

Avian Botulism in Hawai'i: An Historical Analysis of Avian Botulism
Outbreaks and the Establishment of a Hawai'i Waterbird Network for
Improved Wetland Management

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Abstract

Avian botulism is a paralytic disease that kills thousands of waterbirds globally each year. In Hawai‘i, where the endemic waterbird populations are already limited in size, the threat of botulism outbreaks is a large concern. Despite the frequent movement of waterbirds among wetlands throughout the state to meet foraging, refugia, and nesting needs, botulism outbreaks continue to be managed as isolated events by individual wetland managers. Successful containment of avian botulism outbreaks requires efficient communication within and between wetland managers to increase awareness of outbreak potential, increase monitoring, and remove infected carcasses to prevent widespread outbreak. Thus, a critical need exists to assess historical and geographic trends in outbreaks and to increase communication among wetland managers. This project aimed to increase prevention and containment of avian botulism through: (1) reviewing historical avian botulism trends and reporting throughout the state; (2) developing a listserv to alert network participants regarding potential outbreaks; (3) building a website to receive reports of suspected botulism cases and provide educational information. Using the snowball sampling method, a diverse array of wetland managers were engaged in calls for botulism case data and participation in monthly Hawai‘i Waterbird Network meetings from February to May, 2021. Based on collated records from 1993 to 2021, managers reported 830 avian botulism cases, with the bulk of cases reported by agencies managing several large wetlands, and coming from islands with the highest wetland to land ratio. Through a combination of literature review and manager discussion, we found a common set of management challenges, and that increased communication regarding suspected botulism outbreaks not only allowed for timely responses, but increased the implementation of best management practices (BMPs) for other waterbird threats. Key threats identified during stakeholder elicitation included non-native predators, habitat loss, and concerns about climate change. BMPs for waterbird recovery included predator control, regular monitoring, and habitat restoration. This project established a statewide wetland manager network and demonstrated how managers can use a system-wide approach to improve collaboration, communication and enhance social-ecological resilience, in this case, to minimize botulism-induced mortality in Hawaiian waterbirds.

Key words: community network, Hawaiian waterbird, social-ecological system, disease outbreak, best management practices

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Motivation

One third of endangered bird species listed in the United States are endemic to Hawai‘i (Reed et al., 2012; Underwood, 2013). Species disappear at alarming rates because of Hawai‘i’s high species endemism and low population numbers facing multiple threats (USFWS, 1978). Many native Hawaiian wetland birds experience restricted foraging and nesting options due to habitat loss (Van Rees, 2018; Harmon et al., 2021), high predation by invasive species (Christensen et al., 2021; Underwood, 2014), and more recently, a rising threat of avian disease throughout the islands (Reynolds et al., 2020).

In waterbirds, the main disease causing mortality is the paralytic disease, avian botulism. Studies of avian botulism are largely lacking for island systems and Hawai‘i is no exception (Work et al., 2010). Despite annual outbreaks of avian botulism in the Hawaiian Islands threatening our endangered waterbirds (USFWS, 2016), large-scale efforts to assess and mitigate avian botulism outbreaks are lacking. Further, a lack of communication among federal, state, private and nonprofit land managers has hindered control efforts and the development of best management practices (BMPs) to reduce and constrain outbreaks. With the incidence of avian botulism predicted to increase globally with climate change (Espelund and Klaveness, 2014), there is an enhanced need for an understanding of statewide botulism trends.

Wetlands are a vital resource throughout the state, providing ecosystem services such as water filtration, coastal storm protection and habitat for native waterbird species (Reed et al., 2012; Van Rees, 2018; Winter et al., 2018). Wetlands are also foundational for thriving Hawaiian communities and cultural practices, supporting flooded-field agriculture and coastal fishponds (Winter et al., 2018). While the extensive physical connection of wetlands may have been lost due to water diversions for plantation agriculture (Van Rees, 2018), there remains a network of connection as native waterbird species move frequently between habitats (Harmon et al., 2021; Reed et al., 2012; Smetzer et al., 2022). Studies show networks developed around coastal marine management throughout Hawai‘i are models for collaborative sustainable management of resources, species, and strong social-ecological systems (Dacks et al., 2020; Vaughan and Vitousek, 2013). The human network surrounding wetlands needs to reflect the existing interconnection of ecosystems and species to promote adaptive resilience in the face of continued global change (Berkes, 2017).

This project aimed to connect people who care for native waterbirds not only for the protection of these ecologically and culturally valuable species, but also the creation of resilient social-ecological networks (Folke, 2006; Berkes, 2017). In this research we addressed the critical needs of avian botulism communication and building wetland manager networks by collating historical trends in botulism outbreaks across the main Hawaiian Islands, creating a network for manager communication, and creating a website with educational material and BMPs to minimize outbreaks of avian botulism in Hawai‘i.

Background

The scale and connectivity of wildlife populations must match the scale and connectivity of management to be effective (Sterling et al., 2017). Waterbirds disperse freely among wetlands within and among islands throughout the state to meet foraging, refugia, and nesting needs (Underwood et al., 2013; Kawasaki et al., 2019), suggesting these populations would greatly

benefit from increased connectivity among managers. Efforts to protect waterbird species and boost numbers involve habitat restoration and expansion, predator control of invasive mammal species like rats, cats, dogs and mongoose, and improvement to nesting habitat (Runge, 2011). Since wetlands provide primary nesting and foraging habitat for Hawaii's native waterfowl (Reed et al., 2012; Harmon et al., 2021), changes in wetland composition can lead to reductions in nesting success, habitat loss, and increased incidence of animal disease as wetland health deteriorates (Brandis et al., 2020; Anibaldi et al., 2013). In the past few decades, avian botulism has become a larger concern in the Hawai'i wetland manager community (Work et al., 2010; Reynolds et al., 2020), as large outbreaks can be devastating to our endangered species.

Avian botulism is a paralytic disease that kills thousands of waterbirds globally each year (Rocke and Samuel, 1999), and commonly occurs across Hawai'i, with some wetlands experiencing year-round outbreaks, something often restricted to the dry season in non-tropical regions (Rocke and Friend, 1999; Espelund and Klaveness, 2014; U.S. Fish and Wildlife Service, 2016). While the *Clostridium botulinum* bacteria commonly occurs in wetland sediments, certain environmental conditions trigger *C. botulinum* to produce the botulism neurotoxin (BoNT) which bioaccumulates in invertebrates and fish, when eaten by birds it leads to paralysis and eventual death (Brandis et al., 2020; Anibaldi et al., 2013; Friend et al., 2012). Outbreaks occur when an infected bird dies and maggots feeding on the carcass are eaten by other birds, who can travel to neighboring wetlands and eventually succumb to the disease, perpetuating what is known as the carcass-maggot cycle (Espelund and Klaveness, 2014; Friend and Franson 1999). Due to the complexity of environmental relationships such as temperature, pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), salinity and turbidity, targeting and eliminating ecological factors contributing to avian botulism remains a challenge (Rocke and Samuel, 1999; Work et al., 2010; Wobeser, 1997). Current efforts to contain outbreaks of avian botulism within a wetland involve draining or flushing wetlands, hazing birds away from affected areas and quickly removing dead birds to limit the spread of the disease through the carcass-maggot cycle (Espelund and Klaveness, 2014; Friend and Franson, 1999), often requiring costly and timely monitoring (Reynolds et al., 2020).

As some Hawaiian waterbirds, such as the ae'o (Hawaiian Stilt), move frequently among wetlands, while others such as 'alae 'ula have very minimal movements among wetlands (Reed et al., 1998), there is both a high chance for botulism to spread among nearby wetlands, and to differentially impact multiple species of waterbirds. Currently, five endangered and threatened endemic waterbird species are listed in Hawai'i: the Hawaiian Coot ('alae ke'oke'o; *Fulica alai*), Hawaiian Duck (koloa maoli; *Anas wyvilliana*), Hawaiian Stilt (ae'o; *Himantopus mexicanus knudseni*), Hawaiian Gallinule (Moorhen) ('alae 'ula; *Gallinula galeata sandvicensis*), and Hawaiian Goose (nēnē; *Branta sandvicensis*) (USFWS, 2011). In addition to protection under the Endangered Species Act, these species are culturally significant as evidenced by their appearance in ka'ao (myths), mo'olelo (stories), mele (songs), and 'olelo no'eau (proverbs) (Gomes, 2020). Successful containment of large scale outbreaks requires efficient communication among wetlands so managers can increase monitoring at nearby wetlands and quickly remove infected carcasses to reduce further spread (Friend and Franson, 1999; Reynolds et al., 2020).

Objectives

This project's objective was to create a network-based, system-wide approach for a problem that, in the past, was often managed at single sites. We aimed to: (1) evaluate historical trends in botulism outbreaks and reporting across the Hawaiian Islands; (2) develop a listserv and network to unite wetland managers around the issue of avian botulism and disseminate wetland BMPs; (3) build a website to receive reports of suspected botulism cases, send alerts regarding potential outbreaks, provide educational information, and (4) build capacity for shared reporting and record collection of future cases statewide and nationally.

Approach

Historical Data Collection and Analysis

Using a snowball sampling method (Goodman, 1961; Bhattacharjee, 2012), we compiled contact information for wetland managers throughout the state, including managers from state and federal agencies, private landowners, environmental consultants, and nonprofits. As we acquired new contacts, we requested records related to botulism, including the number of carcasses collected, species impacted, wetlands affected on each island and reporting agencies or individuals. Graphs were made in Microsoft Excel. Chi-square analysis performed in R Studio, version 4.0.3.

Hawai'i Waterbird Network, Listserv and Website Creation

The Hawai'i Waterbirds Listserv developed during this project now includes 52 people, with representation from each of the main Hawaiian Islands, as well as some Northwestern Hawaiian Islands. In January 2021, listserv members were invited to join four monthly online meetings that took place from February to May. These meetings connected managers and provided the opportunity to obtain knowledge of wetland and botulism management strategies throughout the state. This coalition of people now functions as the Hawai'i Waterbird Network.

Each meeting had a theme around which we structured large and small group discussions. In February, we focused on connecting attendees, sharing our plan for botulism data collection and analysis, and establishing shared network goals. At the March meeting, we conducted a Wetland Threat Assessment to gauge wetland manager perspectives of the largest threats to our native waterbird species and solicited ideas on where the Hawai'i Waterbird Network could be best utilized. Based on results from the Wetland Threat Assessment, we had various managers present on agency BMPs and new technology, such as avian botulism background and protocol for carcass collection and reporting (USGS), the use of dogs to find botulism infected carcasses (FWS - Kaua'i), large machinery use for wetland restoration (DOFAW - O'ahu), new predator trap technology (ANRP - O'ahu), and UH presentations of current waterbird research and predicted sea level rise impacts on wetlands and waterbird species (Harmon et al., 2021). Following presentations, we used small group discussions to elicit common wetland BMPs for botulism management, restoring wetlands, protecting waterbird species, and managing for resilience. In May, we reviewed outcomes from previous meetings, shared initial botulism summary statistics from collected data, launched our reporting website, and set some network next steps for the coming summer and year.

Through the manager meetings we sourced a range of perspectives regarding how botulism outbreaks are addressed at different sites, the largest threats native waterbirds face, and

BMPs for restoring and maintaining wetland resilience. Literature review of global botulism management and communication networks for natural resource managers informed creation of educational material on our Hawai‘i Waterbirds website, created with Wix.com.

Results

Historical Data Analysis

We collected a total of 2,660 records of avian botulism cases in Hawai‘i spanning from 1952 to 2021. The case reports prior to 1993 come mostly from newspaper records, and lacked the necessary detail for this project's analysis, but remain a valuable resource for future study. My analysis focused on 830 detailed case reports from 1993 to 2021. Summary graphs and statistical analysis show trends of avian botulism case reporting spatially between islands, temporally over season, and by reporting affiliate agency.

Spatial Analysis

Cases of avian botulism have fluctuated through the main Hawaiian Islands over the years but case data shows a general increase in reported cases since 2000 (Figure 1). Overall, the number of reported cases differs significantly among islands (Table 1, Figure 2). Reports from Midway were at a peak between 2007 and 2012. Kaua‘i, specifically Hanalei National Wildlife Refuge and their extensive wetland pond system, have the most reported cases among the islands, particularly from 2010 to 2021. Maui and O‘ahu show consistently low numbers of case reports over the years, followed by Moloka‘i and Lana‘i, with Hawai‘i island reporting the fewest historical botulism cases.

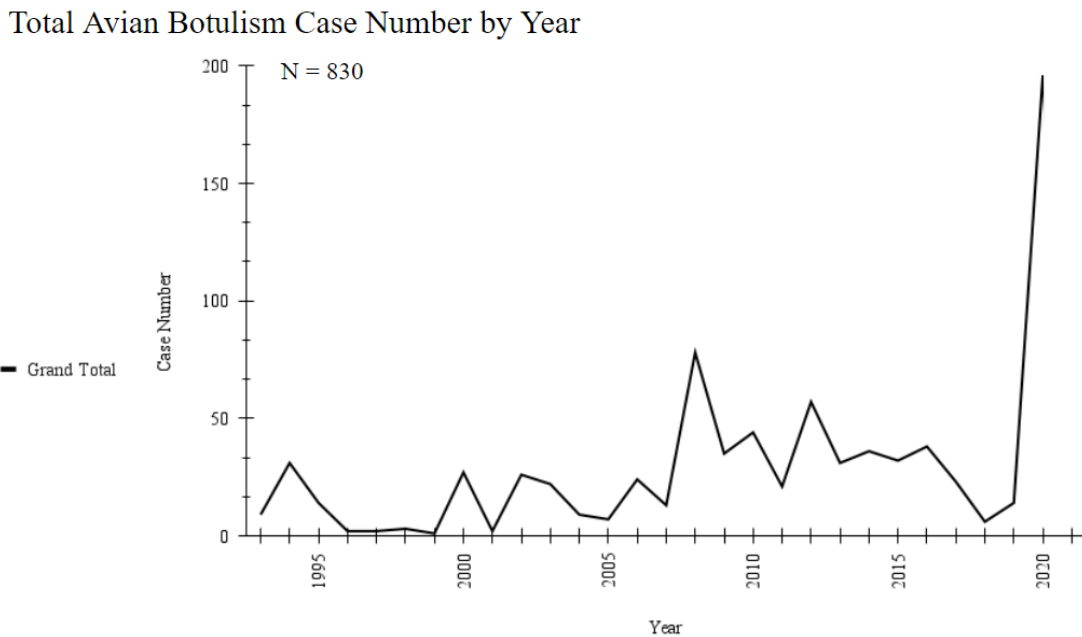


Figure 1. Total avian botulism case reports from 1993 to 2021. General trend increase since the 2000s.

Table 1. *Chi-square analysis of avian botulism reports between Hawaiian islands. Case reports for Molokai (32) and Lanai (15), and the Northwest Hawaiian islands of Kure (24), Laysan (6), and Midway (188) were combined for analysis due to spatial proximity. X-squared= 583.35, df = 5, p-value < 2.2e-16. N = 830.*

Hawaii	Maui	Molokai and Lanai	Oahu	Kauai	Northwest
30	104	47	72	359	218

Avian Botulism Case Number by Year and Island

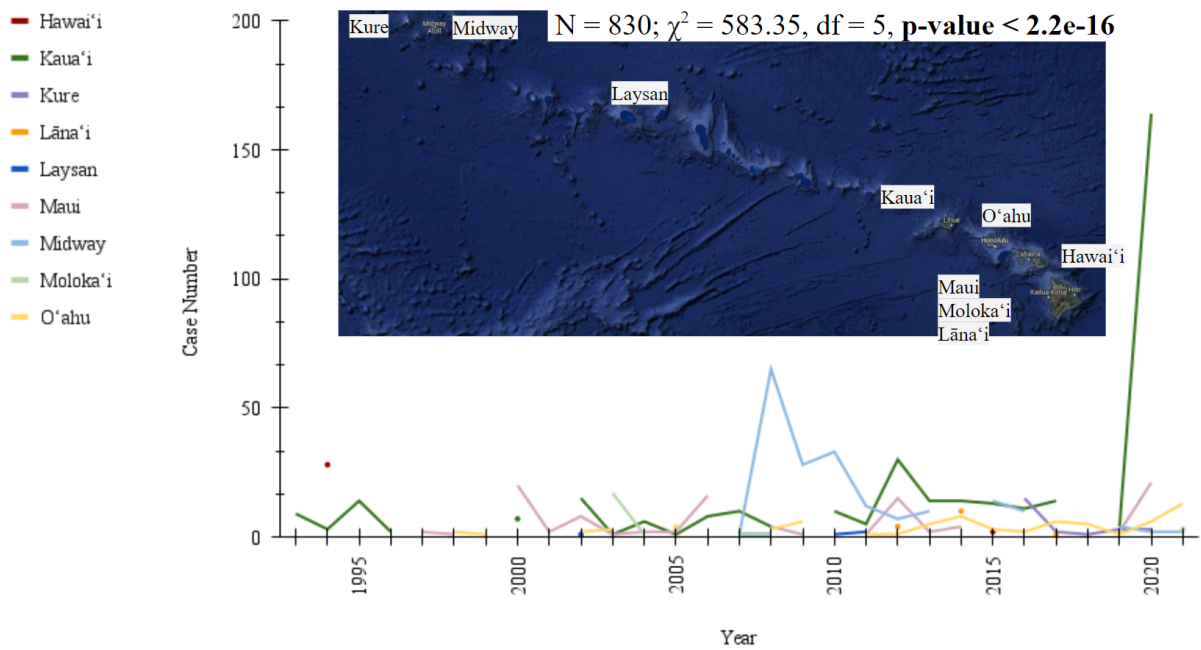


Figure 2. *Avian botulism case reports by island from 1993 to 2021.*

Temporal Analysis

Trends in avian botulism case reporting show a significant difference between Hawai‘i’s wet and dry seasons (Table 2). There are more cases of botulism across islands reported during the dry season (from April to October), especially in August, September, and October (Figure 3).

Table 2. Significant difference of avian botulism case reports through the Hawaiian Islands between the wet season (November - April) and dry season (May - October). Seasons defined by NOAA Climate. The months with the highest cases are the warm dry months of August, September, and October. $\chi^2 = 27.124$, $df = 1$, $p\text{-value} = 1.908e-07$; $N = 662$.

Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
33	49	37	33	69	43	26	65	32	107	77	91

Avian Botulism Case Number by Month and Island

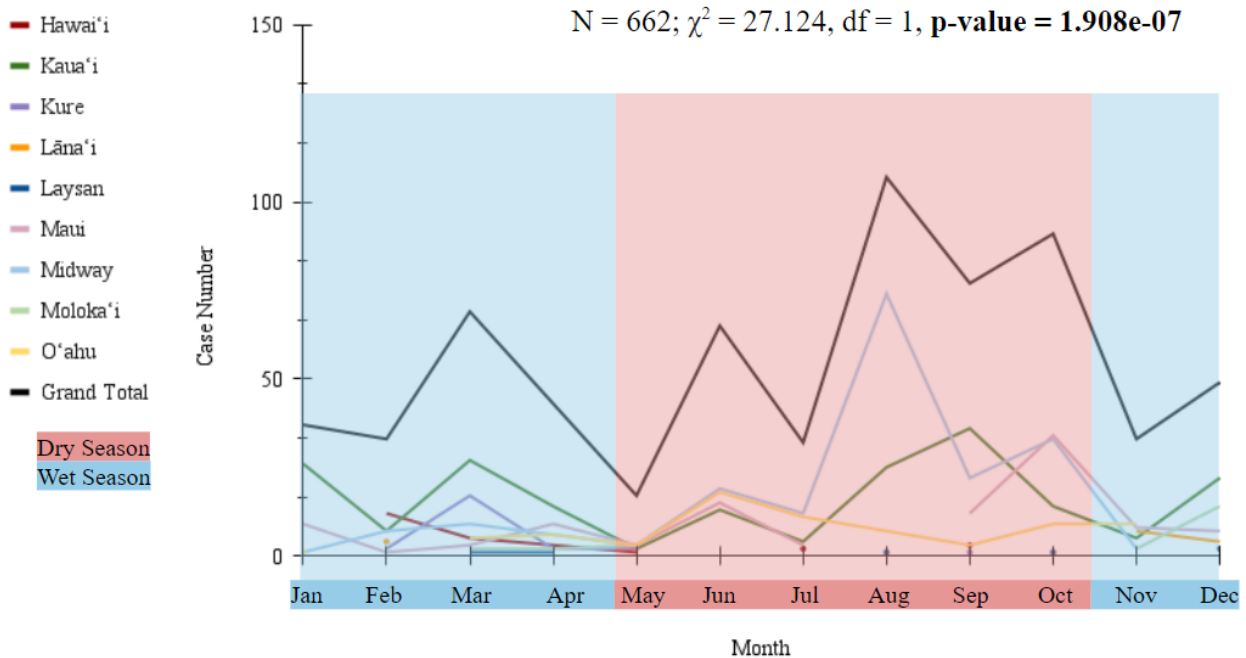


Figure 3. Seasonal trends by month between islands shows higher avian botulism case reports during the dry season, April - October, especially in August, September, and October.

Agency Reporting Analysis

Chi square analysis shows a significant difference in botulism data reporting by agency (Table 3). Agencies were categorized as Division of Forestry and Wildlife (State), Fish and Wildlife Service (Federal), Military (Federal), National Park Service (Federal), and Private and Nonprofit. Fish and Wildlife Services reported the majority of cases, followed by Division of Forestry and Wildlife, and Private and Nonprofit Organizations (Figure 4).

Table 3. *Chi square analysis shows a significant difference among agencies reporting avian botulism cases. $\chi^2 = 1555.2$, $df = 4$, $p\text{-value} < 2.2e-16$; $N = 800$.*

Division of Forestry and Wildlife (State)	Fish and Wildlife Service (Federal)	National Park Service (Federal)	Military (Federal)	Private and Nonprofit
72	604	27	22	75

Avian Botulism Case Number by Reporting Agency

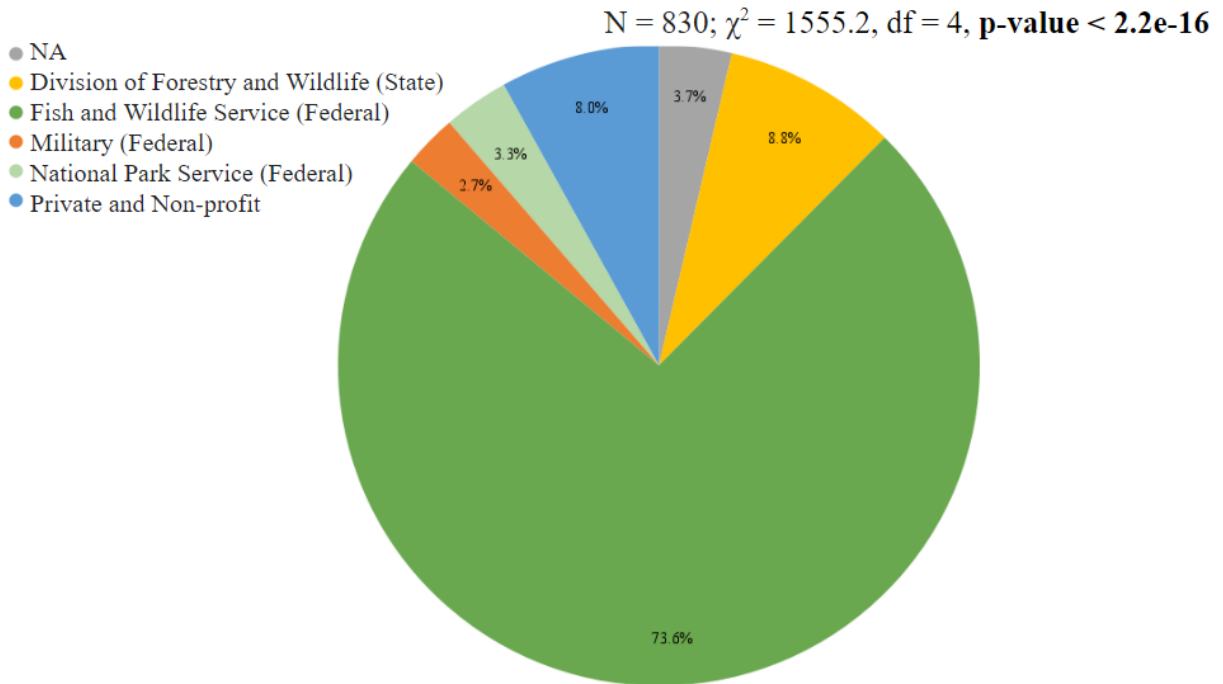


Figure 4. *Avian botulism cases by reporting agencies. The Fish and Wildlife Service (FWS) has reported the majority of cases, followed by the State of Hawai'i Division of Forestry and Wildlife (DOFAW), and Private and Nonprofit agencies.*

Hawai'i Waterbird Network, Listserv and Website

Hawai'i Waterbird Network and Listserv

A total of 52 wetland managers and caretakers representing all main Hawaiian Islands and a variety of land management agencies were added to our Network Listserv. Representation includes Division of Forestry and Wildlife (DOFAW) and Fish and Wildlife Service (FWS) managers from multiple islands, National Park Service (NPS), US Geological Survey (USGS), Military Base wetland managers, and representatives from ten private or nonprofit organizations. Over the period of four Hawai'i Waterbird Network meetings, we engaged 40 different participants, with an average monthly attendance of 21 people per meeting (Table 4). The majority of those present at the network meetings were from private and nonprofit agencies, though all meetings included attendance from state and federal agencies.

In our initial February meeting we did introductions, established network goals and shared background on this project, calling for historical botulism case report data. Over subsequent meetings, network questions revealed the largest concerns for managing botulism included adequate personnel for rapid response monitoring, early detection, communication among managers of outbreak potential and maintaining healthy habitats. The largest threats to native water birds identified by managers were predator control, habitat loss and degradation, botulism, and concerns about climate change, particularly changes in precipitation and sea level rise. Additional concerns included funding sources and public education. The BMPs for avian botulism included regular monitoring with heightened presence during peak seasons and following alerts from nearby wetlands, along with the use of new technology such as dogs and drones to find and remove carcasses during outbreak events. Further BMPs for wetland management other than the standardized predator control and habitat restoration, included ideas of collaboration for funding research and publishing within the network. The Hawai'i Waterbird Network has served the dual purpose of disseminating wetland BMPs and worked as a direct communication and feedback forum for the Wildlife Ecology Lab's collection and analysis of avian botulism data.

Hawai'i Waterbird Website

The Wetland Manager listserv, used for communicating Hawai'i Waterbird updates, also provides the basis for an alert network regarding potential outbreaks reported through our website that I developed during this project: hiwaterbirds.com (Image 1). This website houses information on Hawai'i's endangered wetland birds, research conducted by the Wildlife Ecology Lab, and a reporting button that generates an email to the waterbird network listserv, as well as resources to use for reporting and managing suspected botulism cases. As new reports are made, an alert email goes out to the waterbird manager listserv regarding a potential outbreak. Our partners at USFWS and USGS follow up on reports to facilitate carcass collection and input of case updates into the USGS national wildlife disease tracking database, WHISPers (<https://whispers.usgs.gov>), so current and future reports will be publicly accessible. Our partnership included facilitation of WHISPers database training to local State and Federal managers, as well as a public WHISPers seminar held in the NREM 701 Seminar slot on May 4, 2021. In the summer 2021 we received our first reports to the portal, and several other organizations have used the listserv as an invitation list for wetland workshops.

Table 4. 2021 Wetland Manager Meeting Themes, Questions and Participant Organizations

Date	Meeting Topic	# Participants	Organizations Represented
February 10, 2021	<p>Introductions Network goals Avian Botulism Case Data Request</p> <p>Who is in the room? What is your connection to wetland management? What are your long term goals for waterbirds in the state? What is the hardest part about managing botulism at your site? What has been most successful?</p>	21	Department of Land and Natural Resources - O'ahu Hawai'i Wildlife Center - Hawai'i He'eia NERR - O'ahu Keawawa Wetland - O'ahu Marine Corps Base Hawa'i - O'ahu Moloka'i Non Profit Save our Shearwaters - Kaua'i USFWS - Maui, O'ahu, Kaua'i USGS - O'ahu University of Hawai'i at Mānoa
March 10, 2021	<p>Wetland Threat Assessment</p> <p>What are the top two threats to waterbirds, either at your site or holistically? How and why did you rank your top threats? What are some solutions you use at your site? How can this network be used to address these threats?</p>	24	Army Natural Resources Program O'ahu Department of Land and Natural Resources - O'ahu, Kaua'i Hawai'i Wildlife Center - Hawai'i He'eia NERR - O'ahu Hokualea Resort - Hawai'i Keawawa Wetland - O'ahu Kualoa Ranch - O'ahu Marine Corps Base Hawa'i - O'ahu Moloka'i Non Profit Save our Shearwaters - Kaua'i Tetrattech - O'ahu USFWS - Maui, O'ahu, Kaua'i USGS - O'ahu University of Hawai'i at Mānoa Waimea Valley - O'ahu
April 14, 2021	<p>Wetland Best Management Practices</p> <p>Share what your organization is doing well in promoting waterbird abundance and health?</p> <ul style="list-style-type: none"> - Technology from Hanalei for botulism monitoring (FWS) - Wetland restoration technology (DOFAW) - Predator management techniques (ANRPO) - Sea level rise and habitat restoration practices (UH) <p>What are shared BMPs for expanding and optimizing nesting habitat for our main waterbird species?</p>	22	Army Natural Resources Program O'ahu Department of Land and Natural Resources - O'ahu Hawai'i Wildlife Center - Hawai'i He'eia NERR - O'ahu Hokualea Resort - Hawai'i Kualoa Ranch - O'ahu Marine Corps Base Hawa'i - O'ahu Moloka'i Non Profit Pacific Birds Habitat Joint Venture - Kaua'i Tetrattech - O'ahu Ulupō Heiau and Lo'i - O'ahu USFWS - Maui, O'ahu, Kaua'i USGS - O'ahu University of Hawai'i at Mānoa Waimea Valley - O'ahu
May 12, 2021	<p>Review and Discussion of Network Next Steps</p> <p>What have we accomplished?</p> <ul style="list-style-type: none"> - Reshare network goals, botulism data update, predator paper collaboration <p>What are some visions for the future of waterbird network meetings?</p>	19	Army Natural Resources Program O'ahu Department of Land and Natural Resources - O'ahu, Hawai'i Wildlife Center - Hawai'i He'eia NERR - O'ahu Hokualea Resort - Hawai'i Keawawa Wetland - O'ahu Kualoa Ranch - O'ahu Marine Corps Base Hawa'i - O'ahu Moloka'i Non Profit Pacific Birds Habitat Joint Venture - Kaua'i Tetrattech - O'ahu Ulupō Heiau and Lo'i - O'ahu USFWS - Maui, O'ahu, Kaua'i USGS - O'ahu University of Hawai'i at Mānoa Waimea Valley - O'ahu

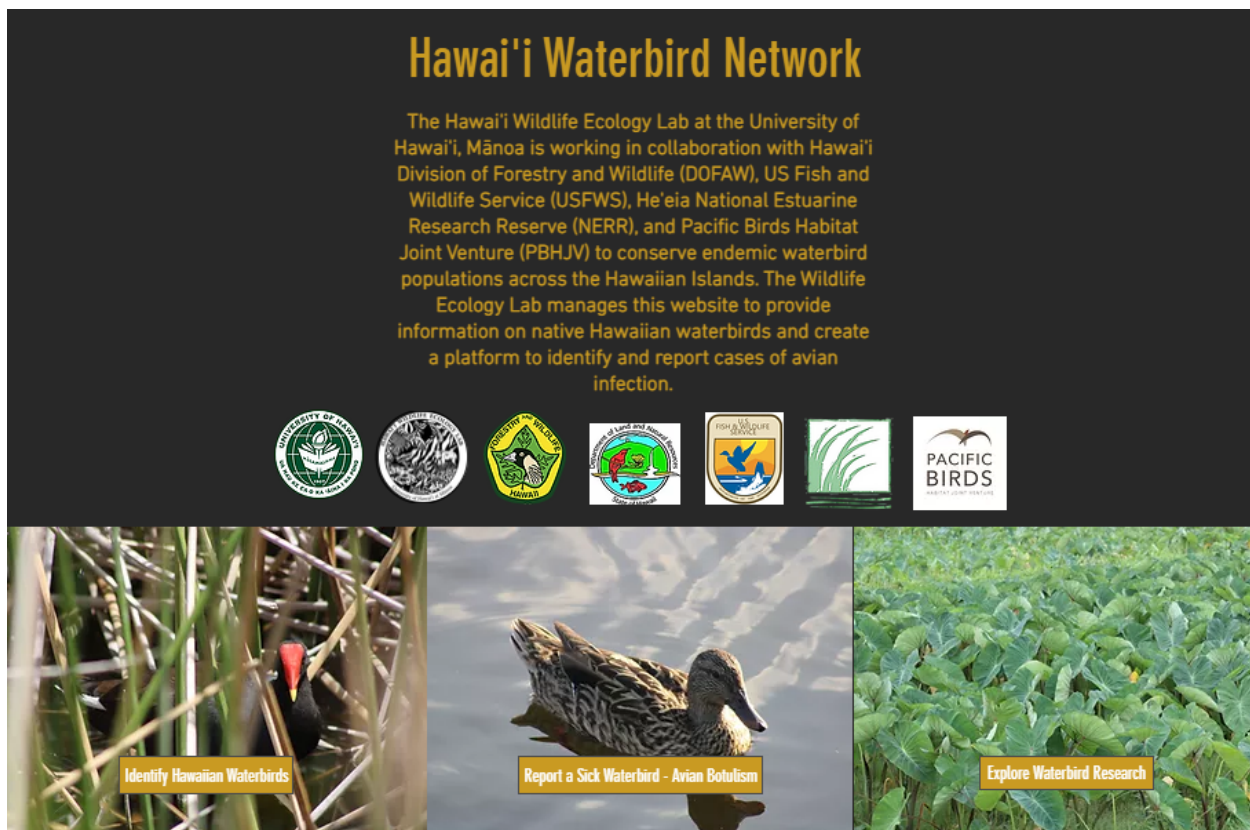


Image 1. The *Hawaii Waterbirds Partnership Website* was created on Wix.com and is maintained by the University of Hawai‘i at Mānoa Wildlife Ecology Lab. This website shares educational information on waterbirds and wetland research, and is a platform for sending botulism reports to the Hawai‘i Wetland Managers Listserv. hiwaterbirds.com

Discussion

Wetlands are naturally resilient systems providing vitally important ecosystem services such as shoreline stabilization, groundwater recharge, flood control, nutrient cycling, water purification and biodiversity habitat (Brimacombe, 2003; Van Rees, 2018; Bhowmik, 2020). Worldwide, wetlands are threatened by land use change, pollution, and climate change (Bhowmik, 2020). Hawaiian agriculture utilized Hawaiian topography and diverted streams to develop extensive flooded-field systems of agriculture (lo‘i kalo) and coastal fishponds (loko i‘a) (Winter et al., 2018). Stream channelization and widespread filling of wetlands and fishponds in the early 1900s resulted in estimates of coastal wetland loss as high as 65% on O‘ahu and 15% statewide (Van Rees, 2018; Wiegel 2011). In Hawai‘i, wetlands are an important natural and cultural resource that provide habitat for many of our threatened native waterbird species (Reed et al., 2012; Van Rees, 2018; Winter et al., 2018). Humans have been managing and altering wetland ecosystems since establishing in Hawai‘i, and it is our responsibility to continue managing wetlands to sustain ecological and human health.

To better manage our unique avifauna on a statewide scale, standardized record-keeping and reporting of threats such as avian botulism cases are critical to identifying high-risk spaces and trends (Russell et al., 2019; Brandis et al., 2020). Networks are also valuable social tools to build not just ecological, but social resilience in the face of issues that span spatial and temporal boundaries, such as avian botulism and climate change (Dacks et al., 2020; Barnes et al., 2015). This project compiled statewide avian botulism reports to create historical case reporting trend analysis spatially, seasonally and by reporting agency. Results show statistical differences among cases reported among islands, with Kaua‘i and Midway reporting the most cases, followed by Maui and O‘ahu. Results also show a statistical difference in reports between Hawai‘i’s wet and dry seasons, with highest reports happening in the dry months of August, September and October. Additionally, reporting varied by organization with the most botulism cases being reported by Federal USFWS, followed by Hawai‘i State DOFAW and Private and Nonprofit agencies.

In addition to historical reporting trend analysis, we produced a platform for reporting botulism cases, and connected wetland managers located throughout the state through the establishment of the Hawai‘i Waterbird Network, and to record cases with a national disease tracking database (WHISPerS). The Hawai‘i Waterbirds Network has provided a forum to communicate wetland best management practices, novel approaches, and open the door for improved outcomes regarding avian botulism, wetland management and resilient social-ecological wetland systems in Hawai‘i. With the substantial movement of waterbirds among wetlands, it is the responsibility of managers to similarly develop a web of communication across the state.

Historical Data Analysis

Spatial Trend by Island

Statewide trends of reported botulism cases by island vary significantly (Table 1), but also correspond to the scale of wetlands and suitable waterbird habitat with more case reports coming from older, wetter Hawaiian islands (Van Rees and Reed, 2008; Harmon et al., 2021; Work et al., 2010). Figure 1 shows a gradual increase of case reports over time, particularly in the 2000s, though we can not be certain if this is representative of increased cases over time or simply increased monitoring and/or reporting from wetland managers. Figure two shows several islands with consistent low numbers over the years, with peaks on Kaua‘i and Midway, islands with interconnected wetland systems home to large waterbird populations.

An outbreak of avian botulism on Midway Atoll in August, 2008, spread rapidly through the dense population of translocated Laysan Ducks (Work et al., 2010). The outbreak on this remote Northwest Hawaiian island was discovered two to three weeks after initial mortality and lasted another 50 days until mitigation measures including regular carcass removal and drainage of the largest pond on Midway, were able to bring case numbers down (Work et al., 2010). The remoteness of this island and limited response ability hindered response and mitigation efforts.

Kaua‘i, as compared to the other main Hawaiian islands, has the highest area of wetlands and potential waterbird habitat (Van Rees and Reed, 2008; Harmon et al., 2021). Thus, it makes sense that the most cases have been reported from Kaua‘i since 2011, mostly from Hanalei NWR, an area home to an expansive population of waterbirds. Large, interconnected wetlands are also harder to monitor for carcasses and lack the ability to easily control water levels or fully

drain wetlands that may be infected, practices used to stop outbreaks (Brandis et al., 2020; Reynolds et al., 2021). Further, the intensive monitoring and rigorous record keeping and reporting, ensures case reports are likely representative of actual cases on Kaua‘i. In part due to their chronically high cases, Hanalei is also a source of novel technology such as using dogs to aid in the detection of carcasses in densely vegetated areas (Reynolds et al., 2021).

Temporal Trends by Season

Hawai‘i, like many other tropical areas, experiences two seasons: the dry “summer” between May and October, and a wet “winter” between November and April (NOAA; Timm et al., 2015). Chi square analysis between avian botulism reports in Hawai‘i’s wet and dry season show a significant difference (Table 2), with case reports peaking at the end of dry season, in August, September and October when the air temperature is highest (Figure 3; Ghazal et al., 2019). Despite a longer tropical warm season, peaks in avian botulism cases in Hawai‘i correspond with global literature of botulism trends, with outbreaks tending to occur more frequently in late summer to early autumn, when abiotic conditions are most conducive to bacterial proliferation (Vidal, 2013; Wobeser et al., 1983; Carpentier, 2000, Perez-Fuentetaja et al., 2006; Russell et al., 2019; Shin et al., 2010). While predicting the main abiotic factors leading to avian botulism outbreaks remains a challenge (Sandler et al., 1993; Espelund & Klaveness, 2014; Prince et al., 2018), understanding Hawai‘i’s seasonal botulism trends is valuable to inform seasonally appropriate management strategies. Hawai‘i epizootic trends reflect key times for managers to heighten search efforts for carcasses to prevent outbreaks. Seasonal botulism spikes in warmer months are also a particular concern with climate change scenarios anticipating longer dry seasons in Hawai‘i, with diminished groundwater flow and higher annual temperatures (Timm et al., 2015; Leta et al., 2018; Ghazal et al., 2019, Brandeis et al., 2020).

Agency Reporting Trends

Analysis of case reporting by agency shows the FWS as the major reporter of avian botulism cases, followed by DOFAW and Private or Nonprofit agencies (Figure 4), which corresponds to Hawai‘i Statewide GIS records of wetland ownership by agency (Hawai‘i Statewide GIS Portal). The largest areas of wetlands suitable for waterbird nesting and feeding are owned by the Federal Government (managed by FWS), followed by the State of Hawai‘i (managed by DOFAW), and private individuals. As Federal and State agencies manage wetland resources to primarily promote waterbird populations and health, these wetlands host larger waterbird populations, which may increase the chance of rapid large-scale outbreaks in FWS and DOFAW managed wetlands once an initial botulism-caused death occurs (USFWS, 1978). FWS and DOFAW also have more regular monitoring for botulism as well as established protocols for reporting suspected botulism cases, compared with private landowners, making their high reporting numbers no surprise. While Federal and State agencies may own the largest parcels of wetlands, there are numerous small disconnected wetlands owned by private and nonprofit agencies which necessitates a broad awareness of botulism monitoring practices and timely standardized reporting to prevent widespread botulism outbreaks.

Management Implications and Future Directions

Analysis of historical avian botulism case data allows us to visualize reported case trends across the Hawaiian Islands and compare them with global literature. This is a vitally important tool in the prediction and rapid management of botulism outbreaks throughout the state. From our analysis we see that reported case trends correspond to islands with larger wetland habitat, outbreaks peak at the end of the dry season from August to October, and that the majority of cases are reported by Federal and State agencies. These analyses are likely a conservative estimate of statewide botulism cases due under reporting from various agencies and wetland owners, the challenge of confirming botulism without doing an autopsy (Perez-Fuentetaja et al., 2006), and differing detail of reports, limiting the amount of analyses we could perform on acquired data. We must ensure a standardized avian botulism reporting and data collection protocol exists, along with access to reports from various wetland managers and caretakers.

In addition to thorough data collection and recording, lasting network connections and reporting platform capacity must be maintained to support long term avian botulism prevention and response measures throughout the state. Our current work with USGS National Wildlife Health Center on inputting new botulism cases to their Wildlife Health tracing database (WHISPers) will ensure records are kept and accessible to managers and the public. Understanding the spatial, temporal and management reporting trends in avian botulism provide the perspective for statewide analysis of and collaborative management of a hard to control threat. This project filled a gap in historical data collection and analysis of avian botulism cases, as well as the establishment of a Hawai'i Waterbird Network connecting various wetland managers across Hawai'i.

Hawai'i Waterbird Network, Listserv and Website

The development of our Hawai'i Waterbird Network, listserv and reporting website (hiwaterbirds.com), will continue to promote ongoing communication of active botulism cases, sets a protocol for case reporting, and opens the door for enhanced manager communication of wetland BMPs.

The monthly network meetings in 2021 (Table 4) created a space to develop manager connections, set network goals and share common perspectives on waterbird threats and BMPs. This network not only started a conversation regarding threat management for native waterbirds (invasive predators, habitat loss and degradation, botulism, climate change), but it also began the development of social capital between agencies and managers of different wetlands (Ostrom and Ahn, 2009; Barnes et al., 2015). Discussions on the Waterbird Threat Assessment led to BMPs beyond the standard physical restoration of wetlands and predator control, to include network collaboration to apply for funding, publish research, public education, and having a network of volunteers to answer a call for botulism rapid response monitoring. This network remains important in the face of climate change, as wetlands and nesting waterbirds will be some of the first affected by sea level rise (Harmon et al., 2021). Network collaboration on developing BMPs, educational resources, and research provides hope for the capacity of further wetland protection and restoration throughout the state, as well as enhanced public perception of wetland value.

Our educational website (hiwaterbirds.com) contains general information on native waterbirds, avian botulism, and existing waterbird research coming out of the Hawai'i Wildlife Ecology Lab. The botulism case reporting feature sends an alert to our wetland manager listserv that a case has been detected, and prepares nearby wetlands for a potential outbreak. The rapid detection and communication of botulism cases is essential to stop the spread of avian botulism between wetlands (Friend and Franson, 1999), and this reporting portal encourages communication of cases across wetland management agencies.

Management Implications and Future Directions

This network is built on several previous iterations of network and botulism reporting efforts. While the majority of our listserv and 2021 network participants are from O'ahu (Table 4), we hope that as this network continues to grow, it will expand to better represent the diverse array of wetland managers and caretakers throughout the state of Hawai'i. The heightened presence of Private and Nonprofit representation in the listserv and network is exciting, particularly given the high number of smaller wetland parcels owned by private individuals. With the potential for heightened lo'i kalo restoration increases across the state (Harmon et al., 2021), it will also become more important to increase the representation of lo'i kalo farmers and agricultural wetland caretakers in our network of waterbird protection.

As we continue to live in an age characterized by rapid global change, resource managers are finding the need to adapt to challenges that arise and accept that just as important as managing ecological systems, we must manage the social systems and create collaborative networks in conjunction with natural resource management (Folke, 2006; Berkes, 2017). A foundation for creating resilient and adaptive social-ecological systems is the building of trust, reciprocal exchange of ideas or institutional knowledge, and network connectedness (Dacks et al., 2020; Walker et al., 2006). The Hawai'i Waterbird Network is a developing effort to create a space for collaborative efforts in addressing not only avian botulism but all challenges in managing our important wetland resources.

Conclusion

This project started as an initiative to address the issue of avian botulism and native waterbird management throughout the State of Hawai'i, and has since expanded to a call for enhanced collaborative space surrounding wetland resource management. Wetlands are part of a global and statewide network of interconnected abiotic features, biodiverse species, and human actors. It is integral to enhance relationships between communities, natural resources, and the people that manage resources to create resilient systems in the face of pervasive challenges such as avian botulism or climate change. This project analyzed spatial, temporal and agency reporting trends of historical avian botulism case reports to provide manager recommendations for addressing avian botulism in Hawai'i. It also started a manager network to build adaptive capacity in the protection of Hawaiian waterbirds and wetlands. The growing threat of avian botulism is one inherently tied into human systems of ecological alteration (Berkes, 2017). To address this issue, it is critical to recognize that sustainable management of resources and species requires not only knowledge of threats, trends, and BMPs, but also strengthening the scale of human interconnections to create large scale and long term change.

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