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Recruitment Dynamics of Invasive Mullet Species, *Osteomugil engeli*, in a Native Hawaiian Fishpond

Abstract

The Native Hawaiian fishponds (loko iʻa) of Hawaiʻi represent an extensive Indigenous aquaculture system that is in the process of being restored and holds immeasurable value as a site of cultural revitalization and sustainable food production. The mullet species *Mugil cephalus*, known as ʻamaʻama in Hawaiʻi, holds cultural and ecological significance in Hawaiʻi and is one of the main species traditionally cultivated in loko iʻa. In the 1950's, *Osteomugil engeli*, the Marquesan mullet or kanda, was accidentally introduced to Hawaiʻi and is now thought to be an invasive species that occupies a similar niche to the ʻamaʻama. Understanding the relative life histories of these two species is crucial when restoring loko iʻa as ʻamaʻama are a much more valued fish for price and palate. In Hawaiʻi, kanda are thought to spawn year round based upon studies of gonad ripeness, while ʻamaʻama spawn on an annual basis in winter. While gonad ripeness and the presence of juvenile kanda in the estuaries support year-round spawning, little is known about the specifics of kanda spawning or juvenile recruitment patterns in Hawaiʻi's coastal estuaries. This study analyzes 2 ½ years of data on observed kanda recruitment into the fishpond of Waiāhole, located on the east coast of the island of Hawaiʻi, in the ahupuaʻa of Waiākea. Results show that there are distinct peaks within kanda recruitment and that these peaks occur more frequently in summer months (May-October) and during the Hoʻonui and Poepoe moon phases in the Hawaiian lunar cycle, which encompass the waxing and full moon phases of each cycle. In addition, when compared to the Hawaiian lunar cycle, total average kanda recruitment during the Hoʻonui and Poepoe moon phases (46.4±2.76 and 51.2±4.04, respectively) was higher than average recruitment during the Hoʻemi (waning) moon phase (29.7±1.93).

Introduction

The loko iʻa (fishponds) of Hawaiʻi make up one of the most developed and complex Indigenous aquaculture systems across Oceania, once serving as a consistent source of food with the capacity to produce around 300-500 pounds of fish per acre annually (Cobb 1903). While the active management of loko iʻa was greatly diminished due to the impacts of Western colonization, a resurgence of Native Hawaiian culture, spurred by extensive activism for Native Hawaiian rights in recent years, has contributed to the renewed effort to restore these spaces to their original function (Keala 2007). Today, loko iʻa hold significant potential as a site of cultural revitalization and source of increased food sovereignty within local communities in Hawaiʻi.

The general structure of loko iʻa is simple yet efficient. These ponds are located along the coast where freshwater inputs mix with ocean water to create a brackish environment. A defining feature of many loko iʻa are their kuapā, or rock walls that separate the ponds from the ocean (Kikuchi 1976). The kuapā prevents fish from entering or leaving the pond and protects the habitat from intense wave energy, while still allowing for passive diffusion of water in and out of the pond through the cracks in the wall. Within the kuapā there are several openings that contain sluice gates called mākāhā, which are made of vertical bars or poles separated by small gaps. Several native species are adapted to the brackish habitat along the coast as adults, but require saltier waters during their larval or juvenile stages. After an initial growing phase in the ocean, these fish enter the pond while small and able to fit through the mākāhā; after some time within the pond consuming the abundant resources, they grow larger and are unable to leave, thus naturally stocking the pond.

Of the native species that follow this behavior (catadromy), a native species of mullet, the ʻama ʻama or *Mugil cephalus* commonly known as the striped mullet in English, is one of the most important for loko iʻa stewards (Manu 2006). This species holds both cultural importance for Kanaka Maoli, which is evidenced by the many locations across the Hawaiian islands named for their connection to the ʻamaʻama, and ecological importance as one of the only native species that has adapted to inhabit the low salinity coastal ecosystems in Hawaiʻi (Manu 2006, Fraiola and Carlson 2017). Based on Kanaka maoli historical knowledge as well as first hand observations, it is known that ʻama ʻama spawn in deep off-shore waters on an annual basis (Major 1978). The current kapu season, or no-catch period, for this species runs from December to March in order to protect mature adults during their spawning period. After spawning, the juvenile ʻamaʻama hatch at sea and spend about 2 months in the open ocean until returning to coastal waters, where they recruit into estuarine environments, including loko iʻa (Major 1978).

In the 1950's, a non-native species of mullet, *Osteomugil engeli* or kanda, was accidentally introduced to Hawaiʻi (Nishimoto et al 2007). The kanda, which is smaller in size compared to the ʻamaʻama, quickly established itself in Hawaiian ecosystems and is today considered invasive. This species is thought to fill a similar ecological niche to the ʻamaʻama, creating the possibility of competition between the two species (Schemmel et al 2019). In recent years, ʻamaʻama populations have decreased while kanda populations have increased (Nishimoto et al 2007), but there are many factors that could be affecting this trend and the relationship between these species has not been studied. The life cycle of the kanda is similar to that of the ʻamaʻama in that they also spawn in the open ocean and recruit into estuarine ecosystems as juveniles. In fact, the two species of mullet are indistinguishable at the age and size at which they enter the pond. One factor that has allowed for kanda populations to grow rapidly is the fact that they are thought to spawn year round. Research on kanda gonad ripeness and the observations of juvenile kanda recruitment support this hypothesis (Schemmel et al 2019), however, the specific details about kanda spawning and subsequent recruitment to coastal ecosystems have not been studied.

This paper uses recruitment data collected at the Kumuola Marine Science Education Center (KMSEC), located on the east coast of the island of Hawaiʻi in the ahupuaʻa of Waiākea, to analyze the observed trends in kanda recruitment over two and a half years. KMSEC manages three loko iʻa that, due to unique circumstances, are connected to the ocean through a single mākāhā. At this site, the mākāhā becomes clogged with debris on a daily basis, blocking entry of fish into the loko iʻa. While this is not ideal for creating a healthy flow of water in the ponds, it allows for the daily sampling of juvenile fish that are entering the pond but end up stuck just outside the mākāhā. This provides a unique opportunity to study recruitment of fish into a loko iʻa and the estuarine ecosystem more broadly as individual fish must be netted and brought inside the walls of the loko iʻa. These observations are generally not possible in natural settings or at other loko iʻa where unrestricted recruitment of fish can occur.

Because juvenile fish recruitment occurs over months and across large spatial scales, it would be a challenge to directly measure all of the relevant factors that may influence these processes. Past research conducted on other near-shore reef fish in Hawaiʻi have shown that recruitment tends to vary by *season*, with higher rates typically observed in the summer (Walsh 1987), as well as by *moon phase* (Caselle and Warner 1996, Bushnell et al. 2010), and suggests that *off-shore currents* have substantial impacts on the movement and transport of larvae (DeMartini et al, 2013), and likely other factors that are yet to be discovered. This study focuses on observed trends occurring solely in the final stages of kanda recruitment, the point at which the juveniles are entering the loko iʻa environment. This research is important because it grants insight into the life cycle of an invasive species, the kanda, which is relevant to those hoping to maintain the health of Hawaiʻi's coastal ecosystems and optimize production of native fish within loko iʻa. This work examines the relationship between kanda recruitment, season and moon phase, with the hypothesis that recruitment will be higher during the summer and will correlate with phases of the Hawaiian lunar calendar.

Methods

Sampling

This study includes data from July 2018 to December 2020, during which time 11,595 juvenile mullet were counted entering the mākāhā into ponds managed by KMSEC . These fish ranged from 2.5 to 3.5 cm in length and, as stated previously, were visually indistinguishable as either *M. cephalus* or *O. engeli*. To differentiate between the two species, KMSEC began a genetics program in 2019 to randomly sample the incoming cohorts (recruits entering the pond in the same day) of mullet and identify individuals as either ‘ama‘ama or kanda using DNA barcoding. The full details for the methodology used will be presented in a forthcoming manuscript.

Throughout 2019, the sampling protocol was to randomly select one individual from any cohort with >10 mullet. Under this sampling method, the genetic identity of an entire cohort with >10 individuals was assumed to be the same as the sample that was taken from it. Therefore, if the random individual taken from a cohort of 100 individuals was identified as *O. engeli*, then this was recorded as a cohort of 100 *O. engeli* individuals. This was modified in 2020 to 1 sample taken for cohorts with >10 individuals, 2 samples taken for cohorts with >50 individuals, 3 samples taken for cohorts with >100 individuals, 4 samples taken for cohorts with >150 individuals, and 5 samples taken for cohorts with >200 individuals. Under the revised method the genetic identity of the cohort was assumed to be proportional to those of the sample(s) taken from it. Therefore, if 2 of the samples taken from a cohort of 100 individuals were identified as *O. engeli* and 1 was identified as *M. cephalus*, the cohort was recorded as being 67 *O. engeli* and 33 *M. cephalus*.

Analysis

For this study, only the data reported for kanda (*O. engeli*) recruitment was used for analysis. Due to the fact that the genetics program at KMSEC did not exist until 2019, the data for 2018 does not report the species of each cohort. However, based on prior knowledge of the ‘ama‘ama life cycle and on the results from data collected in 2019 and 2020, which will be discussed later, it can be said that the chances of ‘ama‘ama recruitment from July to December are extremely low. Therefore, the data from January 2018 to June 2018 were excluded from this analysis to ensure analysis of data only accounted for kanda.

To identify peaks within the kanda recruitment data, a moving average and standard deviation were first calculated for each day. These calculations were based on the recruitment data 10 days prior and 10 days after every day, constituting a 20-day period for which the mean and standard deviation were calculated (excluding days with no data). This was applied to the entire two and a half years worth of data and days where the recorded recruitment was greater than 30 and greater than one standard deviation from the mean, were marked as ‘peaks’. These peaks were then grouped based on whether they occurred during summer or winter months (May-October and November-April, respectively) and by which of the three Hawaiian moon phases they occurred in, creating 6 combinations total. The designation for summer and winter months was based on the kau from the Hawaiian lunar calendar, which represent two distinct seasons, and research reported by Fox et al. 2021, where they found peak recruitment of two Hawaiian reef fish to occur in May-October. This is also supported by other studies on Hawaiian reef fish (Bushnell 2010 and Walsh 1987), as well as an early climate report of Hawai‘i (Blumenstock and Price1967), however they suggested that a five-month summer (May-August) was slightly more representative of climate temperatures. The Hawaiian lunar cycle repeats every 30 days (occasionally 29) is split into three, 10-day phases or anahulu: hoʻonui, poepoe, and hoʻēmi, which translate roughly to what is understood as waxing, full, and waning phases in Western terms. A chi-square test for homogeneity was used to analyze the distribution of the peaks across these variables.

Results

Utilizing the peak identification function described above, 45 peaks (days where the recruitment exceeded one standard deviation from the mean) were identified across the data set. Of the 45 peaks, 12 occurred within the months when ʻamaʻama recruitment was also possible, however the majority of the peaks as well as the majority of overall kanda recruitment occurred during months where ʻamaʻama recruitment was not observed (Fig. 1).

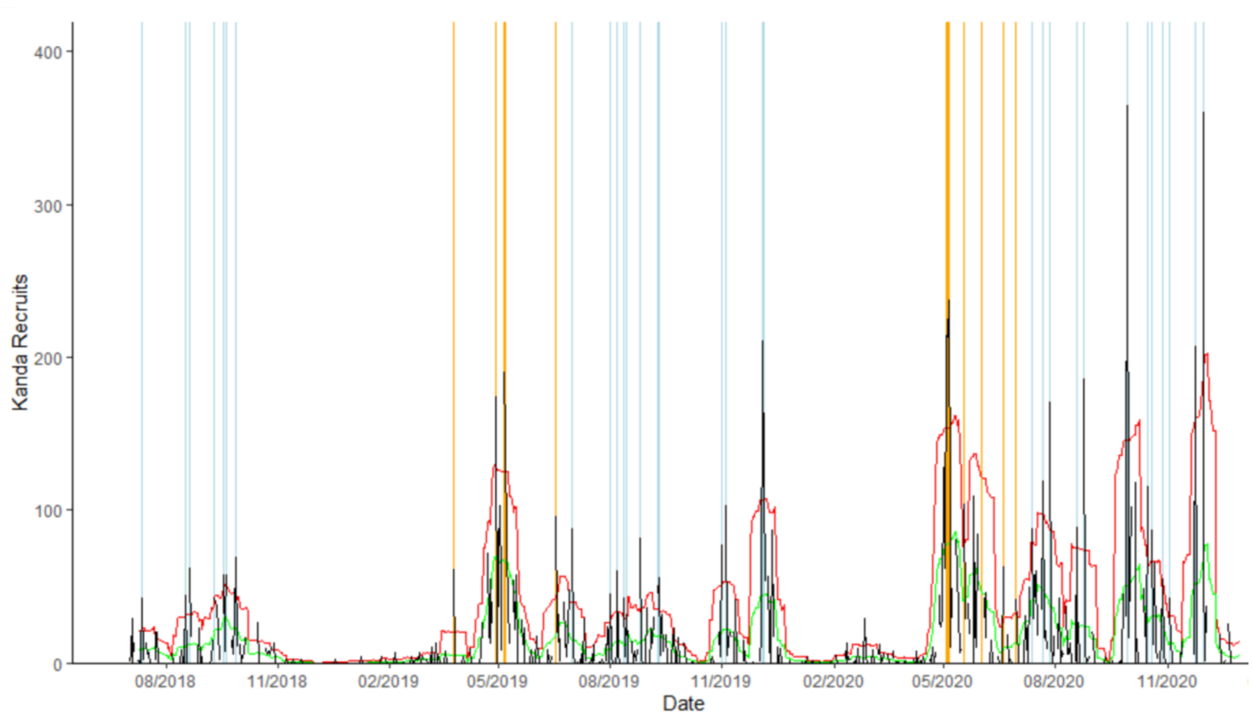

Figure 1: Observed kanda recruitment over time (black line). The green line represents the mean recruitment over a moving 20-day period and the red line represents the calculated value for one standard deviation from the mean. Days where recruitment exceeded one standard deviation from the mean were marked as peaks and are marked with vertical lines. Peaks marked in blue occur in July to December, when ʻamaʻama recruitment is minimal, and peaks marked in orange occur in January to June.

The peaks cluster into three groupings ranging from late April to December for 2019 and 2020, but only last up until October in 2018. The data shows increased total numbers of recruitment each year from 2018 to 2020, with no peaks higher than 100 in 2018 and some reaching above 300 in 2020.

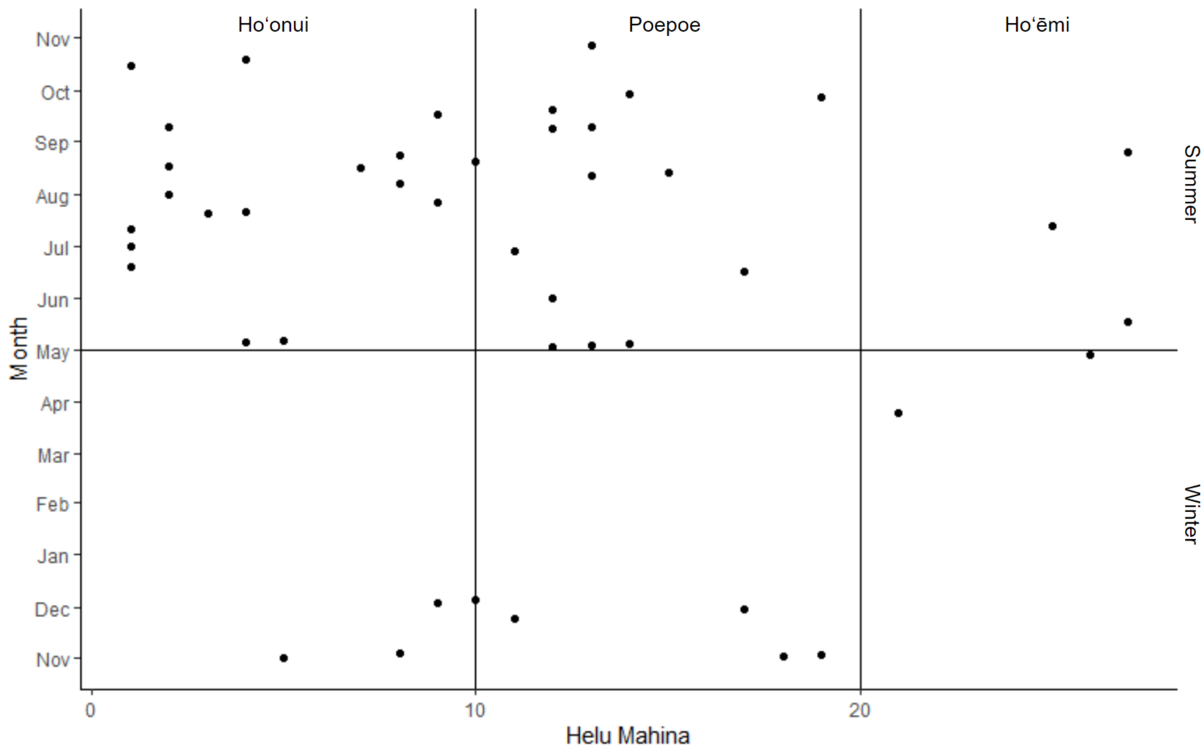

Figure 2: Occurrence of peaks in calendar year vs Hawaiian lunar cycle. Each dot represents one of the peaks identified in Fig. 1. Helu mahina refers to the individual day within the Hawaiian lunar cycle, where days 1-10 are in hoʻonui, 11-20 are in poepoe, and 21-30 are in hoʻēmi. Lines are used to delineate the anahulu and the separation between summer and winter months.

The 45 spikes of recruitment analyzed in this data set occurred largely in summer (May-October) and during the hoʻonui (days 1-10) and poepoe (days 11-20) moon phases. Seventeen peaks occurred in the summer during hoʻonui, while 15 occurred in the summer during poepoe. These two combinations of factors account for 32 of the 45 peaks, with the remaining 13 distributed relatively evenly across the remaining four seasonal and lunar combinations. The chi square test for homogeneity run on this data was highly significant, with a p-value less than 0.001.

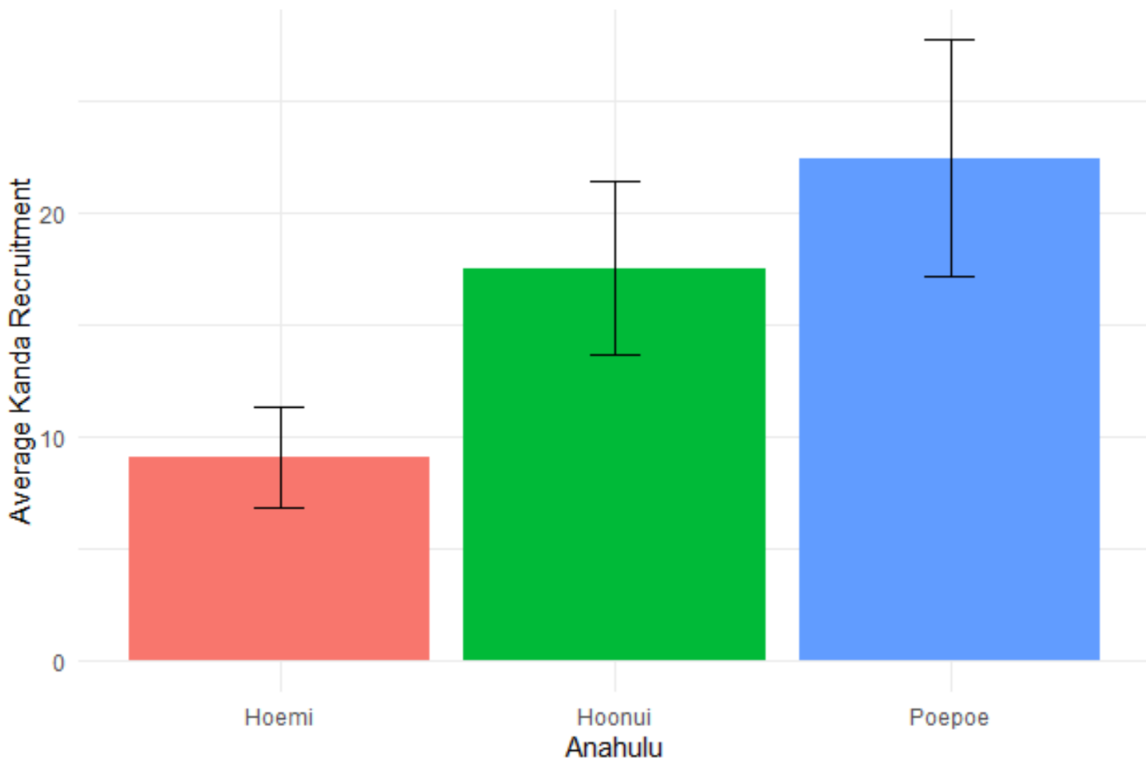

Figure 3: Average daily kanda recruitment by anahulu with standard error (SE). Average daily recruitment during the hoʻēmi moon phase was significantly lower than during the hoʻonui or poepoe moon phases.

The results from Fig. 2 are consistent with those shown in Fig. 3, which depicts the average recruitment for each anahulu. While the separation in standard error shows that hoʻonui and poepoe have higher average recruitment than hoʻēmi, the standard deviation for each group is very high due to the large number of zeros interspersed by large spikes in recruitment. That said, when using a generalized linear model to fit the data to a negative binomial distribution it was found that both hoʻonui and poepoe were both significantly different from hoʻēmi, with p-values of 0.003 and <0.001 respectively, thus verifying the observations made in Fig. 3.

Discussion

Based on the results described above, it can be concluded that peaks in kanda recruitment occur disproportionately during summer months (May-October) and during the anahulu hoʻonui and poepoe. The higher number of peaks during summer matches what other studies have shown for different species of reef fish in Hawaiʻi and may be related to the optimal water temperature conditions for spawning (Danilowicz 1997). However, it is also possible that there are other factors, such as currents, that are affecting the recruitment of kanda during the time between spawning and juvenile return to near shore environments. The observed relationship between moon phase and recruitment is one that has been much less explored in research done on fish recruitment in Hawaiʻi. Caselle and Warner (1996) found that 74% of settlement of *Thalassoma bifasciatum* in the U.S. Virgin Islands occured around a 2 week period surrounding the new moon. Other studies have shown that fish spawning events in the tropics are often linked to changes in the lunar cycle (Bushnell 2010, Lobel 1978, May et al. 1979), there has not been much evidence to show that recruitment is similarly related in Hawaiian fish species. While this data alone may not be able to identify whether the observed recruitment patterns are driven by spawning cues or recruitment cues, this result does give valuable insight into the life cycle of kanda as it relates to the loko iʻa managed by KMSEC and the surrounding ecosystems.

The results also show a high variability in the overall recruitment from year to year, with higher recruitment occurring in 2020. While some thought points to oscillations in El Nino and La Nina (Fox et al. 20012) as the cause of annual variation in spawning and recruitment of fish in the Pacific, this does not seem to be the case in this situation given that El Nino activity was fairly neutral in early to mid 2020 (World Meteorological Organization). However, given that there is a general tendency for high variation in the recruitment of other reef fish in Hawaiʻi and that only three years of data are included in this study, not much can be said about the significance of this observation.

This study offers insight into the complex dynamics of kanda recruitment. While the data only reflects one phase of the recruitment process at a single site, the information gained remains relevant to the loko iʻa of KMSEC and most likely the surrounding nearshore waters and estuarine areas of east Hawaiʻi. Because the data from this study identified defined patterns in kanda recruitment at this level, it demonstrates that there is value in continuing and extending this research beyond the walls of these fishponds in order to make conclusions about kanda recruitment more broadly. To better understand the dynamics of kanda recruitment and the variables that influence it, further research examining the period between spawning and the return of juveniles to coastal ecosystems, including analysis of how prevailing currents and water temperature affect this process is needed. Additional collaborations conducted spanning larger spatial scales would also be beneficial, however not many loko iʻa have the same physical structure that allows for the sampling of recruits at the time scales represented in this study.

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