW, personal communication). Seeds of up to 15 species, including naupaka (*Scaevola sencea*), ma‘o (Hawaiian cotton, *Gossypium tomentosum*), naio (*Myoporum sandwicense*), ‘ilima (*Sida fallax*), and ‘a‘ali‘i (*Dodonaea viscosa*), were broadcast by raking them into the sandy soils. Dwarf naupaka *S. coriacea* and ‘ohai (*Sesbania tomentosa*), both endangered, were planted and watered as needed for the first month until roots were well-established. DOFAW established multiple photo points to evaluate the response of wetland and upland vegetation to management strategies. From 2010 through 2014, native vegetation expanded considerably (Figure 12). During this time, the number of staff and volunteer workdays needed to control invasive plants decreased from 12 to 3–4 days a year. Native species have continued to expand, die-back, germinate, grow, and set seed, depending on abiotic conditions (Figure 13).

Islands of upland and mudflat habitats within Kawai‘ele are only accessible by boat. Therefore, invasive vegetation could only be removed by hand-pulling or cutting or digging with hand tools. DOFAW organized multiple student and community volunteer workdays with up to 30 volunteers to remove invasive vegetation from the islands. Similar to areas of Kawai‘ele where invasive vegetation was removed by heavy equipment, DOFAW staff, kupu interns, and volunteers initially re-visited each island monthly to remove any newly germinated plants and/or re-sprouted vegetation. Soil disturbance from foot traffic and hand tools was apparently sufficient to scarify the soil, as several species of native plants germinated from seed. However, the most common native species on the islands, ‘akulikuli (*Sesuvium portulacastrum*) expanded vegetatively from existing plants.



Self-sustaining, native vegetation at Kawai‘ele Waterbird Sanctuary. Photos by Adonia Henry.



Figure 12. Enhancement of wetland and upland habitats from 2008 through 2014 (clockwise) at Kawai'ele Waterbird Sanctuary, part of Mānā Plains Forest Reserve, Kaua'i. Photos by Jason Vercelli, DOFAW.



Figure 13. Native wetland and upland vegetation during May 2017 (left) and December 2021 (right) at Kawai'ele Waterbird Sanctuary part of Mānā Plains Forest Reserve, Kaua'i. Photos by Adonia Henry.

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APPENDIX A: ABIOTIC INFORMATION RESOURCES

Geology

U.S. Geological Survey

- USGS Hawai'i Geologic Map Data <https://mrddata.usgs.gov/geology/state/state.php?state=HI>
- Sherrod et al. 2007 & 2021 Geologic map of the State of Hawai'i (pdf files and spatial data)
 - <https://pubs.er.usgs.gov/publication/sim3143>
 - <https://pubs.usgs.gov/of/2007/1089/>
 - <https://data.doi.gov/dataset/geologic-map-of-the-state-of-hawaii>

Soils

Natural Resources Conservation Service

Current soil survey data

- Web-based Soil Survey <https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>
 - Soil descriptions, physical characteristics, and chemical characteristics can be downloaded for each soil type in the 'area of interest.'

All published soil surveys

- List of published soil surveys for Hawai'i
<https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=HI>
- Soil Survey of the Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii 1972
https://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/hawaii/islandsHI1972/Five_islands_SS.pdf
- Soil Survey of the Island of Hawaii, State of Hawaii 1973
https://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/hawaii/HI801/0/hawaii.pdf
- Territory of Hawaii Soil Survey 1955
https://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/hawaii/hawaii_territory1955/Hawaii_I_1955.pdf
 - Follow instructions to view archived soil maps associated with the 1955 published soil survey
<https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/state/?cid=stelprdb1262190>

University of Hawai'i

- Hawai'i Soil Atlas <http://gis.ctahr.hawaii.edu/SoilAtlas>
- Dennik and McClellan. 2007. Soils of Hawai'i
<https://www.ctahr.hawaii.edu/oc/freepubs/pdf/SCM-20.pdf>

General

- Richardson & Vepraskas. 2001. Wetland soils: genesis, hydrology, landscapes, and classification, CRC Press LLC, Boca Raton, Florida.

Climate

Western Regional Climate Center (<https://wrcc.dri.edu>)

- Historical Data Summaries for precipitation and temperature (including stations in Hawai'i) https://wrcc.dri.edu/Climate/west_coop_summaries.php
- Pacific Regional Quarterly Impacts and Outlooks https://wrcc.dri.edu/Climate/Quarterly_Impacts/q_impacts_pac.php
- RAWS USA Climate Archive <https://raws.dri.edu> (Hawai'i is under Western U.S.)
- Climate of Hawai'i https://wrcc.dri.edu/Climate/narrative_hi.php

NOAA National Centers for Environmental Information

- Climate at a Glance, city-level climate data for 8 locations in Hawai'i <https://www.ncdc.noaa.gov/cag/city/time-series>
- Climate Data Online (search, mapping, & data tools) <https://www.ncdc.noaa.gov/cdo-web/>
- U.S. Climate Reference Network <https://www.ncei.noaa.gov/access/crn/>
- U.S. Historical Climatology Network <https://www.ncei.noaa.gov/products/land-based-station/us-historical-climatology-network>

University of Hawai'i

- Rainfall Atlas of Hawai'i <http://rainfall.geography.hawaii.edu>
- Internet resources for climatological data https://guides.library.manoa.hawaii.edu/climatological_data
- Historical climate resources (books, journal, microform, microfiche) <https://guides.library.manoa.hawaii.edu/c.php?g=105208&p=686778>

Hydrology

Watershed & Ahupuaa Data

- USGS Watershed Boundary Dataset <https://www.usgs.gov/national-hydrography/watershed-boundary-dataset>
- USGS National Hydrography Dataset <https://www.usgs.gov/national-hydrography/national-hydrography-dataset>
- DAR Watersheds
- Ahupuaa <https://geoportal.hawaii.gov/datasets/ahupuaa/explore>
- Moku (Historical land divisions) <https://geoportal.hawaii.gov/datasets/moku/explore>

Surface and Groundwater Data

U.S. Geological Survey

- Pacific Islands Water Science Center <https://www.usgs.gov/centers/pacific-islands-water-science-center>
- National Water Information System Mapper (zoom to Hawai'i) <https://maps.waterdata.usgs.gov/mapper/index.html?state=hi>

- Realtime Water Data for Hawaii <https://waterdata.usgs.gov/hi/nwis/rt>
- Water-Data Site Information for Hawaii <https://waterdata.usgs.gov/hi/nwis/si>
- Surface-Water Data for Hawai‘i (includes historical observations) <https://waterdata.usgs.gov/hi/nwis/sw>
- Groundwater Data for Hawai‘i (includes historical observations) <https://waterdata.usgs.gov/hi/nwis/gw>
- Water-Quality Data for Hawai‘i <https://waterdata.usgs.gov/hi/nwis/qw>
- Water Use Data for Hawai‘i <https://waterdata.usgs.gov/hi/nwis/wu>

State of Hawai‘i

- DLNR Aquifers & Hydrologic Units
 - <https://geoportal.hawaii.gov/datasets/3bcbe7b290df40b3abf0450f52d9aebb/explore>
 - <https://dlnr.hawaii.gov/cwrm/groundwater/hydrounits/>
- DOH Aquifers
 - <https://geoportal.hawaii.gov/datasets/a292a6aaef148b78634b084e7a5b898/explore>
- Atlas of Hawaiian Watersheds & their Aquatic Resources (DAR & Bishop Museum)
 - https://www.hawaiiwatershedatlas.com/intro_surveys.html
- Hawai‘i Stream Assessment
 - <https://planning.hawaii.gov/gis/download-gis-data-expanded/>
 - https://files.hawaii.gov/dlnr/cwrm/publishedreports/R84_HSA.pdf

Sea Level Rise (SLR)

- Hawai‘i SLR Interactive Map <https://www.pacioos.hawaii.edu/shoreline/slr-hawaii/>
- State of Hawai‘i Climate Change Portal <https://climate.hawaii.gov/hi-facts/sea-level-rise/>
- University of Hawai‘i Sea Level Center <https://uhslc.soest.hawaii.edu>
- NOAA SLR Data Download <https://coast.noaa.gov/slrdata/>
- University of Hawai‘i Coastal Geology Group SLR Coastal Erosion – 0.5 ft scenario
 - <https://geodata.hawaii.gov/arcgis/rest/services/Climate/MapServer/60>
 - https://files.hawaii.gov/dbedt/op/gis/data/slr_cstl_erosn_0_pt_5_ft.html
- Hawai‘i Statewide Data Program – Geospatial Data Portal <https://geoportal.hawaii.gov/search?q=sea%20level%20rise>
- Shoreline erosion/accretion
 - <https://www.pacioos.hawaii.edu/shoreline/hcgg/>
 - https://www.soest.hawaii.edu/coasts/publications/Romine_coas-25-04-17.pdf
 - http://lumahai.soest.hawaii.edu/coasts/publications/Romine_Fletcher_inpress_HI_ShoreChange_Summary_JCR.pdf

Other Miscellaneous Resources

Hawai'i Statewide GIS Program <https://planning.hawaii.gov/gis/download-gis-data-expanded/>
and <https://geoportal.hawaii.gov>

- Historical Land Uses
- LANDSAT
- Land Cover Analyses
- Ocean Data
- Administrative & Political Boundaries
- Census Data, Human Health & Safety
- Facilities, Transportation, & Utilities

APPENDIX B: INVERTEBRATE FAMILIES

Table 22. Non-insect orders of invertebrates in freshwater and brackish lowland wetlands and kalo loi. Data compiled from Englund et al. (2000), McGuire (2006), Gutscher-Chutz (2011).

Phylum–Class	Order	Family	Common Name	Functional Feeding Group
Annelida–Clitellata	<i>Subclass</i> Oligochaeta		Aquatic worm	CG
–Euhirundinae	Rhynchobdellida	Glossiphoniidae	Jawless leech	PP
		Piscicodlidae		
–Polychaeta			Bristleworm	PE,PP,SH,CF,Par
Mollusca–Bivalva	Pelecypoda	Sphaeriidae	Fingernail clam	CF
	Veneroida	Corbiculidae	Asian clam	CF
–Gastropoda	Basommatophora	Lymnaeidae	Pond snail	SC
		Physidae	Physid snail	SC
	<i>Subclass</i> Caenogastropoda –Architaenioglossa	Ampullariidae	Apple snail	SHH
	–Neotaenioglossa	Thiaridae	Thiard snail	SC
Nematoda	Spirurida	Camallanidae	Roundworm	Par
Phylum–Subphylum –Class				
Arthropoda–Chelicerata –Arachnida	Araneae		Spider	PE
–Hydrachnia	Acariformes		Water mite	Par, PP, PV (varies by age)
Arthropoda–Crustacea –Branchipoda	Spinicaudata		Clam shrimp	
–Malacostraca	Decapoda	Atyidae	Freshwater shrimp	
		Cambaridae	Freshwater crayfish	
		Palaemonidae	Grass shrimp	
	Isopoda		Aquatic sow bug	CG
Arthropoda–? –Entognatha	<i>Subclass</i> Collembola	Entomobryidae	Slender springtail	CG
		Isotomidae	Smooth springtail	CG
		Sminthuridae	Globular springtail	CG

Table 23. Insects from aquatic orders in which almost all species have aquatic larvae that occur in freshwater and brackish lowland wetlands, margins of lower stream reaches, and kalo loi. Taxa compiled from Polhemus and Asquith (1996), Englund et al. (2000), Englund (2002), McGuire (2006), Gutscher-Chutz (2011)

Order	Family	Common Name	Functional Feeding Group
Ephemeroptera			
Odonata–Anisoptera	Aeshnidae	Darner dragonfly	PE
	<i>Anax junius</i> (Green darner)*		
	Libellulidae	Skimmer dragonfly	PE
	<i>Crocothemis servilia</i> (Scarlet skimmer)		
	<i>Orthemis ferruginea</i> (Roseate skimmer)		
	<i>Pantala flavescens</i> (Globe skimmer)*		
Odonata–Zygoptera	Coenagrionidae	Narrow-winged damselfly	PE
	<i>Enallagma civile</i> (familiar bluet)		
	<i>Ischnura posita</i> (fragile forktail)		
	<i>Ischnura ramburii</i> (Rambur’s forktail)		
	<i>Megalagrion leptodemas</i> (Crimson Hawaiian damselfly)*		
	<i>Megalagrion pacificum</i> (Pacific Hawaiian damselfly)*		
	<i>Megalagrion vagabundum</i> (Scarlet Kauai damselfly)*		
	<i>Megalagrion xanthomelas</i> (Orangeblack Hawaiian damselfly)*		
Plecoptera			
Trichoptera	Hydroptilidae	Microcaddisfly	VP, SC, CG
	Hydropsychidae	Net-spinning caddisfly	
	Cheumatopsyche pettiti		
Megaloptera			

* Native species.

Table 24. Insects from partially aquatic orders that occur in freshwater and brackish managed wetlands and kalo loi. Data compiled from Englund et al. (2000), Englund (2002), McGuire (2006), Gutscher-Chutz (2011)

Order	Family	Common Name	Functional Feeding Group	
Coleoptera (Water beetles)	Anobiidae	Cigarette beetle		
	Anthribidae	Fungus weevil	SSH, SSG	
	Anthicidae	Ant-like flower beetle		
	Carabidae	Ground beetle		
	Curculionidae	True weevil	SHH, SHD	
	Dystiscidae	Predaceous diving beetle	PE, PP	
	Hydrophilidae	Water scavenger beetle	L=PE; A=CG	
	Limnichidae	Minute marsh-loving beetle		
	Nitidulidae	Sap beetle	SHD	
	Scirtidae	Marsh beetle	L=SC, CG; A=SHH, VP	
	Scolytidae	Bark beetle		
	Silvanidae	Flat bark beetle	SHH, SHG	
	Tenebrionidae	Darkling beetle		
	Staphylinidae	Rove beetles	PE, CG, SHH	
	Canadidae			
	Diptera (True flies)	Cecidomyiidae	Gall midges	VP, PP
Ceratopogonidae		No see-um	PE, CG, SC	
Chironomidae		Midge	All	
Culicidae		Mosquito	CF, CG	
Dolichopodidae		Long-legged fly		
Drosophilidae		Small fruit fly	VP, PP, Par	
Empididae				
Ephydriidae		Salt marsh fly, shore fly	CG, SHH, SC, PE	
Muscidae		House fly		
Phoridae		Hump-backed fly	CG, PE	
Psychodidae		Moth fly, sand fly	CG	
Sciomyzidae		Snail-killing fly	PE, Par	
Sphaeroceridae		Small dung fly	CG	
Stratiomyidae		Soldier fly		
Syrphidae		Flower fly	CG	
Tethinidae				
Tipulidae		Crane fly	SHD, CG, PE	
Hemiptera (True bugs)		Anthocoridae		
		Aphididae	Aphid	VP
	Ciadellidae	Cicadas, Leafhopper	VP	
	Corixidae			
	Cydnidae	Burrower bug	VP	
	Delphacidae	Plant hopper	VP	
	Gerridae	Water strider		
	Lygaeidae	Seed bug	VP	
	Mesoveliidae	Water treader	PP	
	Miridae	Plant bug	VP	
	Notonectidae	Backswimmer	PP	
	Pleidae	Pygmy backswimmer	PP	
	Pseudococcidae	Mealybug	VP	
	Reduviidae	Assassin bug	PP	
	Saldidae	Shore bug		
	Tingidae	Lace bug		
Lepidoptera (Aquatic caterpillars)	Crambidae	Pyralid moth	SHH	
	Gracillariidae	Leaf minor		
	Noctuidae	Cutworm	SHH	
	Tineidae	Clothes moth		
Neuroptera	Hemerobidae	Brown lacewing	PE	

Table 25. Insects with terrestrial life cycles that occur in freshwater and brackish lowland wetlands and kalo loi. Data compiled from McGuire (2006), Gutscher-Chutz (2011)

Order	Family	Common Name	Functional Feeding Group
Hymenoptera (Wasps)	Braconidae	Braconid wasp	Par
	Eucoilidae	Wasp	
	Eulophidae	Wasp	
	Formicidae	Ant	PE, SHH, CG
	Icheumonidae	Wasp	
Isoptera	Kalotermitidae	Termite	SHG
Orthoptera	Acrtididae	Grasshopper	SHH
Psocoptera	Ectopsocidae	Bark lice	
	Lepidopsocidae	Barklouse	SC
	Perientomidae	Bark lice	
	Peripsocidae	Bark lice	
	Psocidae	Bark lice	
Thysanoptera	Thripidae	Common thrip	VP