

Recruitment dynamics and fishery characteristics of juvenile goatfishes *Mulloidichthys* spp. in Hawai'i

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Abstract

The most common goatfishes in Hawai'i, *Mulloidichthys flavolineatus* and *M. vanicolensis*, comprise a unique resource due to their cultural, ecological and biological significance. These species exhibit pulse-type recruitment to nearshore areas during the summer months. Such pulses of juvenile fishes provide prey for pelagic and nearshore fishes and support a popular directed fishery. However, limited scientific information exists on juvenile stages of these fishes, known locally as oama, despite their contribution to coastal ecology and the extensive nearshore fisheries. Here we resolve growth rates, habitat preferences, hatching dates, size and age structure, as well as fishing catch rates based on new recruits in 2014 and 2015. We sampled 257 *M. flavolineatus* and 204 *M. vanicolensis* to compare ecological and fisheries characteristics between species and years. Both show strong habitat segregation, with *M. vanicolensis* found almost exclusively on hard and *M. flavolineatus* on soft substrates. Oama recruited in anomalously high numbers in 2014, a trend reflected in a higher catch per unit effort. In contrast, 2015 recruits grew faster, were heavier on average and hatched later than during 2014. Both species have calculated hatch dates in March to July, with *M. vanicolensis* hatching earlier, recruiting earlier and being consistently larger than *M. flavolineatus*. This baseline information regarding recruitment and early life-history characteristics can enhance management for other data-limited species that comprise a substantial component of nearshore fisheries in Hawai'i.

KEYWORDS

age and growth, early life history, Hawai'i, *Mulloidichthys*, nearshore fisheries, recruitment pulse

1 | INTRODUCTION

Fishing is integral to traditional and contemporary Hawaiian lifestyles (Friedlander *et al.*, 2013; Pooley, 1993; Tissot *et al.*, 2009; Titcomb, 1972). Commercial fisheries in Hawai'i mainly target pelagic species (e.g., tunas and billfishes), with nearshore species accounting for <1% of the commercial landings (DAR, 2015). In contrast, the number of non-commercial fishers in Hawai'i is estimated to be 200,000–400,000, compared with 3715 registered commercial fishermen in 2015 and the nearshore catch of these fishers is c. 10 times

greater than their commercial counterparts (McCoy *et al.*, 2018). Despite the social, economic and cultural significance of ocean resources to this island state, there are still many data-poor fisheries. The popular nearshore fishery for juvenile goatfishes (Mullidae; locally known as oama) is a prominent example.

The most common goatfishes in Hawai'i are the yellow stripe goatfish *Mulloidichthys flavolineatus* (Lacépède 1801) and the yellowfin goatfish *Mulloidichthys vanicolensis* (Valenciennes 1831). The juveniles of these species aggregate in large numbers in shallow nearshore areas around the main Hawaiian Islands (MHI) during the summer and

autumn (June–September), ranging from boat harbours and canals to sandy bays and reef flats (Sato *et al.*, 2008; Tagawa & Tam, 2006). They are considered a delicacy by local fishers, as well as being popular bait to catch larger coastal predators such as jacks (Carangidae; Holland *et al.*, 1993). Despite their abundance, as well as their fisheries and ecological importance, there is limited scientific information on the life history and biology of these species. However, extensive traditional and local ecological knowledge exists because of their cultural importance, as well as grey literature and anecdotal information in the popular press. Fishery management of oama is rudimentary, as is the case for many coastal fisheries in Hawai'i (Friedlander *et al.*, 2017). For example, the current fishing restrictions apply only to *M. flavolineatus*, with a bag limit of 50 fish day⁻¹.

The limited body of research on goatfishes in Hawai'i is almost exclusively focused on adults (Holland *et al.*, 1993; Meyer *et al.*, 2000; Moffit, 1979). There has been some characterisation of spawning (Cole, 2009), but few studies exist on their recruitment and early life histories. Recruitment dynamics of juvenile goatfish, along with reproductive size and spawning of adults, are poorly known. Information is also lacking on the interaction and differences between the juvenile stages of these two species although they appear to share similar recruitment characteristics. One prominent gap is the differences in habitat preference between these goatfish species.

Understanding early life history characteristics provides fundamental information for fisheries management and ecology (Sale, 2004). This is particularly true for *M. flavolineatus* and *M. vanicolensis* that are heavily exploited during their post-recruit juvenile stages, when nearshore fishers target them with hook and line. Identifying essential recruitment habitat also plays a pivotal role in fisheries management, especially when they are occupying nursery habitats during specific, discrete times during the year. The predictable temporal component of these goatfishes' recruitment presents ample opportunity to study their early life-history characteristics.

The objectives of this study were to examine and compare early life history characteristics for *M. flavolineatus* and *M. vanicolensis* from north shore locations on the island of Oahu, Hawai'i, USA, during the summer of 2014 and 2015 and characterise habitat settlement preferences and an index of abundance using catch per unit effort (CPUE) over the course of each sampling season. Baseline life-history and recruitment information will prove valuable in informing management decisions in Hawaii's dynamic fisheries and climate regimes.

2 | MATERIALS AND METHODS

Oama collections were made under protocol 15–2271 from the University of Hawai'i Institutional Animal Care and Use Committee.

2.1 | Samples sites and collections

Haleiwa Harbour and Kawela Bay on the north shore of Oahu were chosen as sampling sites (Figure 1) due to their remoteness, the co-

occurrence of both species and potential lack of competition with other anglers. Samples were obtained from local fishers throughout the fishing season starting in May through October in 2014 and 2015. Standard fishing gear used by local anglers consisted of a retractable fibreglass hand pole, 2 pound (c. 1 kg) test fluorocarbon fishing line, a clamp split shot lead and a size 20 limerick hook (www.mustad-fishing.com/product/limerick?color=Duratin). Bait consisted of tuna scraps or skipjack tuna *Katsuwonus pelamis* (L. 1758) belly. Fishing and sampling occurred in very shallow waters, ranging from 0.3 to 1 m deep.

Haleiwa Harbour and Kawela Bay both have soft bottom habitats consisting of mud or sand, adjacent to hard bottom rock and reef habitat (Figure 1). After visually locating the schools of target species, we recorded habitat type, number of each species caught, fishing duration, location and CPUE ($n\ h^{-1}$ fished). Fishes were kept on ice by anglers before later processing in the laboratory. Mass (M , g), fork length 399, total length (L_T , cm), species, date and location were recorded for each specimen used in the study. A specific identification number (ID) was designated for each fish; each head was removed, placed in a Whirl-Pak bag (Nasco; www.enasco.com) and stored frozen.

2.2 | Dissections and otolith analysis

Both sagittal otoliths were removed and cleaned with water and a small paintbrush. Otoliths were dried, then placed in small vials with ID labels. Sagittal otoliths were mounted concave side up on glass slides with the glue Crystal Bond 409 (www.agarscientific.com; Wilson & McCormick, 1997, 1999). Otoliths were initially mounted on microscope slides such that the core area was just inside the slide edge while the postrostral side protruded over the edge of the slide. The exposed post rostrum was ground down to the edge of the slide with 40 μm lapping film. The glue was reheated and the polished face was then placed face down on the slide and the rostral end was ground with 40 μm film again to produce a transverse section. This second round of grinding stopped when the otolith core region was exposed. A series of manual polishings were achieved using 3 μm lapping film, followed by 0.3 μm film until daily growth increments (DGI) were visible outward from the core to the dorsal side outer edge of the otolith. Otolith readings were conducted under $\times 40$ objective magnification and a $\times 10$ eye piece on a compound microscope.

2.3 | Growth

Each fish was aged by conducting blind counts of the DGIs with a second reading conducted by a different reader. Deviations between readers at $\leq 10\%$ were deemed acceptable (Zerbi *et al.*, 2001) and resulted in only one specimen removed from analysis. Growth was modelled with a linear relationship $t = a L_F + b$, where t is age (days), a is the scaling parameter for the slope and b is the y-intercept (theoretical length at age 0). A multiple linear regression was used to determine if age, location, year, or species were significant indicators

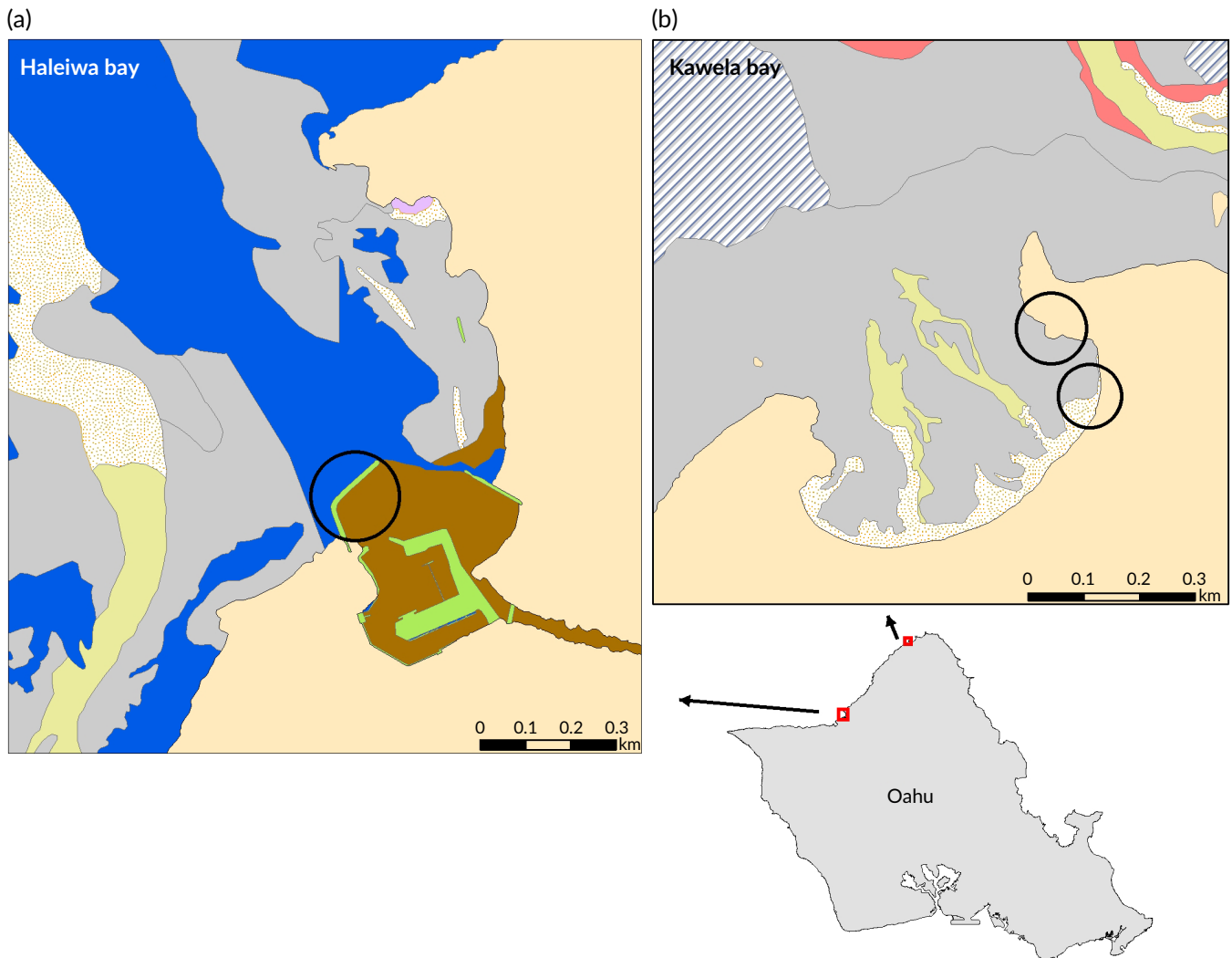


FIGURE 1 Benthic habitat maps for (a) Haleiwa Harbour and (b) Kawela Bay showing sampling sites (○) for juvenile *Mulloidichthys flavolineatus* and *M. vanicolensis* located on the north shore of Oahu, Hawai'i, USA. Benthic habitat (■) Aggregate reef, (■) artificial, (■) land, (■) mud, (■) pavement, (■) pavement with sand channels, (■) rock/boulder, (■) rubber, (■) sand, (■) scattered coral/rock, (■) spur and groove, and (■) unknown

of L_F . ANOVA was used to compare growth rates between 2014 and 2015, and between *M. flavolineatus* and *M. vanicolensis*. The length-mass relationship was described by $M = a L_F^b$.

Hatch dates were obtained by subtracting the fish's age in days from the capture date. A Kruskal-Wallis rank-sum test was used to compare hatch dates between years, species and a combination of species and years.

2.4 | Catch-per-unit-effort

Nominal CPUE was calculated by dividing the number of fish caught by the duration (in hours) of each fishing trip supervised by the lead author. CPUE data were collected on each substrate type at both locations. Due to the high variation in the data and large number of zero values, a moving average analysis was conducted over a window

of three values. This softened the extremely high values and reduced the impact of the zero values (Yanez *et al.*, 2001).

3 | RESULTS

3.1 | Sample collections

A total of 461 juvenile *Mulloidichthys* spp. were retained for analyses: 257 *M. flavolineatus* and 204 *M. vanicolensis*. Ten *M. flavolineatus* were excluded from the analyses because they exceeded the 17.8 cm L_F (7 in) size designation of oama and were unlikely to be early-season young-of-the-year recruits. This is based on gonad histology data from Hawai'i that indicates first maturity begins at 18 cm L_F and 16.5 cm L_F for *M. flavolineatus* and *M. vanicolensis*, respectively (Cole, 2009). The L_F range of *M. flavolineatus* was 8.5–17.6 cm (mean \pm SD = 10.2 \pm 1.1 cm) and for *M. vanicolensis* 9.0 to 15.0 cm (mean

\pm SD = 11.9 ± 1.0 cm; Figure 2). A total of 302 fishes were aged, comprising 171 *M. flavolineatus* and 131 *M. vanicolensis*. Some fishes were not aged due to constraints such as broken or cracked otoliths. Ages ranged from 61 to 185 days (mean \pm SD = 83.5 ± 15.4 days) for *M. flavolineatus* and 72 to 141 days (mean \pm SD = 101.5 ± 13.3 days) for *M. vanicolensis*. Habitat type was nearly exclusive for each species, with all but three *M. flavolineatus* (< 1%) captured on soft substrate and all but three *M. vanicolensis* (1.5%) captured on hard substrate. Captured *M. flavolineatus* were tan and yellow in colour compared to the red-orange of *M. vanicolensis*.

3.2 | Early life-history characteristics

A significant linear relationship was found between L_F and age ($r^2 = 0.82$, $P < 0.001$). There was no significant difference in growth rates (regression slopes) between species (Supporting Information Figure S1) and all

fishes combined in 2015 grew significantly faster than in 2014 ($F_{1,294} = 20.93$, $P < 0.001$; Figure 3).

Juvenile *Mulloidichthys* spp. also had a significant relationship between L_F and M ($r^2 = 0.96$, $P < 0.001$; Table 1). Fishes in 2015 were heavier, on average, than in 2014 ($F_{1,436} = 8.63$, $P < 0.01$) and *M. vanicolensis* were heavier at a given length compared with *M. flavolineatus* ($F_{1,436} = 37.39$, $P < 0.001$). A comparison of mean L_F revealed no significant differences between years, but *M. flavolineatus* were shorter on average than *M. vanicolensis*.

Hatch dates clustered during the spring and summer months (March–September; Figure 4). *Mulloidichthys* spp. in 2014 hatched earlier than in 2015 ($\chi^2 = 39.73$, $P < 0.001$) and *M. vanicolensis* hatched earlier than *M. flavolineatus* overall ($\chi^2 = 22.03$, $P < 0.001$). Pelagic larval duration (PLD) for both species was unattainable because of the difficulty in identifying a consistent settlement mark or change in DGIs appearance that delineated the transition to the reef environment.

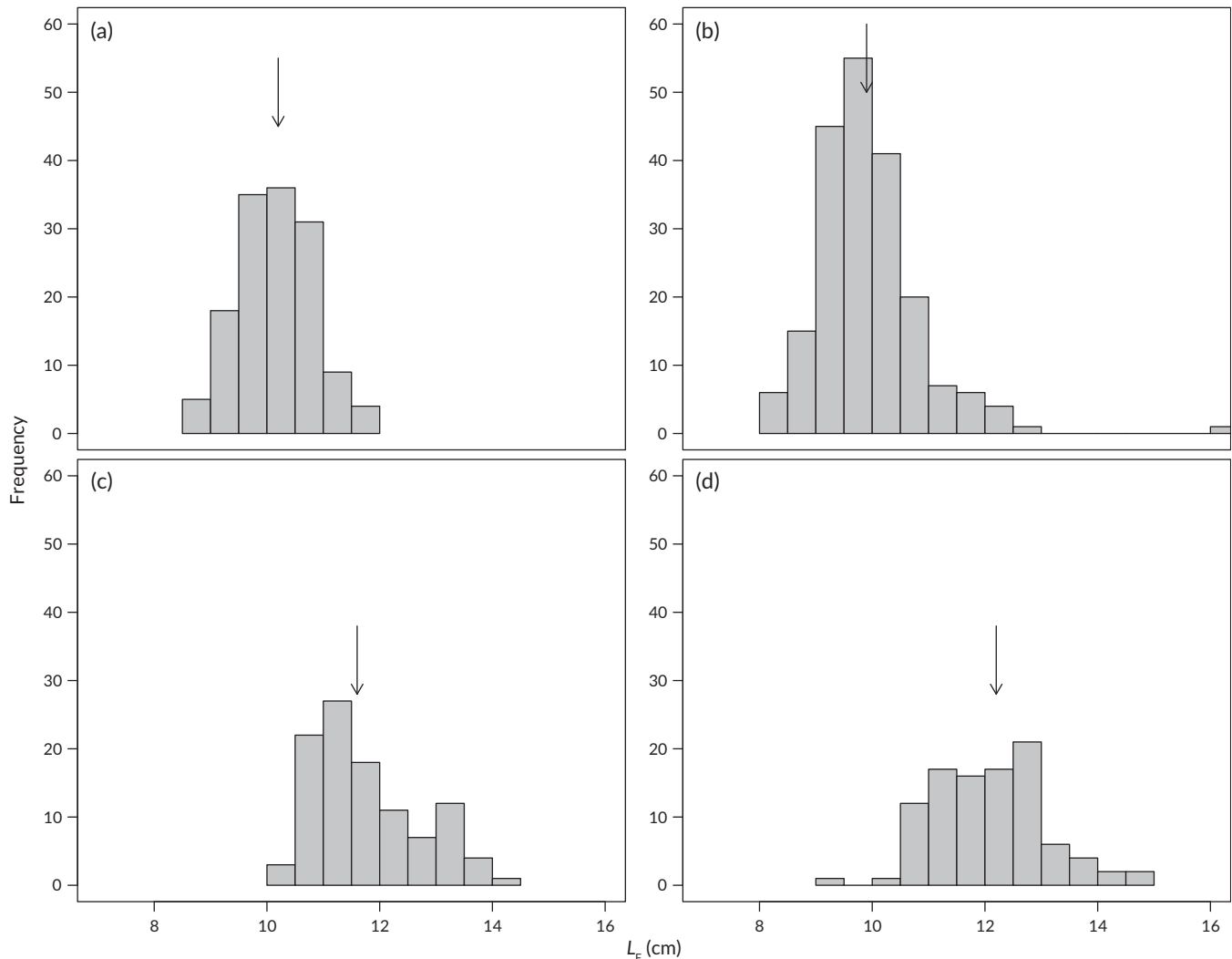


FIGURE 2 Fork length (L_F)-frequency histogram of juvenile *Mulloidichthys flavolineatus* in (a) 2014, (b) 2015) and *M. vanicolensis* in (c) 2014 and (d) 2015) sampled on the north shore of Oahu, Hawai'i, USA. Mean sizes for *M. flavolineatus* was significantly shorter compared to *M. vanicolensis* ($F_{1,455} = 399.63$, $P < 0.001$). \downarrow , Median fork length

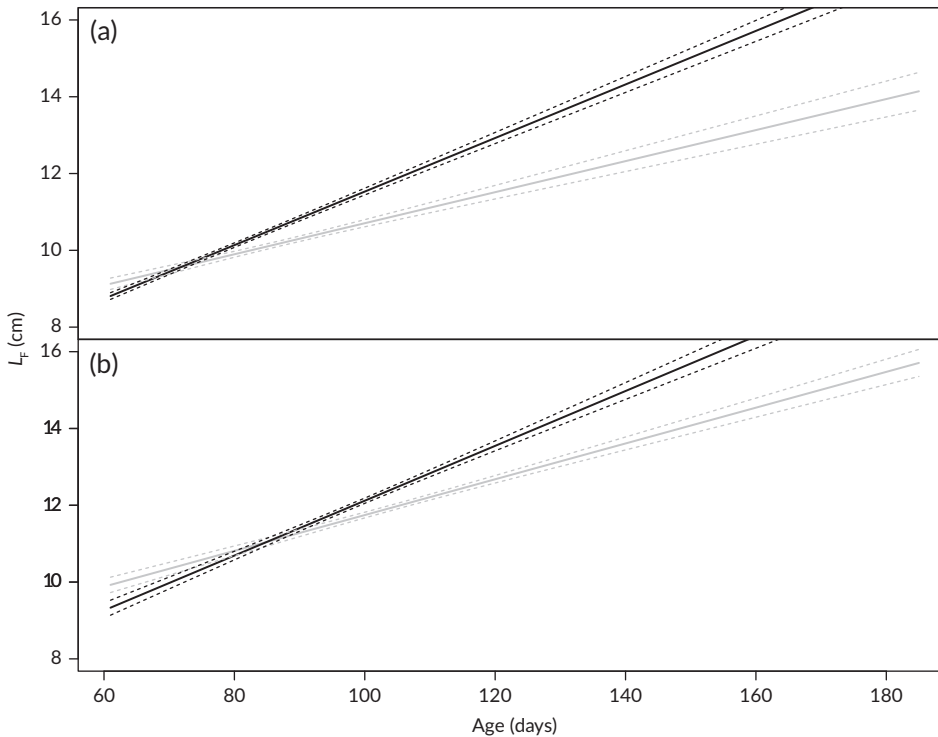


FIGURE 3 Growth curves for for juvenile a) *Mulloidichthys flavolineatus* and b) *M. vanicolensis* in 2014 (—) v. 2015 (---). ····, ····, SE

Species	Year	Location	Collected	Aged	<i>a</i>	<i>b</i>
<i>M. flavolineatus</i>	2014	Haleiwa	70	33	0.0027	3.6965
		Kawela	68	34	0.0029	3.6965
	2015	Haleiwa	50	47	0.0046	3.6503
		Kawela	69	57	0.0046	3.6503
<i>M. vanicolensis</i>	2014	Haleiwa	66	39	0.0029	3.6965
		Kawela	39	23	0.0029	3.6965
	2015	Haleiwa	56	44	0.0050	3.6503
		Kawela	43	25	0.0049	3.6503

TABLE 1 Number of juvenile *Mulloidichthys* spp. sampled, aged, and length–mass ($y = ax^b$) parameters for all species, sites, and years

3.3 | Catch per unit effort

Nominal CPUE ($n \text{ h}^{-1}$ fished) collected from June to October in both years provided 158 data values between both habitat types and among both locations. Values ranged from 0 to 29 fish.

h^{-1} for *M. flavolineatus* and 0 to 55 fish h^{-1} for *M. vanicolensis*. CPUE values were lower in 2015 compared with 2014 and peaks were earlier in 2014 compared with 2015 (Figure 5). *Mulloidichthys vanicolensis* peaked earlier than *M. flavolineatus* in 2014 (Figure 5) and the *M. vanicolensis* peak in 2015 was later compared with 2014 (Figure 5).

4 | DISCUSSION

The annual recruitment of oama into shallow water habitats in Hawai'i is atypical among coral-reef fish species in terms of their characteristic pulse appearance, their accessibility to shoreline fishers and the

cultural significance of this juvenile food fish. In the western Pacific Ocean, a fishery for oama (known there as ti'ao) also occurs on the islands of Guam and Saipan in the Marianas Archipelago where their annual recruitment, availability and cultural importance are similar to Hawai'i (Myers, 1989). Although both oama species inhabit the oceanic islands of the western and central Pacific Ocean, genetic analysis indicates no evidence of population divergence across this expanse (Lessios & Robertson, 2013). Presumably their long pelagic larval duration (45–50 days) and subsequent larger size at recruitment (5–10 cm) contributes to this connectivity. Furthermore, their benthic-phase life history is characterised by a relatively short mean lifespan (5–6 years) and an early onset (by age 1) of reproductive maturity (Nadon, 2017). These benthic-phase life-history traits are more characteristic of near-shore pelagic species and distinguishes them from most coral-reef fish species targeted by island fisheries (Birkeland, 2017).

The 2014 high recruitment event differed from typical annual recruitment as it was reported from areas beyond Hawai'i in the

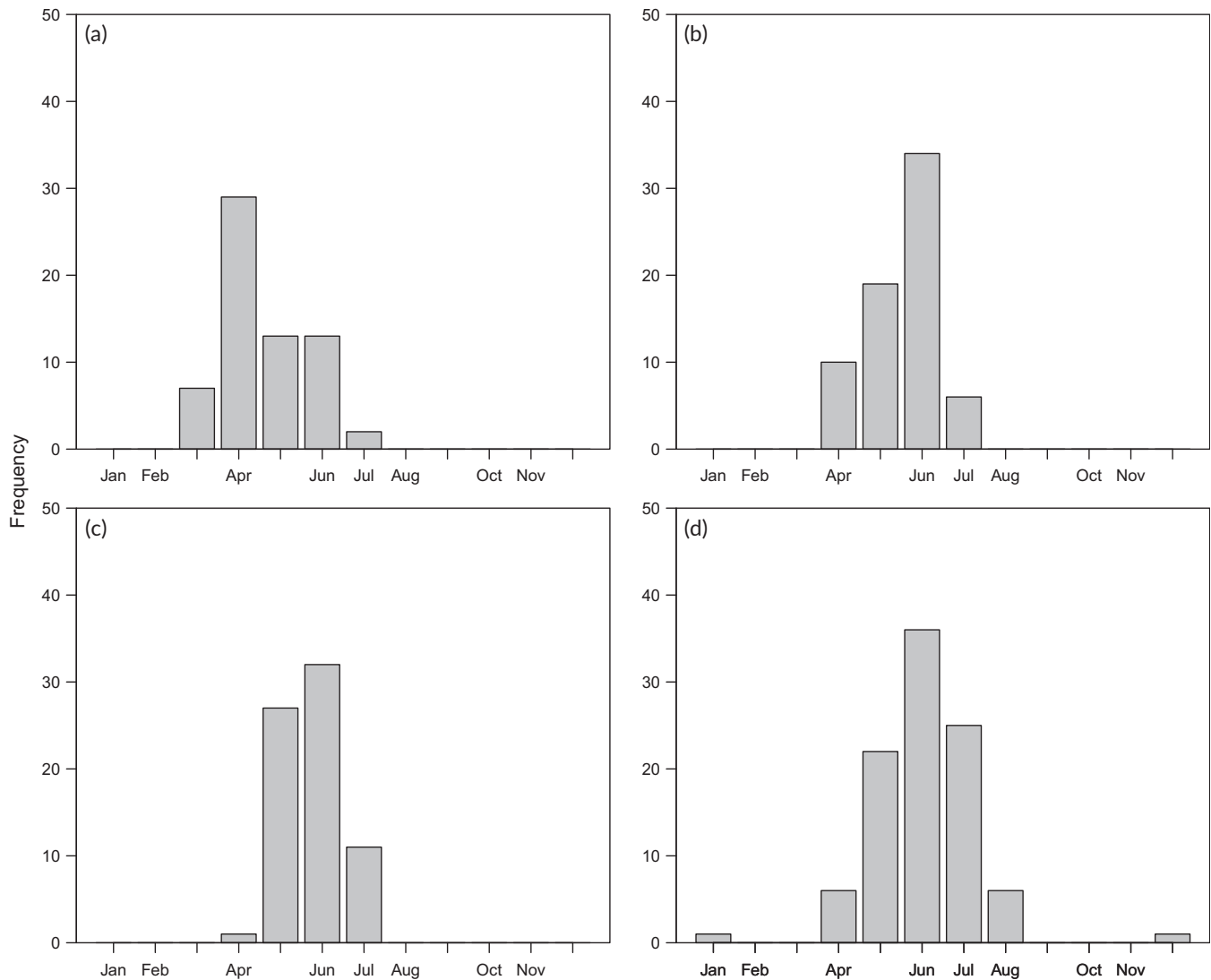


FIGURE 4 submitted as Fig 5 Hatch dates juvenile *Mulloidichthys vanicolensis* in a 2014, b 2015, which hatched earlier than *M. flavolineatus* c 2014 and d 2015. Hatch dates for both species were later in 2015 than in 2014

central Pacific Ocean and consisted of a multispecies pulse in Hawai'i including 6–8 coral-reef fish species reported from shallow-water reef areas (Talbot, 2014). This 2014 phenomenon provided the rare opportunity to evaluate early life-history characteristics of recruits associated with an average recruit year (2015) and a rare boom year (2014). We observed high recruitment, based on catch rates, at both study sites for both species in 2014 compared with 2015. Recruitment was also earlier in 2014 compared with 2015. This 2014 recruitment pulse may have resulted from favourable oceanographic conditions that affect the timing and magnitude of recruitment (Sponaugle, 2015), but cannot explain why these few particular reef-fish species and not others, attained high recruitment levels.

The dramatically higher recruit densities in 2014 may have increased competition for food and shelter leading to increased post-settlement mortality (Dahlgren *et al.*, 2006; Hixon *et al.*, 2012). Experienced anglers agreed that the 2014 season was the best in 20–30 years. While the increased abundance benefited anglers, it also resulted in reduced growth rates. Spatial recruitment patterns of these

juvenile goatfishes are concordant with local ecological knowledge, but in 2014 many anglers reported schools occupying alternate (presumably poorer quality) habitats, such as polluted and stagnant canals and runoff channels. Classic density-dependent mechanisms affect recruitment by reducing available refuge habitat, leading to stunted growth or increased predation (Forrester, 2015). Higher resolution of daily growth, especially before and after a settlement mark, would indicate more precisely when reduced growth occurred. These conditions can increase both natural and fishing mortality and diminish the contribution of a year class to enhance both adult population size and reproductive success.

Juvenile *Mulloidichthys* spp. abundance influences the health of coastal ecosystems in Hawai'i. Mullidae are ecosystem indicators and engineers and excessive extraction, especially on unregulated species such as *M. vanicolensis*, may have a ripple effect through the near-shore environment (Uiblein, 2007). Many nearshore predators depend on strong goatfish recruitment to ensure growth and healthy populations, according to both traditional knowledge and scientific

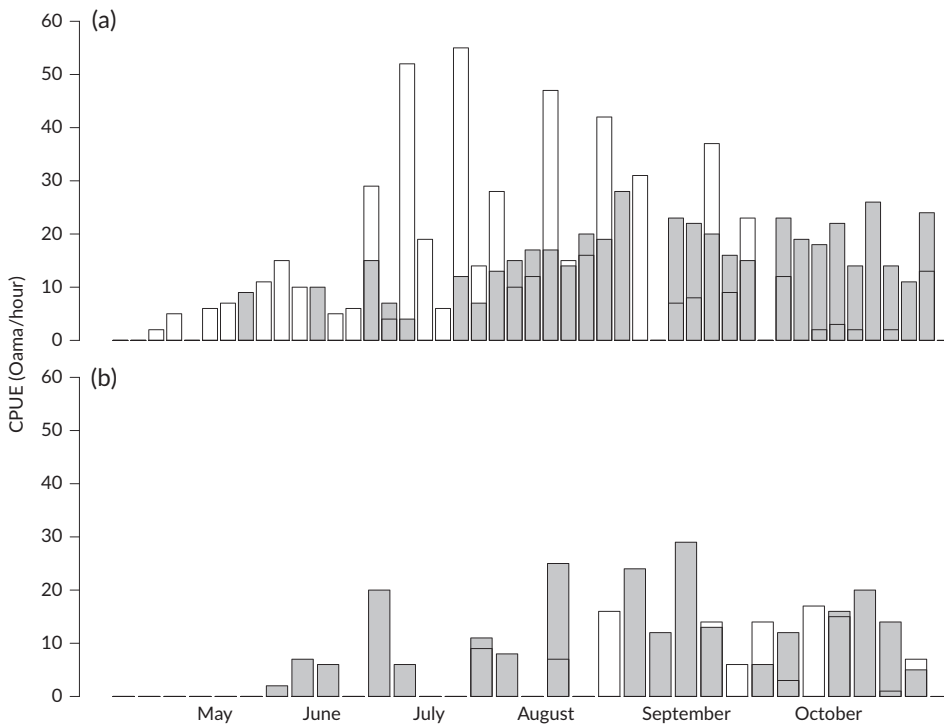


FIGURE 5 Catch Per Unit Effort (CPUE) for *Mulloidichthys flavolineatus* (■) and *M. vanicolensis* (□) in (a) 2014 and (b) 2015

investigation (Meyer *et al.*, 2001; Tagawa & Tam, 2006). In addition, pre-settlement oama are found in the stomachs of offshore pelagic predators such as skipjack tuna, wahoo *canthocybium solandri* (Cuvier 1832), as well as seabirds (Harrison *et al.*, 1983; Oyafuso *et al.*, 2016; Waldon & King, 1963; Yuen, 1959). Therefore, recruitment, abundance and growth patterns of these two goatfish species can impact several trophic levels.

The juvenile fishery targeting the annual recruitment of oama into shallow reef habitats in Hawai'i and in other island locations in the western and central Pacific Ocean is not unprecedented. A larger scale fishery, in terms of catch levels, targets the juvenile recruits of several species of Siganidae (rabbitfishes) on tropical islands of the western Pacific Ocean, particularly in the Philippines and Guam (Bagarinao *et al.*, 1986; Hensley & Sherwood, 1993). Juvenile siganids seasonally recruit to shallow reef flats forming large dense schools that are traditionally harvested using fishing nets (Kami & Ikehara, 1976; Teitelbaum *et al.*, 2008). However, in certain areas, especially the Philippines, annual harvests are considered to be excessive leading to concerns of growth overfishing (Ramirez, 2013; Soliman *et al.*, 2009). Similar concerns extend to the net harvests of juvenile *Mulloidichthys flavolineatus* in Guam, which underwent an order of magnitude decline in annual catch during 1985–1991 (Hensley & Sherwood, 1993).

Traditional harvesting of oama in Hawai'i does not include the use of fishing nets as practised in the western Pacific Ocean for both *Mulloidichthys* spp. and juvenile siganids. Therefore, future management reviews should carefully consider any loopholes in the current regulations that could unintentionally allow the introduction of new fishing practices capable of mass capture of oama. Currently, oama can only be taken with hook and line in Maui, thereby restricting mass harvest methods. A bag limit of 50 fish day⁻¹ applies to *M. flavolineatus* but there is no catch limit on *M. vanicolensis*, so large unsustainable harvest

methods remain unrestricted. A similar regulatory lapse was exploited to harvest sea cucumbers (Holothuria) to the point of depletion in some areas of Hawai'i (DAR, 2016). Protecting shallow nearshore nursery habitats from various net uses will also greatly benefit juveniles, especially since relatively small reserves are able to generate adults that have a larger range (DAR, 2007; Holland *et al.*, 1993; Meyer *et al.*, 2000). Future management strategies may also want to distinguish between the two species of oama, as the results here indicate biological and ecological differences that could influence sustainable harvest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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