Environmental drivers of non-commercial reef fisheries in Guam

BY
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AN ABSTRACT OF THE THESIS of Leilani Sablan for the Master of Science in Biology, presented, July 25 2023

Title: Environmental drivers of non-commercial reef fisheries in Guam

Guam’s non-commercial reef fisheries are prevalent and essential for society and culture, yet they remain poorly understood when compared to their commercial counterpart. This study examined the variable influence of season, geography, and lunar phase on harvested biomass, catch composition, and landed size of reef-associated landings from Guam’s dominant non-commercial fishing methods. Creel surveys were conducted over a one-year snapshot period from 2021 to 2022, sampling 5474 fishes comprising a total of 2025 kg of landings. Hierarchical regression trees for environmental factors showed season was the most important predictor of landings, where the calm seasons were predicted to yield the most kg/day. Lunar phase was a secondary predictor of landings. Catch composition differed across seasons and geographic regions with higher effect by geography. Species with habitat preferences characteristic of the windward coast (i.e., wave-exposed, shallow reefs) became more exploited as winds and surf fell during the calm periods of the year. Lunar phase was the top predictor of size within the spearfishing sector, whereas season best predicted size for bottom fishing. Beyond environmental predictors at a method level, regression trees were also generated for top species. Species-level analyses highlight the interplay of phenology and fisheries, with fish behavior presumed to be dictating the success of fisheries in space and time. Results from this study aim to guide and improve ongoing fisheries management strategies in Guam and provide the first predictive framework of landings, composition, and size for Guam’s coral reef fisheries.

Approved: ___________________________________
Dr. Peter Houk, Chair, Thesis Committee

ACKNOWLEDGEMENTS

Studying coral reef fisheries within my home of Guam has been an eye-opening experience that has only made my love for my island grow. Saina ma’ase to my advisor and chair, Dr. Peter Houk, for encouraging me to pursue a new branch in marine science, allowing me to grow as a scientist, fisherwoman, and servant to my community. To the rest of my committee members, I am deeply grateful to each of you for committing your time and efforts in ensuring the success of my graduate studies. The insurmountable amount of knowledge I have gained from each of you has made me much more confident and prepared to take on the world of fisheries.

I also want to thank my family, my #1 supporters who never allowed me to give up on my studies no matter how difficult personal matters got. I hope that once again, I have made you all proud. And to my darling William, who helped me build every single measuring board for my project and encouraged me to continue going strong despite the days I felt academically burnt out.

Lastly, I want to thank all the participants of my study who assisted in sending and gathering catch-and-effort data. It is fishing members like each of you that I do what I choose to do. You all inspire me to believe that working in fisheries – which ultimately entails working with people – is not as daunting as I first believed it to be over two years ago. I have learned a plethora of fishing knowledge from all of you, and I have gained valuable friendships I will cherish for a lifetime. This project would not have been possible without you. Saina ma’ase.

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I. INTRODUCTION

Importance of coral-reef fisheries

The diversity and productivity of coral reefs support coastal communities and island nations worldwide by providing economic, social, and cultural benefits (Moberg et al., 1999; Cesar et al., 2003; Loper et al., 2008; Bell et al., 2009). Reef-associated fishing represents an important activity by supporting food, livelihood, and culture (Cisneros-Montemayor et al., 2016). Economically, coral reef fisheries yield $6.8 billion in net annual benefits globally (Burke et al., 2011). Coral-reef fisheries also build and strengthen social networks by perpetuating long-standing fishing traditions, providing essential protein, and preserving cultural values (Plagányi et al., 2013; Zeller et al., 2015). These benefits are of significance to approximately half a billion people that rely on them, and the loss of our coral reefs would ultimately result in the loss of these benefits.

Guam's coral-reef fisheries

Guam is a US territory in the Pacific that depends on its coral-reef fisheries like most Pacific islands. Overexploitation of Guam's reef fisheries is a long-standing issue, with evidence of declining targeted species and overall landings for over two decades (Lindfield et al., 2014; Taylor et al., 2014; Weijerman et al., 2016; Houk et al., 2018). Studies have also shown that overfishing of large-bodied fishes such as *Cheilinus undulatus* and *Bolbometopon muricatum* has resulted in their replacement by smaller-bodied counterparts such as smaller-bodied surgeons and parrotfishes (Houk et al., 2018; Lindfield et al., 2014). Despite significant reef-fisheries declines in Guam, non-commercial fisheries are still prevalent and essential for society and culture. Yet, non-commercial fisheries throughout the Pacific remain poorly understood when compared to their commercial, pelagic counterpart. Understanding the dynamics of landings, species composition, and size structure of Guam's non-commercial fisheries is necessary to improve ongoing fisheries management planning efforts.

Threats to coral-reef fisheries

For decades, anthropogenic threats such as overexploitation, climate change, and land-based pollution have negatively affected reef-associated fishes. Ocean warming caused by climate change decreases biodiversity (Cheung et al., 2009), shifts community composition (Edmunds et al., 2014), affects the distribution and connectivity of fish (Munday et al., 2009), affects reproduction and growth of recruits (Pankhurst & Munday 2011), changes physiological performance, and decreases population productivity (Pörtner & Peck 2010). Sedimentation, a type of land-based pollution, prolongs larval development (Wenger et al., 2014), reduces reef fishes' ability to find suitable habitat (Jones 1991; McCormick 2009; Munday et al., 2009), impairs home range movement and foraging (Wenger et al., 2012; Wenger et al., 2013), and disrupts chemoreception by which fish avoid predators (Hartman & Abrahams, 2007). Nutrient enrichment from land-based pollution can cause macroalgae to increase rapidly at a rate in which herbivorous fishes may not be able to keep up with. This results in the algae outcompeting corals, leading to habitat loss and reducing fish biodiversity (Rasher et al., 2013). Fishing pressure also contributes to stress on coral reef ecosystems. Fishing of predators, large herbivores, and small herbivores can decrease system resilience resulting from reduced trophic interactions (Houk et al., 2017). Additionally, the removal of predators can lead to a significantly skewed ratio of small to large herbivores (Houk et al., 2017), resulting in fluctuations of algal biomass that can become uncontrolled. Among the suite of threats to coral-reef fisheries, fishing pressure is often the strongest driver of negative change within Pacific islands with limited urban development (McLean et al., 2016). Therefore, managing fishing pressure on coral reefs is necessary to maintain fisheries yields and reef resilience in the face of climate change (Houk et al., 2014).

Long-term creel monitoring in Guam

Guam's Division of Aquatic and Wildlife Resources (DAWR) initiated monitoring of fishing activity and landings using creel surveys in the 1960s. This program was refined in 1982 and now consists of two monitoring projects by Guam DAWR: 1) inshore, shore-based fishery and 2) offshore, boat-based fishery. The offshore fishery focuses on methods targeting pelagic and deep dwelling species with commercial value, such as trolling and deep-bottom fishing. Additionally, the offshore fishery also captures boat-based spearfishing and shallow bottom-fishing. The inshore fishery targets reef fish in shallow-water (≤ 30 m) primarily caught for recreational, subsistence, and cultural reasons. This fishery particularly comprises shore-based methods such as talaya (cast net), spearfishing, shoreline casting, and other shore-based methods. DAWR's creel surveys typically capture about 1,600 pounds of reef fish per year, randomly interviewing fishers throughout the year on all days and times. Interception surveys are voluntary. While annual volumes may not be huge, consistent monitoring since the 1970s reflects excellent temporal data that is representative of each year acquired by Guam DAWR. The creel dataset by Guam DAWR is a combined effort for both commercial and non-commercial catch.

To complement their creel program, DAWR also conducts participation surveys that aim to understand the frequency of fishing events and types of methods utilized across Guam. For instance, hook-and-line fishing comprises 70.6% of the total fishing effort, followed by cast net (14.4%), spearfishing (5.7%), gill net (5.3%), and hook and gaffs (2.7%) (Weijermen et al., 2016; Table 1). Yet, the contribution made by spearfishers was thought to have been much higher, representing one of the top shore-based methods in most Pacific islands. Some studies suggested this was an artifact of refusal of the creel surveys by spearfishing participants, largely by the SCUBA spearfishing contingent, since 2005 (Lindfield et al., 2014; Houk et al., 2018). More recently, fishing of Guam's reef-associated species is thought to be more of a recreational or subsistence fishery, while pelagic fisheries were responsible for most of the commercial landings (Allen and Bartram, 2008). The present study aims to provide better resolution to these estimates.

Table 1. Dominant fishing techniques found within Guam's fishing community between 2007-2012. *Spearfishing represents one of the most used fishing methods of shore-based fishing, but the mean effort listed reflects the refusal of creel surveys largely by SCUBA spearfishing participants. In addition, interception of spearfishers is difficult considering the short window of opportunity and precise timing of interception upon spearfishers exiting the water. Table taken from Weijermen *et al*., 2016.

Gear type	Mean effort (gh) (% of total)	Mean catch (kg)	CPUE (SE) (kg/gh)
Hook and line	145,309 (70.6%)	17,828	0.08 (0.02)
Cast net	29,555 (14.4%)	4,108	0.10 (0.02)
Snorkel spear*	11,736 (5.7%)	2,137	0.19 (0.06)
Gill net	10,918 (5.3%)	9,807	0.56 (0.18)
Hooks and gaffs	5,554 (2.7%)	2,139	0.36 (0.16)
Surround net	552 (0.3%)	555	0.67 (0.08)
Scuba spear	155 (0.1%)	58	0.34 (0.04)
Drag net	141 (0.1%)	133	0.97 (0.35)

What we know: Past studies utilizing long-term creel data

Many studies have utilized these long-term creel data to understand trends in the reef-associated fishery of Guam. When compared to 23 other island nations, Guam's fish biomass was second lowest and whose score was indicative of fisheries collapse (MacNeil et al., 2015). Other islands within the same chain, including Saipan and Rota, scored better than Guam in this same study whereby fish biomass was almost three times less. The most recent annual Stock Assessment and Fishery Evaluation (SAFE) for Guam reported a total catch of 8.6 tons in 2020. This low fishery yield may be explained by a decrease in the number of fish landed, smaller sizes at capture, and/or reduced coral-reef habitat in Guam compared to other islands (Myers, 1993; Lindfield et al., 2014). Zeller et al. (2015) used human population and consumption data, coupled with recent DAWR landings data, to reconstruct recreational fish landings in Guam over the past 50 years. This study estimated an 86-94% decline in landings may have occurred, however, this time period was also associated with Guam's commercialization and the increasing arrival of western food products. A more recent study by Weijerman et al. (2016) provided further evidence for this declining trend by revealing that fishers maintained similar fishing effort throughout the years; however, Guam has experienced an overall reduction in catch success and landings since the late 1980s.

In addition to the decline in fisheries landings, shifts in catch composition were noted by several studies (Weijerman et al., 2016; Lindfield et al 2014; Houk et al., 2018). These studies revealed that smaller-sized species and species with stronger compensatory density dependence have come to dominant landings in recent years, in addition to overall decreases in size structure for the combined landings. Larger, more desirable species that have become rare include Cheilinus undulatus, or Napoleon wrasse, large-bodied parrotfishes such as Chlorurus microrhinos, and large snappers and groupers. Landings are now dominated by a combination of acanthurids and small-bodied scarines, yet the persistence of some large-bodied herbivores remains, such as Naso unicornis and Kyphosus spp. (Houk et al. 2018; Lindfield et al., 2014).

These general trends in species replacement and size structure are expected with growing exploitation based upon findings from many nearby islands in Micronesia (Taylor et al., 2014;

Houk et al., 2017). In summary, larger-bodied species are vulnerable due to their slow maturation and growth, and they are less frequently landed now during favorable times when specific environmental conditions existed (i.e., wind, waves, seasons, and moon phases).

Environmental predictors of non-commercial fishing: a key gap in knowledge

Previous studies provided a generalized view of what may be occurring within Guam's coral-reef fisheries through time and several key-species trends, but similar studies characterizing Guam's non-commercial fisheries do not exist. To date, there have been no published studies examining trends in catch composition, size structure, harvested biomass across seasons and lunar phases to determine environmental drivers of Guam's non-commercial fisheries. Fishing during times of favorable conditions is known to be an indicator of overexploitation in Pacific Islands (Houk et al 2017). As fish stocks slowly become depleted over time in these islands, fishers become increasingly reliant on favorable environmental conditions to increase catch success. This indicator has yet to be assessed for Guam, and analysis to this degree for Guam's non-commercial fisheries has yet to be conducted. This information is needed to help management plans evolve to meet the needs of both commercial and subsistence fishers.

Similar studies meeting the objectives of my present study have been conducted in Saipan and Kosrae. A recent study conducted by Houk et al (2017) used catch records and fisher interviews to assess hierarchical indicators of Kosrae's fishery status by characterizing catch-and-effort trends with respect to environmental factors. Houk et al used commercial data, and results revealed that lunar phase was the most important predictor followed by season, elucidating the constraint of catch and effort by environments. Buenos-Cuetos et al (2013) investigated similar environmental constraints in Saipan, which is north of Guam and also part of the Marianas Archipelago. Results elucidated the reliance of favorable conditions to increase catch success, with increased success during the calm, dry months from May to October. Consequently, as wind speeds decreased on the windward side of Saipan during these calmer months, those less-exploited reefs became more accessible, and catch was reported to be significantly higher than other times of the year (Figure 1).

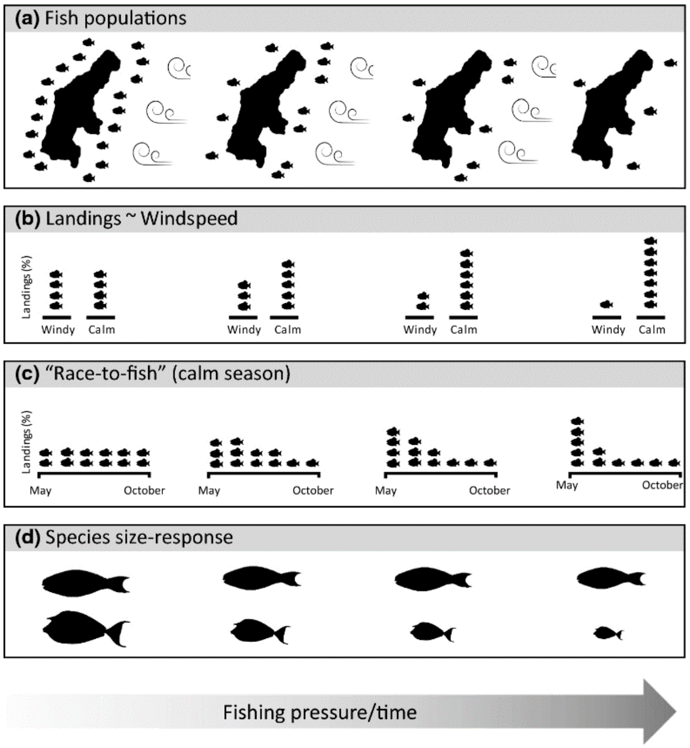


Figure 1 (Taken from Cuetos-Bueno et al 2019) Hypothesized responses to growing fishing pressure through time. Localized depletions are hypothesized to reduce fish stocks in the more accessible, leeward reefs through time (a) resulting in growing calm-vs-windy landings ratios (b). Within calm months, “race-to-fish” dynamics might evolve for desirable target species once favorable conditions emerge (c). Alongside growing spatial gradients, fishing pressure is also expected to diminish size structures or result in the replacement of slower-growing species with faster-growing counterparts (d).

II. OBJECTIVE AND HYPOTHESES

The objective of my study is to determine the environmental factors driving non-commercial catch-and-effort trends across Guam throughout a one-year period to capture all seasons, months, and relevant weather patterns. This thesis will formally characterize and assess Guam's non-commercial fisheries, being the first study to place sole emphasis on this sector.

1) Do non-commercial fishing methods contribute similarly to harvested biomass and catch composition?
    - H_{01}: Top methods contribute similarly in harvested biomass and catch composition.
    - H_{A1}: Top methods differ in their contribution to harvested biomass and catch composition.
2) Do non-commercial fishing methods contribute similarly in frequency and distribution around Guam?
    - H_{02}: Non-commercial fishing methods have similar frequencies of occurrence and are evenly distributed around Guam.
    - H_{A2}: Certain non-commercial fishing methods have greater frequencies of occurrence than others and are unevenly distributed around Guam.
3) Are season and lunar phases significant predictors of harvested biomass, average daily size, or catch composition within Guam's non-commercial fisheries?
    - H_{03}: Season and lunar phase are not significant predictors of landings, size, or species composition.
    - H_{A3}: Season and lunar phase are significant predictors of landings, size, and species composition.

- Landings are significantly larger in biomass during the calm, dry seasons. Given this, when winds fall during these seasons, the windward coast experiences significantly more harvested biomass than rough, wet seasons.

III. MATERIALS AND METHODS

Study area

Guam is the largest island in the Marianas Archipelago, located 13.4443° N, 144.7937° E. Seasons are well-defined for Micronesia, where the calm period is from May to October whereas the windy period is associated with November to April. The eastern windward coast of Guam experiences high wind and surf most times of the year, thereby limiting access to fishing. Year-round fishing typically occurs on the western leeward coast of Guam; not only is it calm throughout the year, but it is very accessible due to numerous marinas and shore-based entries. Fishing is an essential activity in society and culture in Guam; both non-commercial and commercial fishing of reef-associated fisheries currently exist. Hook-and-line, spearfishing, shallow bottom, and talaya fishing are among the top contributors to fishing participation. My study focuses on gathering creel data from these top fisheries.

Independent catch and effort data collection

Two different approaches were taken to gather the data needed for my study, which utilized a *creel* survey to estimate fish biomass, catch composition, and fish size. Creel surveys are interviews with non-commercial fishers that collect information on the species landed, species size, gear type, location of harvest, and fishing effort. The first approach utilized to gather creel data was through random interceptions throughout the island, in which the surveyor drives around a route and intercepts fishers throughout that route to conduct interviews and measure their fish.

Fishers were asked if catch was to be sold or kept, and only catch that was being kept were utilized in my analysis to ensure a non-commercial focused study. These interceptions were conducted on both weekdays and weekends throughout the daytime and nighttime.

Secondly, my present study utilizes an independent partnership-based creel collection that has never been done before for Guam. This was accomplished by forming partnerships with fishers who were met and interviewed during the aforementioned interception surveys and willing to participate in sharing data for the long-term. By building partnerships, networking with fishers, and remaining in constant communication with fishers, we were able to meet with them post-fishing upon notification to collect creel data. When the number of partnerships formed was appropriate enough to allow a representation of the fishing population, random interceptions were conducted to a lesser degree to focus on partnerships. Data on catch composition, size, and weight will be collected following previously used methods (Houk *et al*., 2017), which utilizes a standard measuring board with a mounted camera (Image 1). Length-to-weight relationships will be based upon regional estimates from ongoing fisheries-dependent research across Micronesia. Estimates that are not available for the region will be identified through FishBase.

Fishers willing to participate in the study also had the option to submit digital documentation of their catch. Fishers were asked to fill out the same interview form and include a reference object of known length in their photos, such as measuring tape (Images 2 & 3). Photos were then imported to Image J software, where the reference object was used to draw estimates of the fishes within the image.

Image 1: **Methodology for collecting catch data.** Catch photos were taken using an Olympus TG-6 mounted over a measuring board. Actual fork-lengths and species ID were derived from these photos. Approximately 20 fish could be measured per minute, making it an extremely effective means of gathering catch data.

Image 2: Photo submission by participants after a night of bottom fishing. Reference object is measuring tape.

Image 3: Photo submission by a participant after a day of cast netting (talaya).

Catch and effort data from these surveys were conducted over a one-year snapshot period (June 2021 – May 2022), which allowed the assessment of total annual catch and differentiate patterns in fishing intensity and activities throughout the year. Surveying over a one-year period provides a snapshot of Guam's fisheries. As fishing in Guam is associated with both shore- and boat-based fishing, my study recorded data captured by both activities. In addition, both daytime and nighttime fishing activity were captured.

Statistical analyses

Data will be analyzed via R Studio® using several approaches according to the respective hypothesis. Log-linear, chi-square test analyses were used to test for differences in frequencies for each top method across seasons, regions, and lunar phases. Multi-way analysis of variance (ANOVA) and Tukey post-hoc tests were conducted to assess differences in biomass harvested for each gear type. Permutational ANOVA (PERMANOVA) was conducted to determine if catch composition significantly differed across top methods. Additionally, PERMANOVAs were used to determine if season, region, and lunar phase were significant factors contributing to differences in catch composition. Using the VEGAN package (Oksanen et al., 2017), pairwise Adonis was run to determine where those differences in seasons and regions lied, and SIMPER function revealed which species contributed the most to composition differences. Principal component ordinations plots were used to visually interpret the PERMANOVA results. Fish size distributions were examined with respect to the various methods using Kolmogorov-Smirnov tests to determine any significant differences. Boosted regression trees (BRTs) were used to determine the hierarchy of significance for each environmental variable contributing to average daily biomass and average daily fish size.

IV. RESULTS

General trends within Guam's non-commercial fishing methods

The total catch recorded between June 2021 and May 2022 was 2025 kg, comprising 5,474 individual fish measurements. In total, spearfishing harvested 1000 kg, shallow-bottom fishing 709 kg, and talaya fishing 216 kg, ranking them as the top three methods captured during this study period. ANOVA analysis revealed significant differences in harvested biomass across the top three methods ($p = 0.003$), with post-hoc tests indicating bottom fishing biomass differs from talaya ($p = 0.005$) but is similar to spearfishing. Peaks in monthly mean biomass were highest during the summer months for spearfishing and bottom, and highest during the fall for talaya (Fig 2a, b). Catch composition was found to be distinct across all three methods of spearfishing, shallow-bottom fishing, and cast net fishing (PERMANOVA F statistic = 10.37, $p < 0.001$, Fig 4a). Spearfishing catch constituted mainly of Scaridae, Carangidae, and Acanthuridae. Shallow-bottom fishing catch comprised snappers and emperors, and also contributed to the largest individuals being caught across all methods (K-S tests, $p < 0.001$). Cast net fishing targeted surgeons and was the method known to catch the smaller fish. While my study was able to capture large volumes of talaya fishing, we were unable to capture all seasons; therefore, we omitted talaya fishing from seasonal and regional analyses.

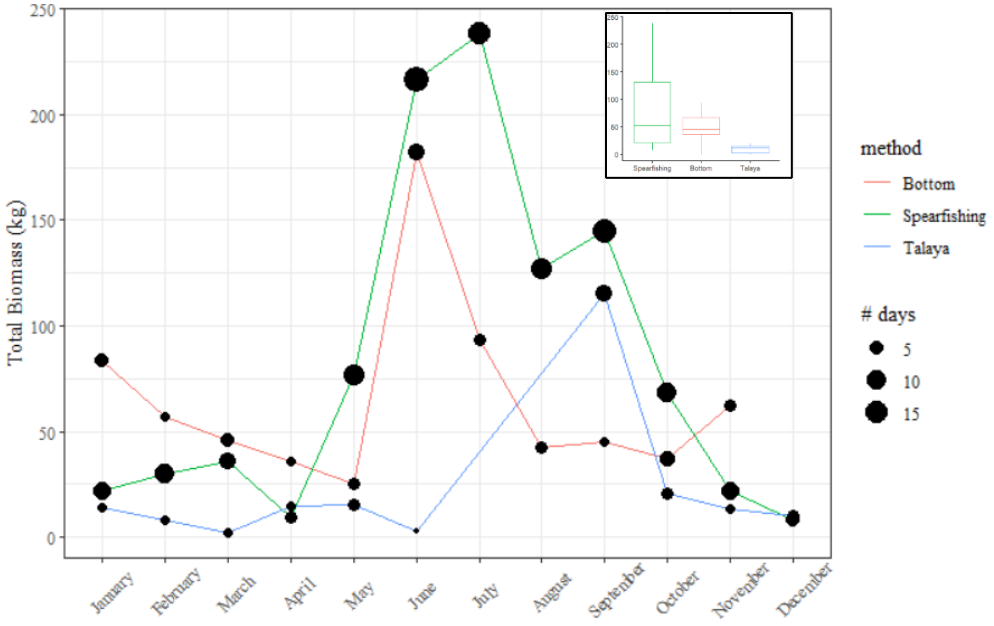


Figure 2a. Monthly total biomass (kg) for top examined methods from 2021-2022. ANOVA analysis revealed significant differences in harvested biomass across the top three methods (p = 0.003), with post-hoc indicating bottom fishing biomass differs from talaya (p = 0.005) but is similar to spearfishing. Point size is correlated to the number of days recorded.

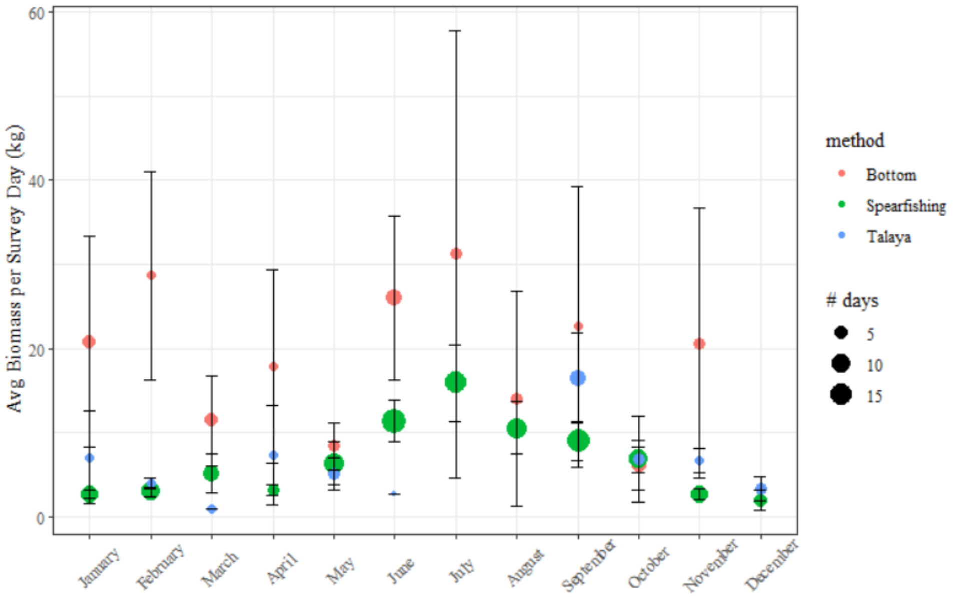


Figure 2b. Average daily biomass (kg) per month, per survey day; bars represent standard error.

Spearfishing

A total of 177 spearfishing events were captured in my study. Spearfishing events were not equally distributed across moon phases or seasons (Figure 3). Fishing events were highest during summer (n = 72), moderate in the fall (n = 55) and lowest during the spring and winter (42 and 40, respectively). Within the spring season, fishing events were most frequent during the new moon in the northwest and southeast regions of Guam (Pearson's residuals >2, p = 0.02, log-linear models). Fishing frequency and landings were highest in the summer; both fishing frequency and landings were lowest during winter months. Landings peaked in the windward coast in the summer as winds fell, and gradually decreased as winds picked up towards the end of fall-beginning of spring (Figure 4). Average daily landings in the windward region were double more than leeward harvests during the calm periods.

Season was the most important predictor of landings, with summer yielding the highest average daily landings within the spearfishing sector (Fig 5a, TREE model estimates = 12.7 kg, R^2 = 15%). Within the spring season, spearfishers used wind speed as an important determinant for fishing, with lower-category winds yielding the highest average landings (9.42 kg/d). Moon was a secondary predictor of spearfishing landings, whereas a full moon during the fall/spring seasons yielded the second-highest daily average landings of 9.42 kg. Season also had a significant effect on species composition within the spearfishing sector (Figure 6, PERMANOVA F-statistic = 2.14, p < 0.001). Spring catch composition differed from summer and fall, and summer catch differed from winter. SIMPER results revealed species driving these composition differences, in which some top species were more abundantly harvested during certain seasons and within a particular region (Figure 7). In support, catch composition in the windward versus the leeward was significantly different (PERMANOVA F-statistic = 3.1, p =

0.001), whereas the differences were driven by species such as *Kyphosus vaigiensis* (east), *Scarus forsteni* (west), and *Caranx papuensis* (west), among others. Moon phases did not appear to have any effect on catch composition but were the most important predictor of daily mean size (Fig 5b, $R^2 = 3\%$). Based on the regression tree, fish caught during a new moon during the fall were predicted to yield the largest average size fish.

Hierarchical regression trees were also applied at a species level to understand how environmental factors can predict landings and size for Guam's top species. Season, geography, moon played key roles for species under the spearfishing sector. *Chlorurus frontalis* and *C. microrhinos* are two highly targeted parrotfish species in Guam, and both showed moon and season contributing to landings over the one-year period. Moon phase was the most important predictor of landings for *C. frontalis* ($R^2 = 35\%$), where new and full moons during the summer contributed to higher daily landings of 6 kg/day. Season was the most important predictor of *C. microrhinos* landings, followed by moon phase. New moons during the summer contributed similarly to *C. microrhinos* landings and were the top predictors following season (TREE model estimates = 1.9 kg/d, $R^2 = 35\%$). *Chlorurus frontalis* was predicted to be largest in the eastern region, while *C. microrhinos* was predicted to be largest in the western region. The surgeonfishes *Naso unicornis* and *N. lituratis* are two highly targeted species within Acanthuridae. Season was an important environmental predictor across both surgeonfishes. Both species had the highest landings associated with summer and fall during mid-moon phases, averaging 3.9 kg/d for *N. unicornis* (Figure 8a, $R^2 = 37\%$) and 1.2 kg/d for *N. lituratus* ($R^2 = 14\%$). The smallest individuals of *N. unicornis* caught were during the winter (Figure 8b), while fall was correlated with the largest individuals harvested.

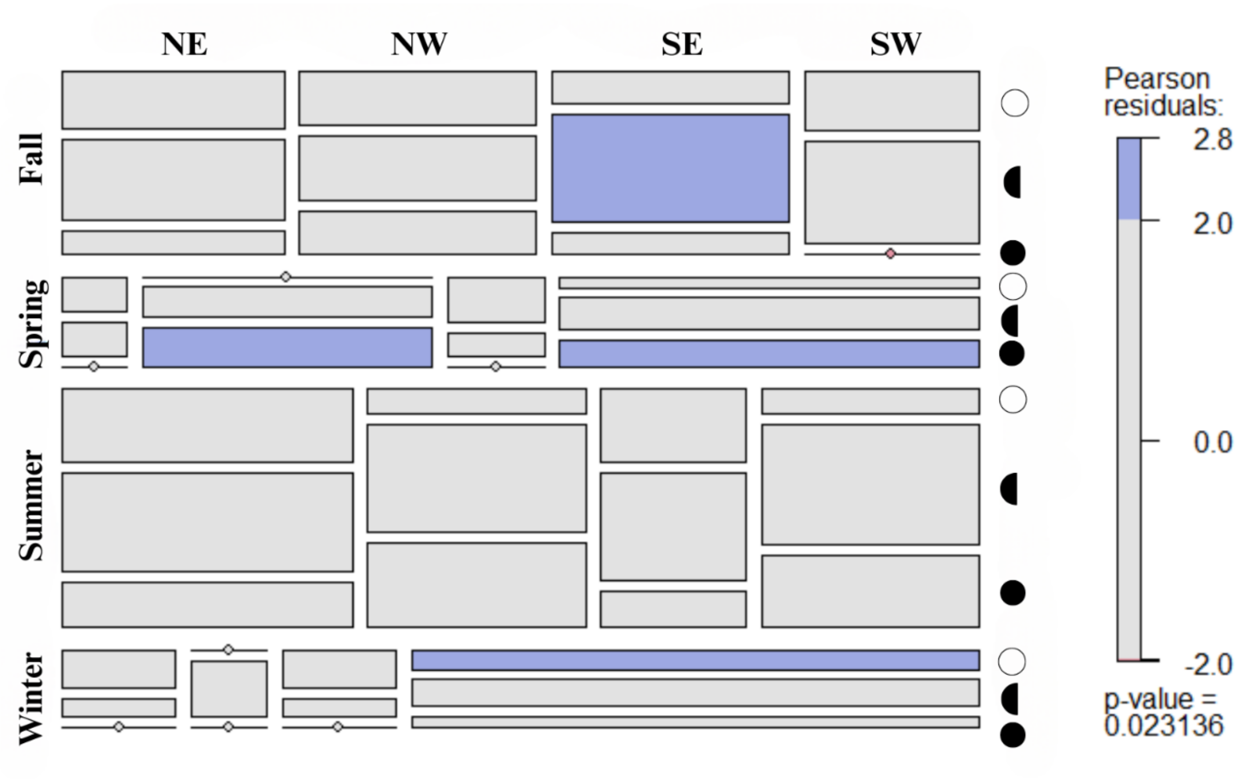


Figure 3. Fishing event frequencies within the spearfishing sector by season, moon phase, and region (Pearson's residuals >2, p = 0.02, log-linear models)**.** Box sizes represent proportional frequencies across the study year (summer > fall > spring > winter). Blue colors indicate higher-than-expected fishing frequencies, while gray colors are not different than expected by chance.

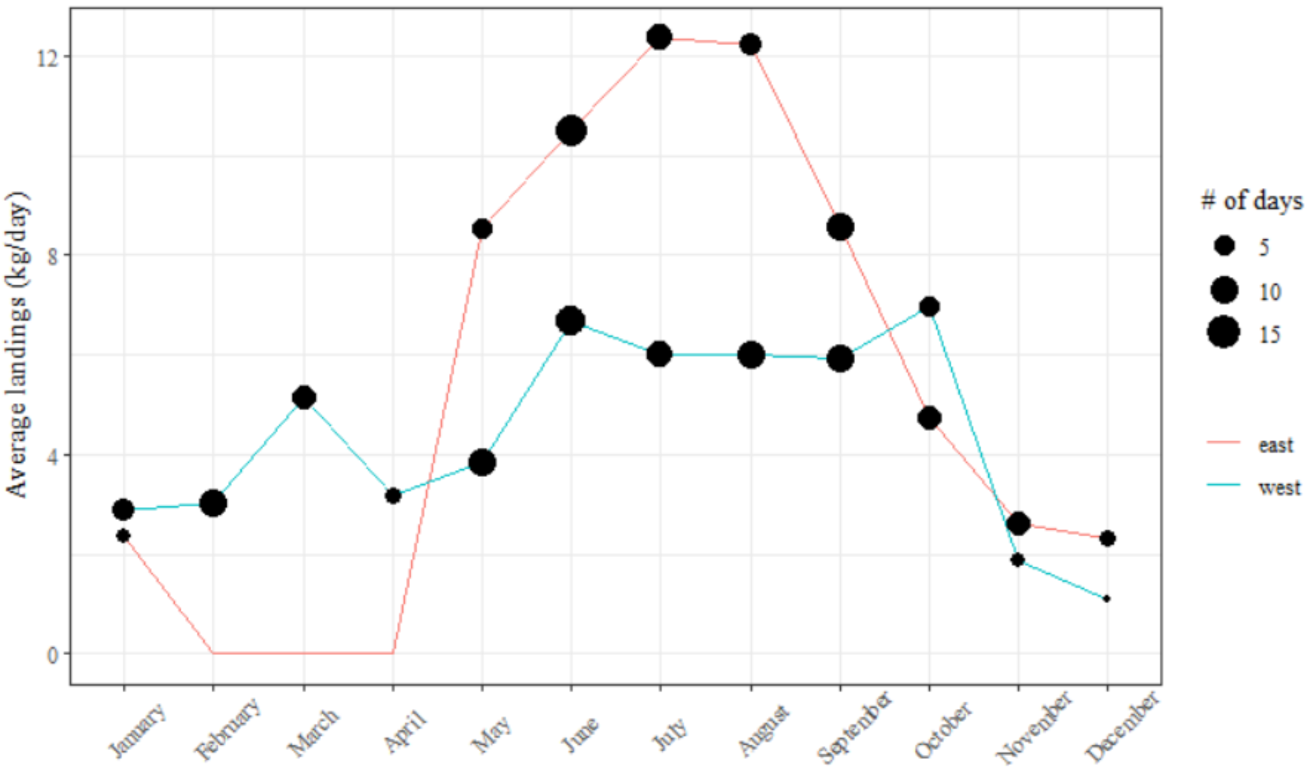


Figure 4. Average daily landings in the leeward (blue) versus windward (blue) within the spearfishing sector. Differences in windward and leeward landings in the spearfishing sector were evident in my study. The leeward experienced minor peaks in the summer with not much difference in average landings compared to other seasons. In contrast, the windward experienced clear boom-and-bust dynamics as the calm periods within the summer allowed for more access to windward reefs, resulting in higher catch success. Average daily landings in the windward coast were double than leeward harvests during these peak periods of the calm season.

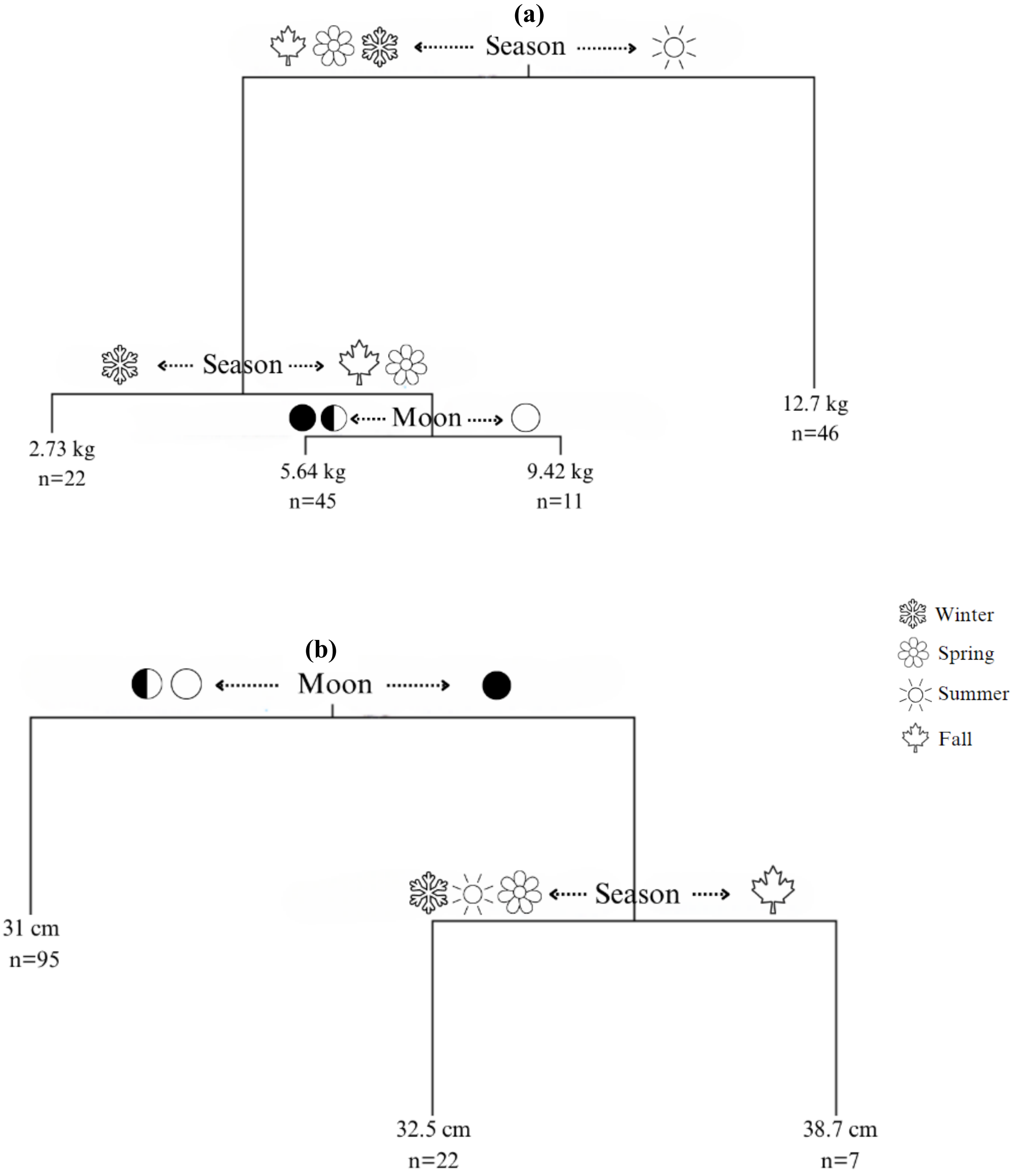


Figure 5: Regression tree results show significant predictors of catch success in terms of average daily landings and average daily size. **(a)** Season is the most important predictor of landings ($R^2 = 15\%$), with summer yielding the highest average daily biomass (kg), and winter yielding the least. **(b)** On the other hand, moon was the most important predictor for size ($R^2 = 3\%$), with new moons during the fall yielding the largest average mean size (cm).

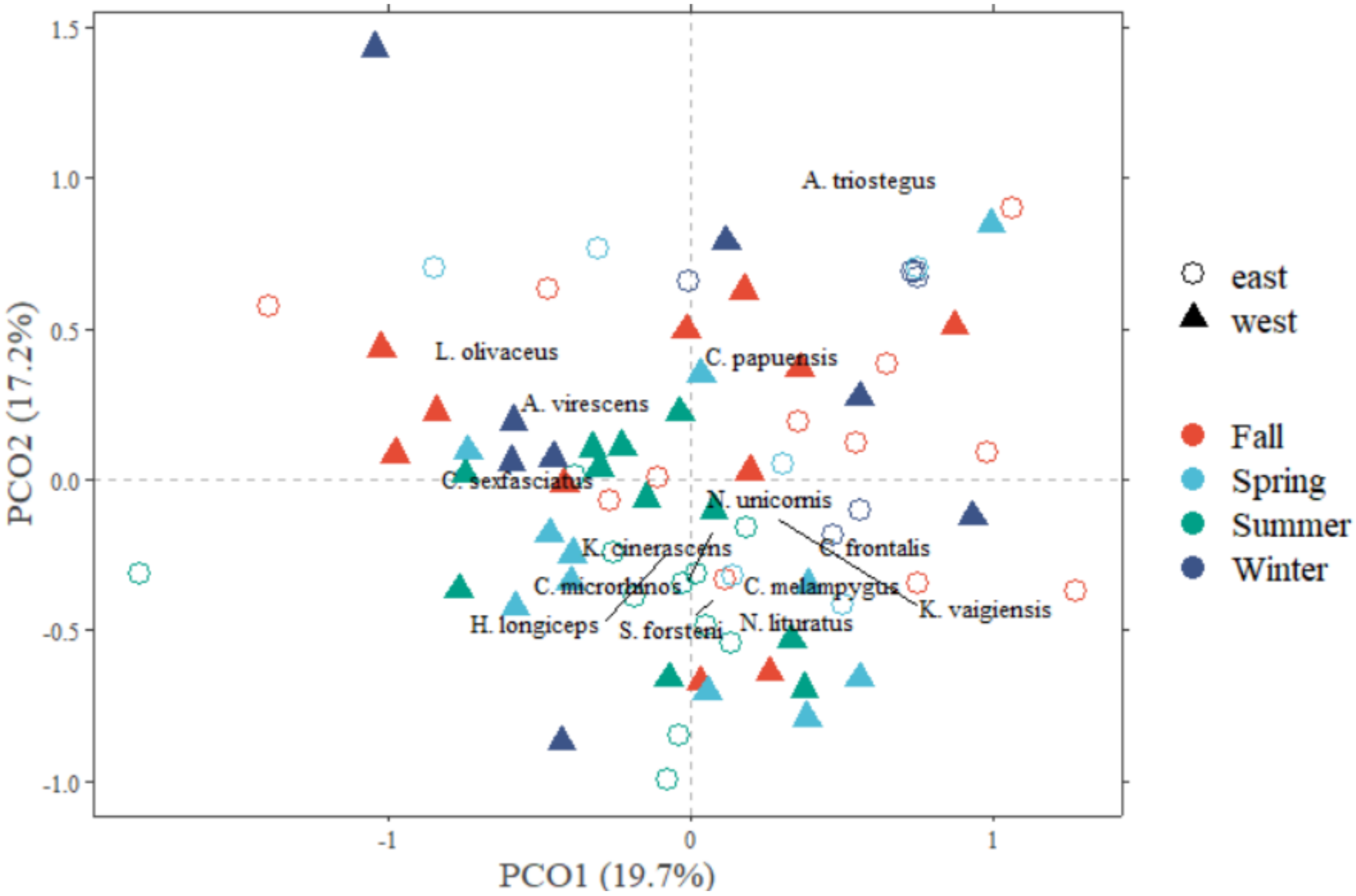


Figure 6: Principal coordinates ordination (PCO) plot for catch composition differences within the spearfishing sector across seasons and coasts. PCO1 accounts for 19.7% of the explained variance, with PCO2 accounting for 17.2%.

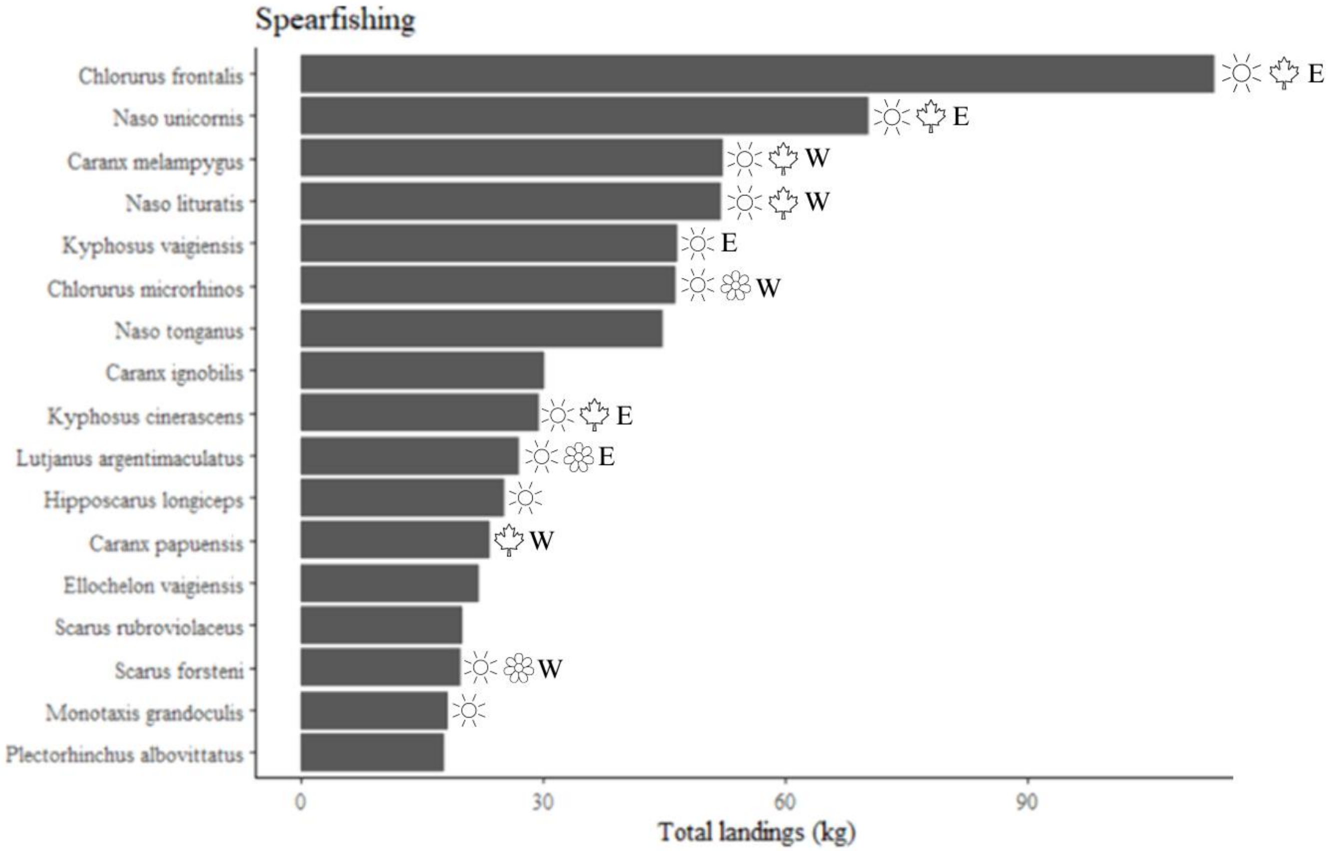


Figure 7: Bar plots of top species within the spearfishing sector by total biomass (kg), with symbols denoting which seasons and coasts (east or west, E or W) respective species were most frequently harvested. Season had a significant effect on species composition within the spearfishing sector (PERMANOVA F-statistic = 1.9, p = 0.001), as well as region (PERMANOVA F-statistic = 3.3, p = 0.001). SIMPER analysis was run in R to determine which species were the drivers of composition differences across seasons and regions based on abundance.

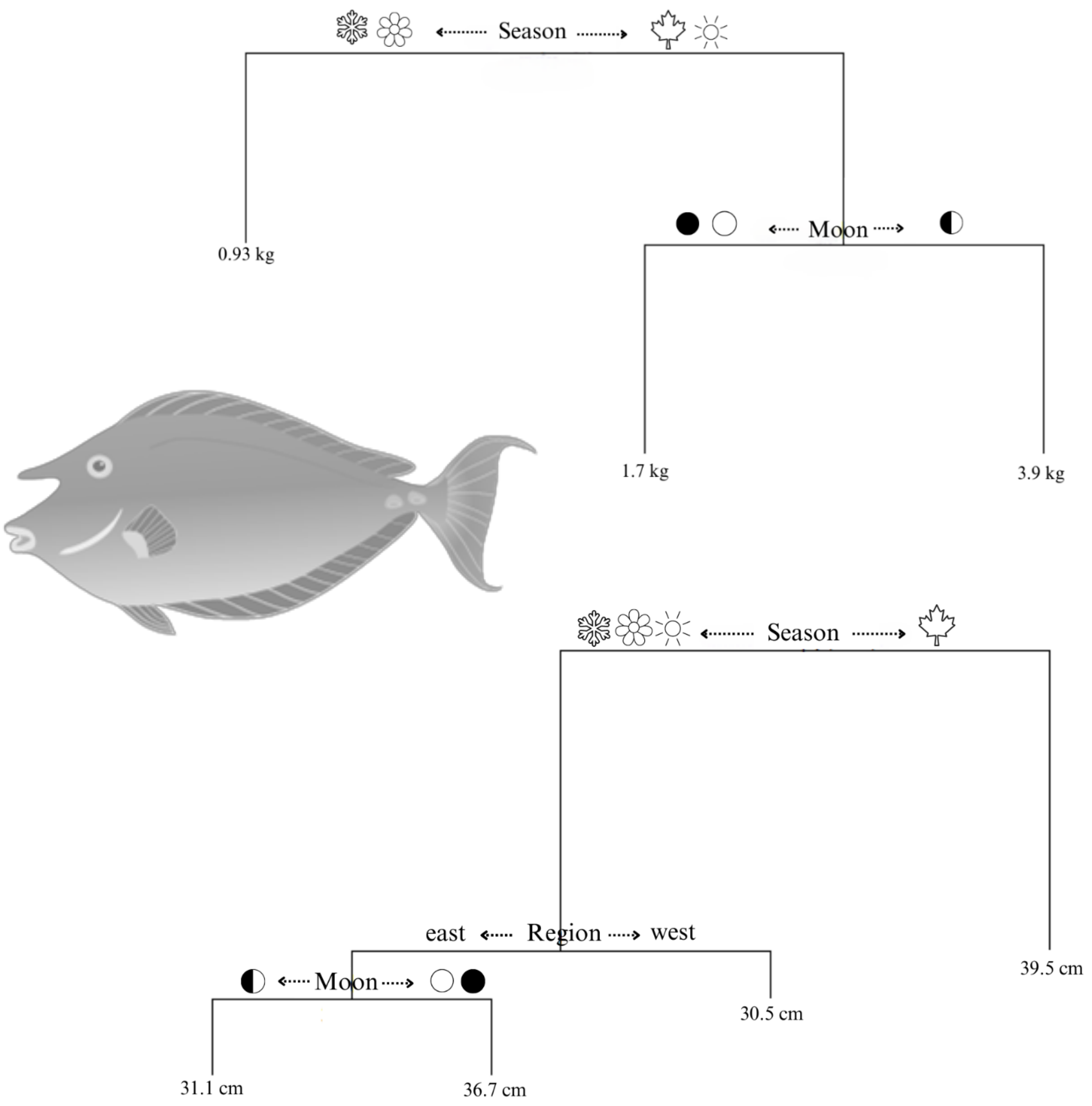


Figure 8: (a) Environmental predictors of average daily *N. unicornis* landings. Season was the most important predictor, followed by moon ($R^2 = 37\%$). Summer and fall during a mid-moon yielded the highest average daily landings of 3.9 kg**. (b) Environmental predictors of daily average *N. unicornis* size**. Season was the most important predictor, with the largest individuals caught during the fall at an average of 40 cm ($R^2 = 23\%$).

(Please see supplementary information for other regression trees of Guam's top species. Tataga' used as an example for landings and size trees for individual species assessments.)

Shallow bottom fishing

A total of 48 shallow-bottom fishing events were captured in this study. Bottom fishing events were equally distributed across seasons but unequally distributed across moon phases (Figure 9). Events were highest during summer and fall (n = 14 and 14, respectively) and lowest during spring and winter (n = 10 and 10, respectively), though the difference in events numbers is insignificant. Season was the most important predictor of daily landings, with moon as a secondary driver. Catch success was greatest during summer and winter seasons during a mid or new moon (Fig 10a, TREE model estimates = 25.7 kg/d, $R^2 = 10\%$). Season also had a significant effect on species composition (Fig 11, PERMANOVA F-statistic = 2.91 for seasonal differences, p = 0.005). Species-based proportional landings remained similar during winter and spring. Summer and fall showed distinct catch compositions. SIMPER analysis revealed driving species of composition differences across seasons and regions based on abundance (Figure 12), such as higher landings of *Lethrinus rubrioperculatus* in the summer and fall in the west coast. Moon phases did not appear to have any effect on catch composition. Season was also shown to be the most important predictor of average daily size (Fig 10b, $R^2 = 6\%$). Based on the tree, predicted average daily size appears similar across seasons.

Hierarchical regression trees at the species level for top species within the bottom fishing sector also reveal how season, geography, and moon can predict landings and size. *Lutjanus gibbus*, for example, was the top snapper harvested under this sector. Season was the most important predictor of *L. gibbus* landings, where summer and winter yielded the highest biomass per day at 6.6 kg/day ($R^2 = 18\%$). Geography was the top predictor of average daily size, with windward catches on the eastern region predicted to yield the largest average daily size at 34 cm ($R^2 = 37\%$). *Lethrinus rubrioperculatus* was the top emperor fish harvested within bottom fishing, and season was also the top predictor for this species. Spring harvests were on average 9 kg/day (R^2 = 30%). In contract, geography best predicted size with an average of 28 cm/day in the eastern, windward region (R^2 = 20%), though size differences across regions and seasons do not appear significantly different. Figure 13 provides a summary of Guam's top non-commercial species across both spearfishing and bottom fishing sectors, and which factor is the most important (i.e., the upper most factor on respective regression trees) in predicting landings and size for each species. Environmental predictors for top species within Guam's non-commercial fisheries can be helpful in generating management recommendations at a species-specific level based on moon, season, and geographic region. Lastly, understanding the size distributions of top landed species in the east versus the west coast can also be helpful in management. Fish with habitat affinities for the windward coast are able to reach larger sizes when compared to the leeward region (Figure 14), due to dangerous winds and seas shielding high amounts of fishing pressure. Fish with habitat affinities for the leeward coast, such as *Chlorurus microrhinos*, clearly exhibit larger sizes when compared to the windward coast, demonstrating the role of habitat in fisheries landings and dynamics.

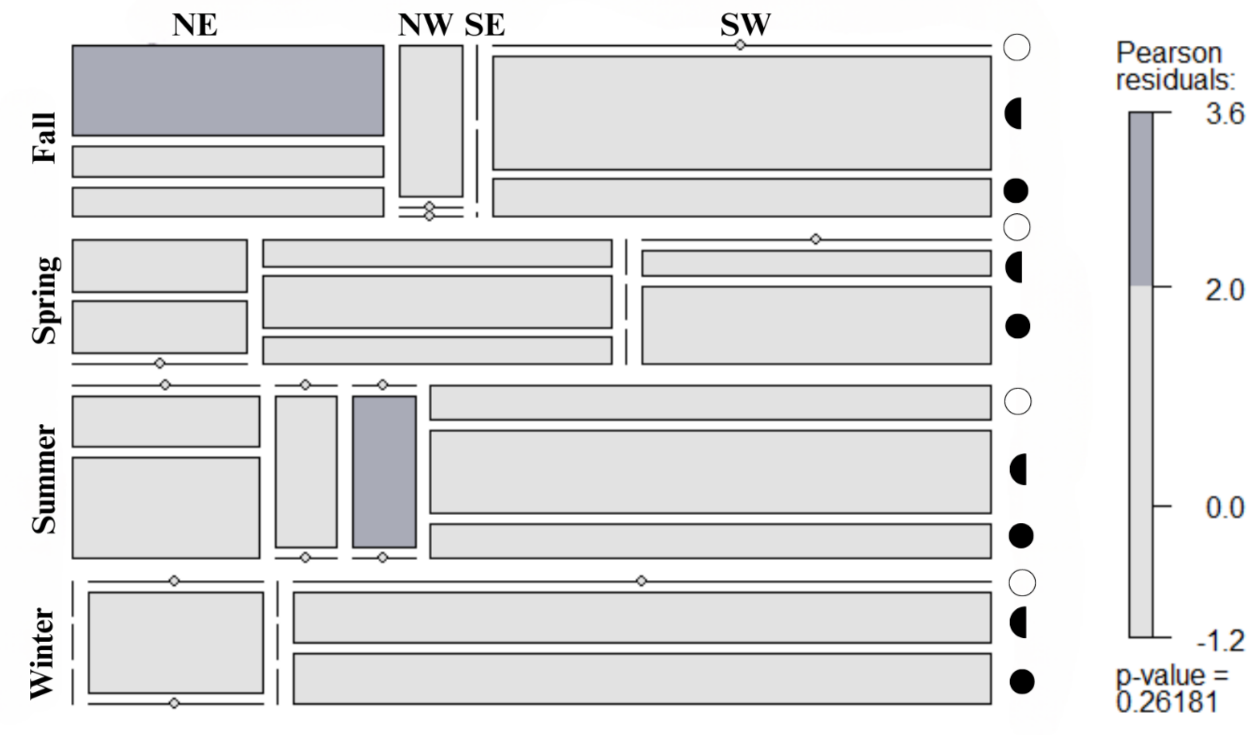


Figure 9: Fishing event frequencies within the bottom fishing sector by season, moon phase, and region. Log-linear model results show no significant association or interaction patterns among the categorical variables but is still informative in understanding fishing frequencies within this sector (Pearson's residuals >2, p = 0.2, log-linear models).

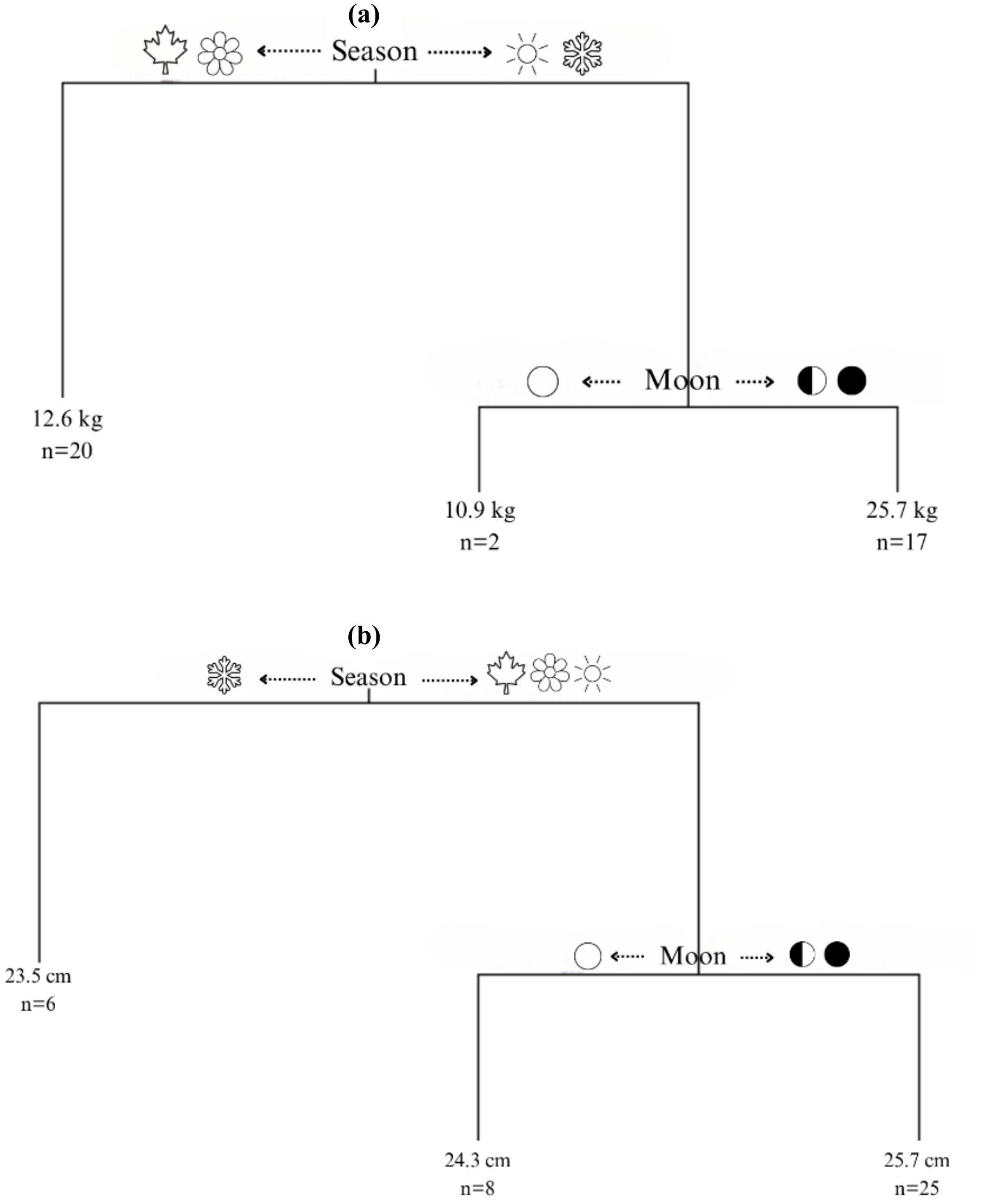


Figure 10: Environmental predictors of daily biomass and size within the shallow bottom fishing sector. Season was an important predictor for both **(a)** average daily landings (R^2 = 10%) and (**b**) size (R^2 = 6%). A mid/new moon during the summer and winter months yielded the largest mean daily size. Average daily size was almost equal across seasons and moon phases. Line lengths in the regression tree are proportional to the amount of variance explained.

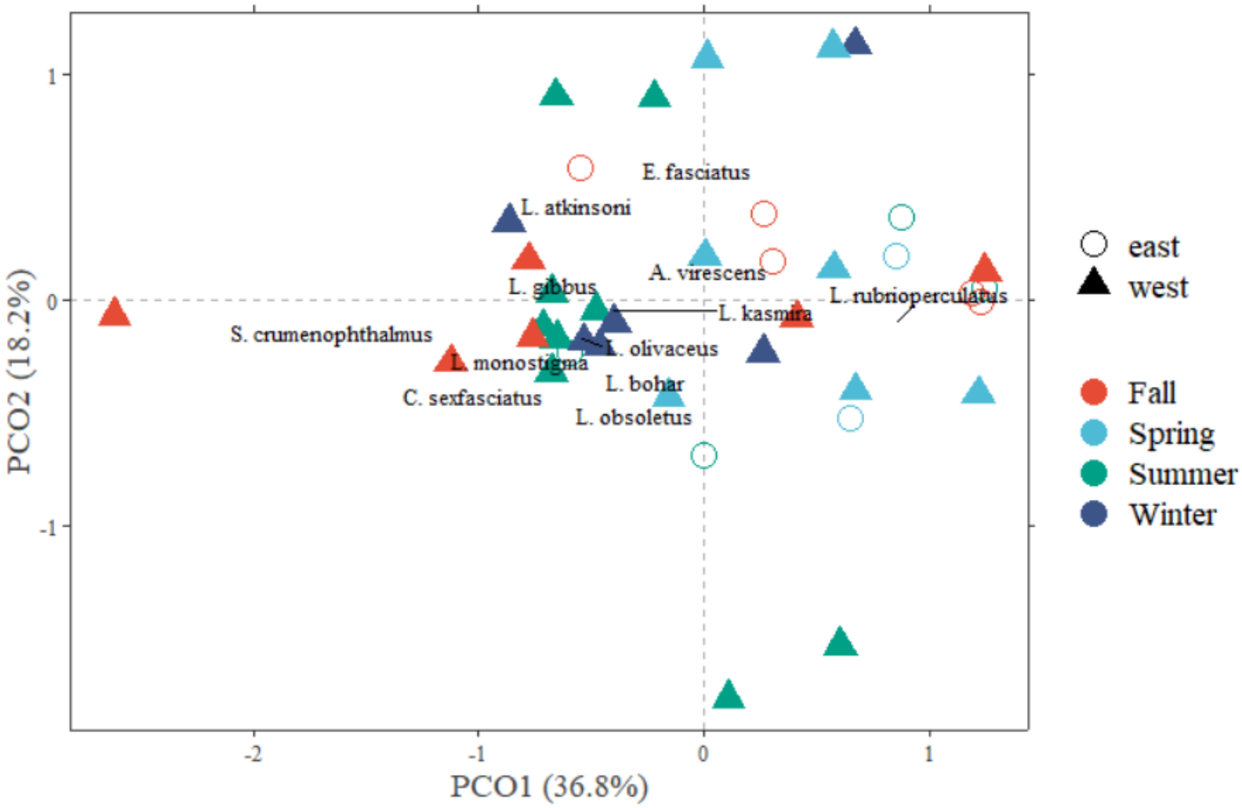


Figure 11: Principal coordinates ordination (PCO) for species differences within the shallow bottom fishing sector across seasons and the west/east regions. PCO1 accounts for 36.8% of explained variance and PCO2 for 18.2%.

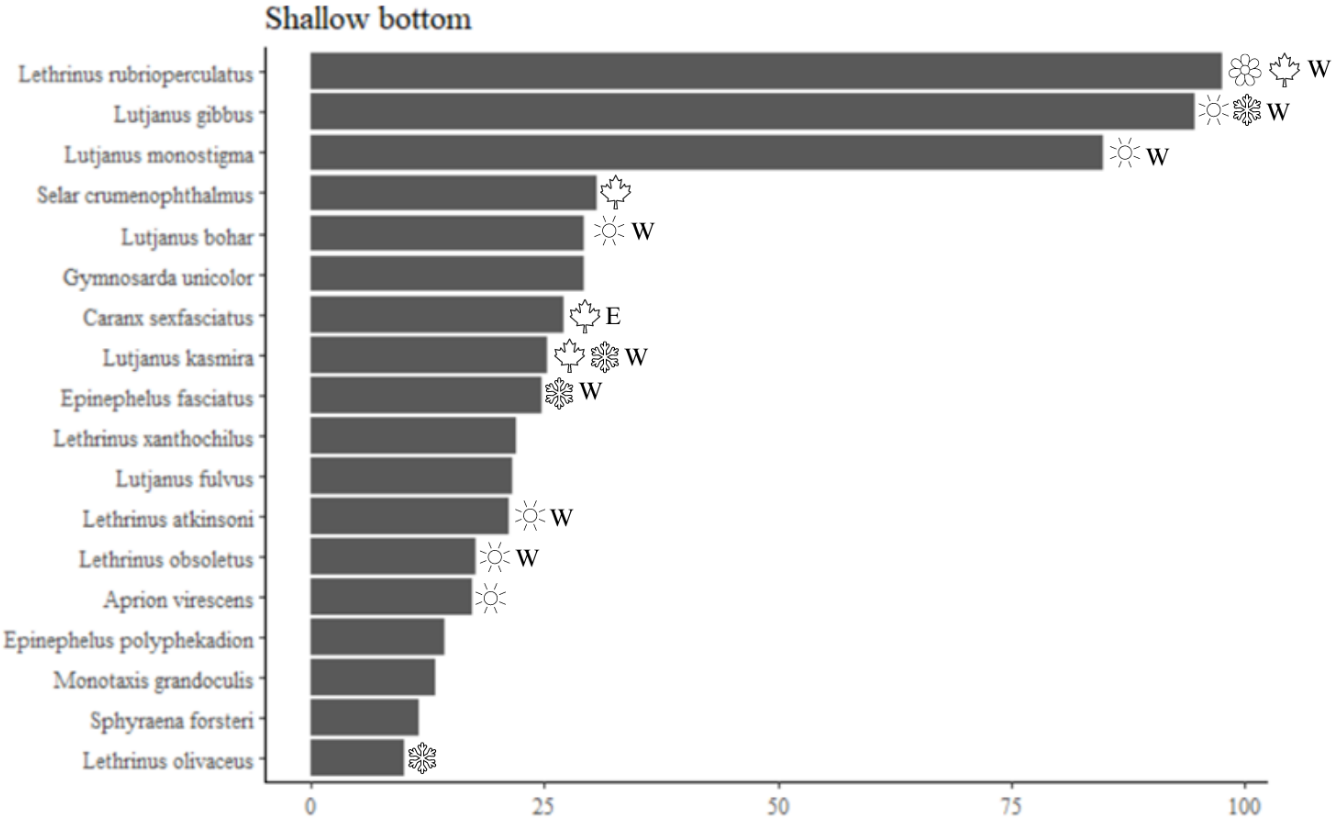
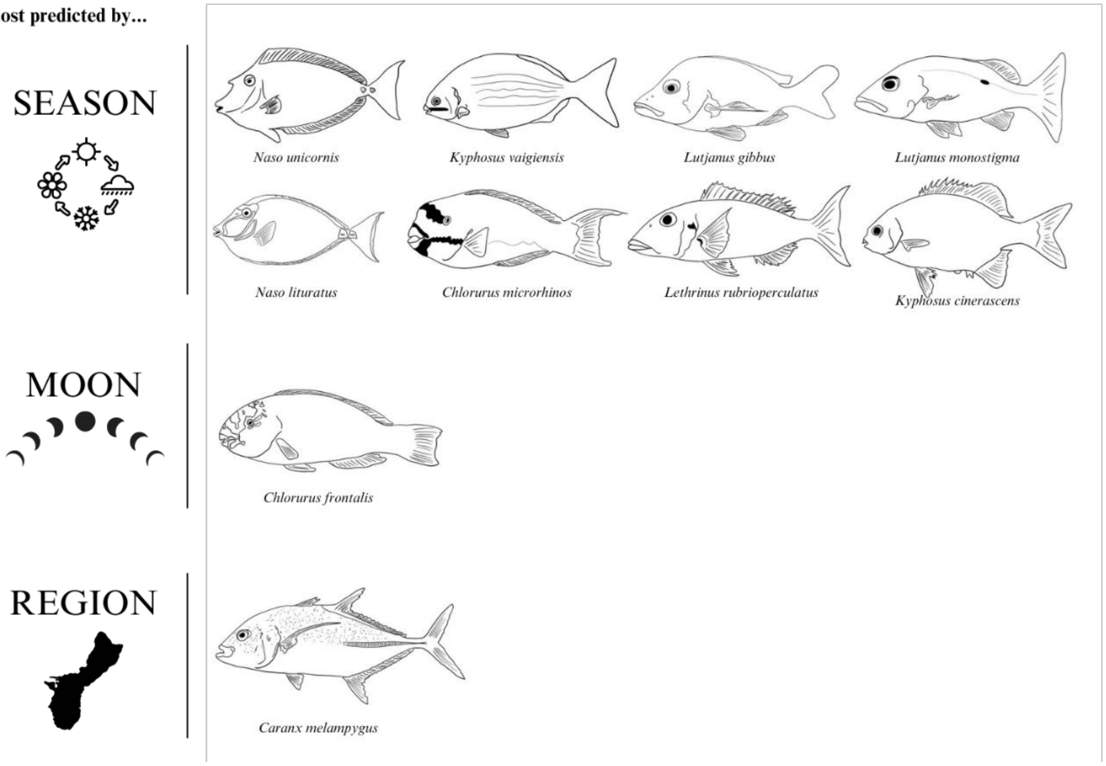


Figure 12: Bar plots of top species within the shallow bottom fishing sector by total biomass (kg), with symbols denoting which seasons and coasts (east or west, E or W) respective species were most abundantly harvested within. Season had a significant effect on catch composition (PERMANOVA F-statistic = 1.7, p = 0.02), as well as region (PERMANOVA F-statistic = 3.2, p = 0.003). Spring catch differed from summer and winter, and summer catch differed from fall. Catch composition in the east side was different from the west side. Moon had no significant effect. SIMPER analysis was run in R to determine which species were the drivers of composition differences across seasons and regions based on abundance.

(a) Average daily landings most predicted by...



(b) Average daily size most predicted by...

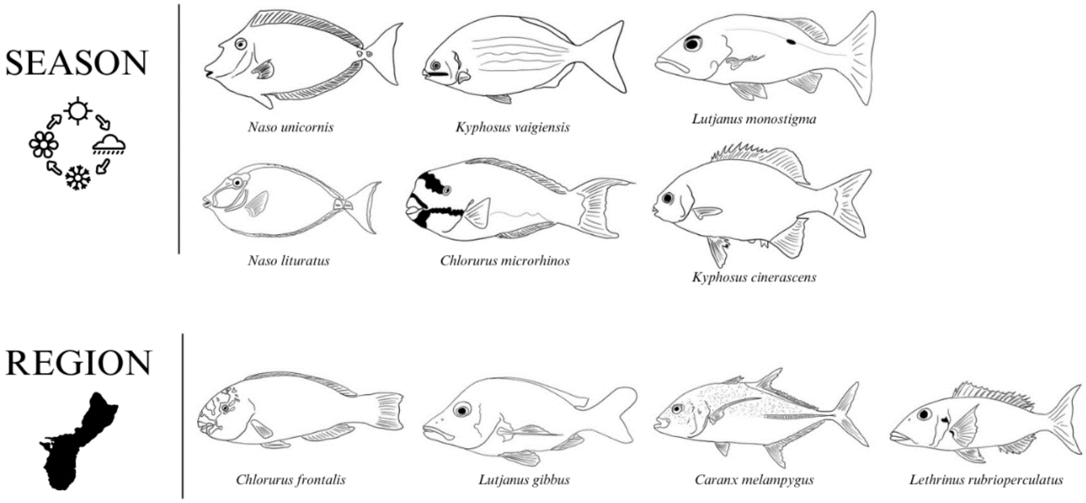


Figure 13. Schematic summarizing the most important environmental predictors of (a) average daily landings and (b) average daily size of Guam's top landed species in the non-commercial fisheries. Species-level regression trees, which detail these factors, can be found in the supplemental information.

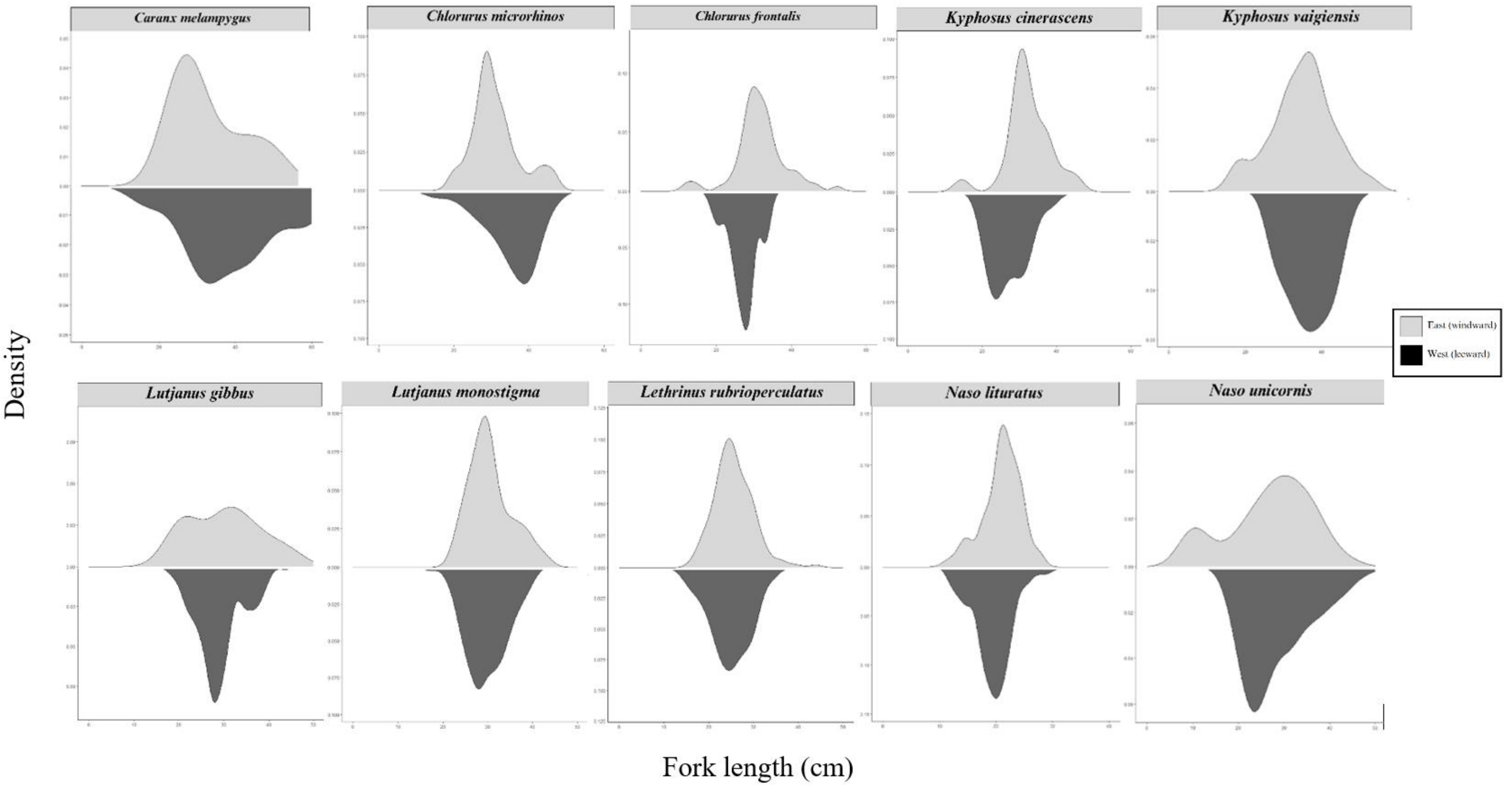


Figure 14. Size distributions in the eastern and western regions of Guam for species that comprised the top ten landed within Guam's non-commercial fisheries.

V. DISCUSSION

The present study revealed significant influences of geography, seasons, and moon phases on non-commercial coral-reef fish landings on Guam between 2021 to 2022. The findings highlighted the interplay between phenology (biological rhythms associated with seasons and moon phases) and weather (limitations to accessibility) in driving catch-and-effort across two predominant fishing sectors: spearfishing and bottom fishing. Hierarchical analyses further detailed how each of these factors influenced landings, catch composition, and fish size in unique ways to predict annual trends at both the method- and species-level. My present study thus provides the first predictive framework of landings, composition, and size for Guam's coral reef fisheries. Collectively this builds upon previous studies of catch-and-effort trends within Guam's coral reef fisheries and many surrounding Micronesia islands and helps to inform management.

"Seasons of exploitation"

Season was the most important environmental predictor of landings for the two largest fishing sectors, spearfishing and bottom fishing, with moon phase as a secondary predictor. Weather patterns and seasons are well-defined in Micronesia. Calm periods are associated with summer and fall, whereas the windy periods are associated with spring and winter. The latter seasons bring strong winds and high seas, where wave exposure acts as a natural barrier limiting fishing access to eastern exposed reefs, thereby limiting catch success. Results revealed summer and fall yielded the highest catch success (kg/day) for spearfishing, whereby the most favorable conditions nearly tripled the mean daily biomass compared to spring and winter when conditions were unfavorable. Access to fishing grounds for spearfishing, an often shore-based method, depended on calm, safe conditions to venture over the reef crest. In contrast, boat-based, shallow bottom fishing is typically restricted to the leeward side of Guam where boat ramps are located, conditions are safest for boat navigation, and fuel costs are lowest. When winds and waves decreased during the summer and fall months, total harvested biomass from the windward coast across spearfishing nearly quadrupled when compared to other times of the year. In nearby Saipan, increased landings of several top species, such as *Chlorurus microrhinos*, became more and more dependent upon the start of the calm season when less exploited reefs became accessible over a 10-year period (Cuetos-Bueno et al, 2018).

Facing similar environmental regimes, higher catches in Guam's dominant fisheries showed similar reliance to optimal seasonal conditions to obtain peak landings, most especially on the windward coast of Guam where harvests are more successful compared to leeward reefs. I that as the easily accessible leeward reefs gradually become depleted over time, more and more fishers will depend on windward harvests during the calm seasons for increased catch success, whereby daily harvested biomass is doubled when compared to leeward harvests. Although used to describe commercial landings, "race-to-fish" dynamics (Sys et al., 2017) are applicable to this scenario to some extent, as fishers take to windward reefs immediately once they have become accessible, knowing fishing is more successful within this region. Beyond Guam and Saipan, the reliance of increased catch success upon environmental factors such as seasons is a commonly observed response to fishing pressure (Myers and Worm 2005) and the magnitude of this dependence should be monitored on a long-term basis to ensure the sustainability of Guam's nearshore fisheries.

Windward versus leeward effects

While seasons were the greatest predictor of overall catch-and-effort trends, catch composition and sizes were best predicted by geography, or whether species were landed on windward versus leeward reefs. Certain top species were more prevalent in spearfishing landings from the windward coast than the leeward, such as *Chlorurus frontalis* and *Naso unicornis.* Many of these species are known to have an affinity for shallow, wave-exposed habitats (Taylor et al 2014), and it is evident that these species became highly targeted during the calm season as their habitats became more accessible. In general, research on parrotfish by Taylor et al (2014) in Guam showed that life histories were well predicted by fishing access, whereby greater landings of large-bodied species were recorded on the windward coast, but some species also had specific affinities to the windward reef habitat. Other species within my study within both spearfishing and bottom fishing sectors were also noted to have greater contributions from the windward coast of Guam, including *Kyphosus vaigiensis*, *K. cinerascens*, *Lutjanus argentimaculatus*, and *Caranx sexfasciatus*. In contrast, top species with greater contributions to the leeward coast included *C. melampygus*, *N. lituratus*, *C. microrhinos*, *C. papuensis*, *Scarus forsteni*, *Lethrinus rubrioperculatus*, *Lutjanus gibbus*, *L. monostigma*, *L. bohar*, *L. kasmira*, *Epinephelus fasciatus*, *L. atkinsoni,* and *L. obsoletus*. Geographic findings may be difficult to disentangle from seasonality; geographic preferences could be due to habitat differences of desired species and/or fishing pressure that may have altered catch success on the windward/leeward coasts through time. In support, past studies examining Guam fisheries catch data have revealed that geographic trends in species-based landings have evolved to some extent over the past several decades (Houk et al 2018). In sum, reef accessibility in the calm season clearly plays a key role in catch success for many large-bodied species, however, habitat affinities also play a significant role in landings patterns observed for many others. Most top landed species were larger on average (up to 17%) on the windward compared to the leeward side of Guam. Similar shifts in size distribution of landings, catch composition, and catch success in windward versus leeward reefs have been noted in other studies from nearby Micronesia islands for the spearfishing sector (Houk et al. 2012, Taylor et al. 2014, 2015). It appears that windward reefs of Guam serve as almost a natural marine preserve during the windy months when access is limited, and fish populations are not experiencing the same magnitude of fishing pressure by spearfishers and much-less (and almost non-existent) by bottom fishers.

In synthesis, trends on the windward coast for bottom fishing are less of concern from a management perspective, although spearfishing trends revealed in my study show that regulations could be used to support a more consistent catch-success, and more consistent financial/social benefits, for fishers instead of the boom-and-bust dynamics that were observed. Further monitoring of catch success and species composition between leeward and windward is recommended along with more detailed species-based information provided below. In combination with future stock assessments, we can further identify specific management options that have the greatest chance for success.

Interplay of phenology and fisheries landings

While lunar phase was not the most important predictor of landings, it was still a secondary predictor of landings for both spearfishing and bottom fishing and was even the top predictor for size within the spearfishing sector and a secondary predictor for size within the bottom fishing sector. Lunar cycles are known to influence fish behavior, with periodicity in spawning being a notable correlation to moon phases, where many species utilize the influence of tidal currents caused by the moon to better disperse larvae away from reefs and into the open ocean (Johannes 1978, Robertson et al. 1990, Sponaugle and Pinkard 2004). In marine environments, the different lunar cycles are correlated to tidal fluctuations due to the magnetic pull of the Earth (Stolov 1965). The behaviors of different marine species are altered by the resulting tidal changes, including behaviors such as foraging, spawning, and movement (Connell 1961, Lohmann et al. 2008). Brightness within the marine environment as a result of varying lunar cycles also affects fish behavior, notably through predator-prey interactions where visually-dependent predators may benefit from foraging when their environments are more brightly lit while prey may benefit from lowly lit environments (Palmer et al. 2017; Prugh and Golden, 2013). Anecdotal evidence from members within the bottom fishing community in Guam who prefer to fish during new moon phases corroborates my results, revealing higher success of landings during new moons, presumably when prey increase their activity in the protection of darkness from predators. The interplay between phenology and fisheries evident in my study demonstrates the influence that biological patterns have on landings success, whether these patterns are known to us or not.

Species-level predictors for top species

Hierarchical influence of season, coastal region (i.e., exposure differences), and lunar phase were also applied at a species-level, providing valuable insight as to the sensitivities of top species to environmental factors on an annual basis. The phenology of reef fishes largely dictates fisheries success in that spatial and temporal landings evolve around the biology of species whether that be movement, reproduction, foraging, among many others – and whether we are knowledgeable about these behaviors or not. At the species level, season and lunar phase have the potential to predict both landings and size, which is presumed to be correlated to species-level phenology. Close examination of *N. unicornis*, for example, shows higher daily landings in the mid-moons of fall and summer. This species reaches peak spawning during the new and full moons from July to September (Taylor et al. under review). Thus, landings are nearly double during the mid-moon of these months when *N. unicornis* is not spawning, when individuals of this species are more dispersed, versus when they are aggregating at specific locations during spawning periods. This study highlights the most important predictors of top species landings and size across spearfishing and bottom fishing, elucidating seasons of exploitation at a species level which may also aid in management strategies. By increasing our knowledge of the phenology and biology of species, we can consequently understand the dynamics of these factors in fisheries as well as the anthropogenic influences on said biological rhythms. In sum, we see the potential that hierarchical environmental predictors may have in the management of reef fish at the species-level, where life history traits can serve in combination to predict catch success and peak harvesting periods.

Contemporary vs historical findings

My study represents the most recent assessment of coral reef fisheries in Guam. Contemporary results address a gap in trends of over 15 years, with previous research having assessed data between 1985 to 2006. Informal analysis reveals how species dominating landings more than ten years ago may be similar or different to present-day landings. Some species continue to dominate landings within the spearfishing sector, including *N. unicornis*, *C. melampygus*, *N. lituratus*, *K. vaigiensis/cinerascens*, *Chlorurus microrhinos*, and *Hipposcarus longiceps*. Interestingly, *C. frontalis* rose to the top of the landings list. Findings from Houk et al in 2018 saw that declines in *C. microrhinos* and *Scarus rubroviolaceus* were accompanied by non-significant increases of *C. frontalis.* This large-bodied, long-lived, and highly valued parrotfish reaches sexual maturity at a young age and has a fast growth rate early in the life span (Taylor and Choat 2014). Though these life traits likely contribute to some extent to this species' rising dominance, it is more likely that my study may have better captured *C. frontalis* landings when compared to DAWR's creel surveys. Surprisingly, *C. microrhinos* – a species with concerns of disappearing from landings as fishing pressure increases – continues to dominate landings, suggesting it may not be as concerning as we historically thought and/or is benefiting from the SCUBA spear ban in 2020. The persistence in landings across these top species, as well as the decrease in contribution from others, may hint at which species are faring well against fishing pressure over time (i.e., “winners”) and which species may be in decline (i.e., “losers”) or how preferences in target species may be shifting within the fishing community.

In addition, contemporary findings at the species-level elucidate how landings for top species decreasing in contribution over time (i.e., “losers”) may be constrained by environments. The most recent assessment for *C. microrhinos¸* for example, continues to slowly disappear from spearfishing landings as fishing pressure increases (Houk et al., 2018). My results revealed that catch success for this species was highest during spring and summer in the leeward reefs. Instead of consistent landings throughout the year, results elucidated landings are now variable in time and space and more constrained towards these environments. Thus, as species become scarcer, fishers may be tapping into environmental regimes of desirable species in order to obtain more successful landings. All in all, current findings build upon previous trends for Guam and adds to the plethora of knowledge we have at both the method and species level in aiding in management planning efforts for Guam’s reef fisheries.

Management

Findings from this study can assist in ongoing fisheries management planning for Guam. Results revealed windward and leeward regions as two spatially distinct and temporally fluctuating fishing grounds; a clear gradient exists in fish biomass, size, and catch composition with differences in peak landings across seasons. Spatial management units may be considered for windward and leeward coasts of Guam; zonation of commercial and non-commercial fishing grounds could be of benefit to the fishing community while also conserving biodiversity and size. Designating reefs that can withstand commercial versus non-commercial fishing pressure should carefully consider factors such as food security, economic benefit, and fishing skill to respective fisheries. The depleting reefs of the leeward coast of Guam would benefit from non-commercial harvests only, with some zones/reefs open to commercial fishing. The northwest reefs of Guam are both commercially and non-commercially important, with large volumes of commercial reef catch anecdotally harvested within this region on an annual basis with commercial boats regularly launching from Agana Boat Basin. Designating some of these reefs as commercial take-zones while leaving the easily accessible southwest reefs of Guam for non-commercial only would ensure both commercial and non-commercial fishers are able to acquire the resources they need while alleviating fishing pressure. The windward spatial management unit could reflect similar regimes, except commercial zones would have to be designated in the southeast to ensure commercial fishers residing in southern Guam have closer access to fishing grounds; this gives northern and southern commercial fishers equal access to resources. Unregulated commercialization of reef fisheries unrestricted by policies, in combination with more effective fishing technology, may be the driving force of leeward depletion, thus spatial management units divided by zonation would aide in the recovery of the leeward coast’s slowly depleting fish stocks while still allowing fishing to occur at regulated levels.

At the method-level, results clearly show that both predominant fishing methods of spearfishing and bottom fishing have specific concerns unique to method. Regression trees revealed seasons of exploitation are not as evident within the bottom fishing sector when compared to spearfishing, thus seasonal regulations (where size- and effort-based policies can come into play) would not be beneficial for bottom fishing but would be for spearfishing.

Spearfishing on the windward coast occurs quite intensively during the calm periods of the year; size and/or effort policies for this method may be considered during these seasons of exploitation, more so for the windward coast but nonetheless still for the leeward coast due to the selectivity for species and size by this method. While spearfishing clearly needs more regulation, bottom fishing nonetheless is regarded as a method with effectiveness in harvesting large volumes of biomass per trip as supported by my results; consideration of quota- and size-based policies for driving species within this sector would ensure sustainable harvesting. The ability to select for species and size by both spearfishing and shallow bottom fishing sectors makes size-based policies one option to address Guam's fisheries.

Managing fisheries really comes down to size-based or effort-based policies. Should we consider the volume that is being caught regardless of size, or should we consider size-at-capture without considering volume? Species-based regression trees hinted on how species may best be managed by effort/landings, size, or lunar cycles based on predictive power. It would certainly be wise to consider how my present findings resonate with previous ones in regard to trends and sensitivities of species, and how each study can serve in combination with one another to create the best management strategies at the species-level.

Non-commercial fisheries remain an important component of Guam's society and culture, yet disentangling non-commercial from commercial fisheries is not as straightforward as it seems. Many fishers throughout Guam are often a combination of non-commercial and commercial, selling catch for profit while also retaining some for subsistence purposes. Disentangling such complexity would be quite a feat but would be beneficial in understanding the interdependencies of both sectors to reef-associated resources and how each sector would best benefit from unique policies and regulations. My study revealed an incredible amount of non-commercial fishing exists in Guam, but this ratio to commercial fishing remains unknown. Nonetheless, it is clear the fishing community largely depends on reef fisheries as part of society and culture, and conserving such resources would ensure the conservation of these important aspects for future generations of fishers.

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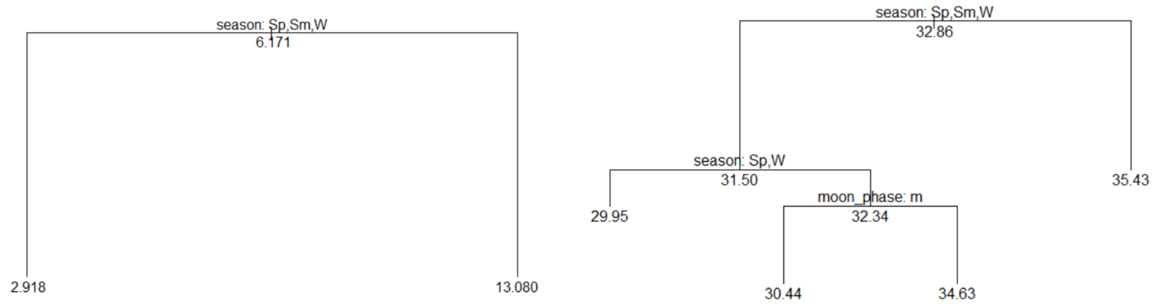
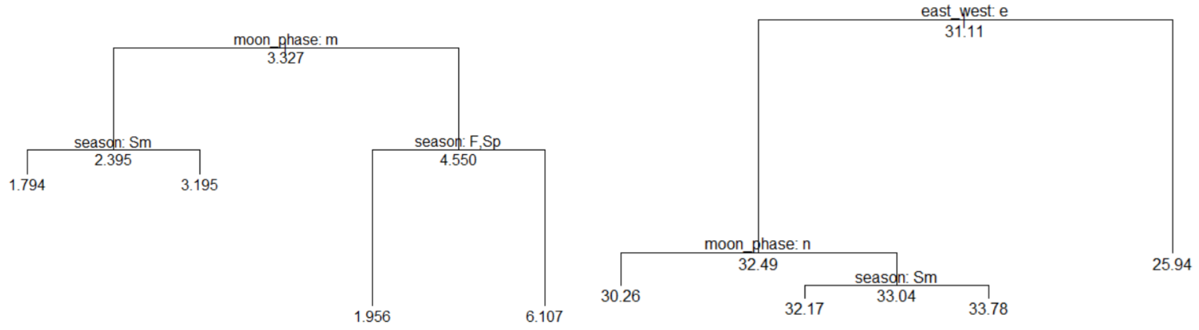
Supplementary Information

Predictors of daily landings (left) and daily average size (right) for top species harvested in non-commercial fisheries in Guam

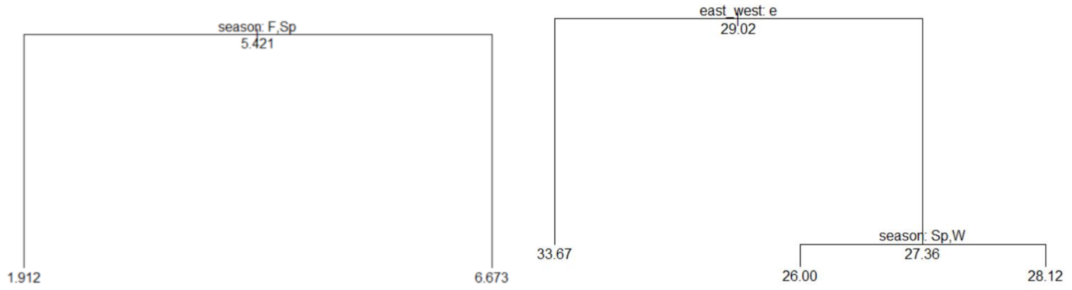
Kyphosus vaigiensis



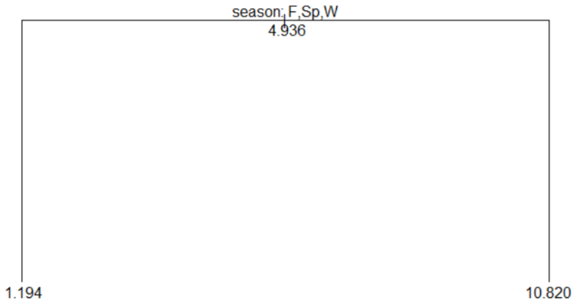
Chlorurus frontalis

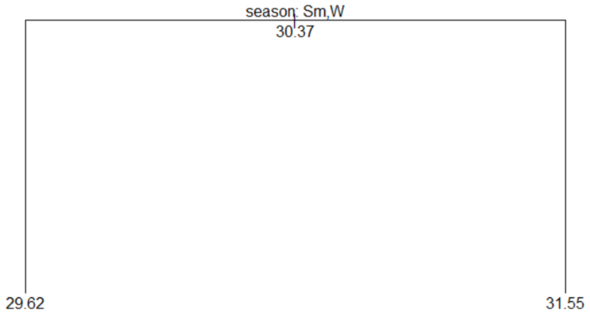


Lutjanus gibbus

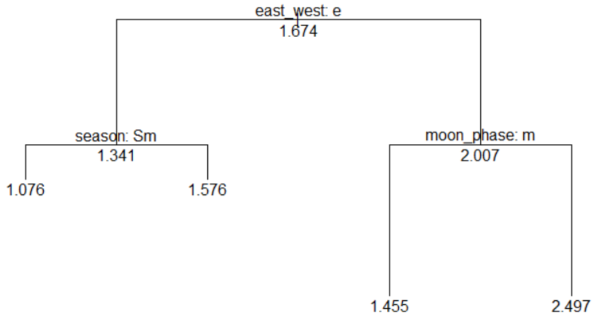


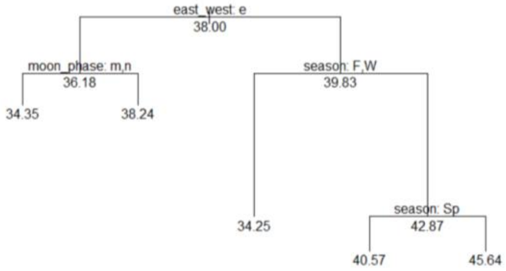
Lutjanus monostigma



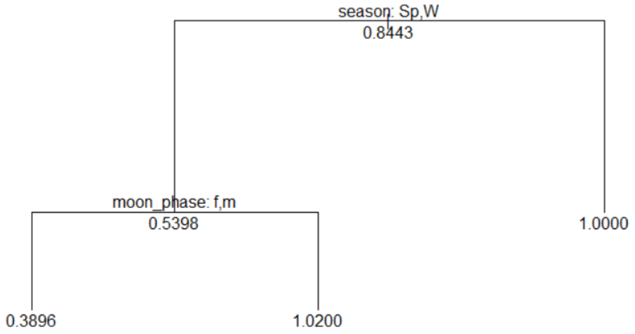


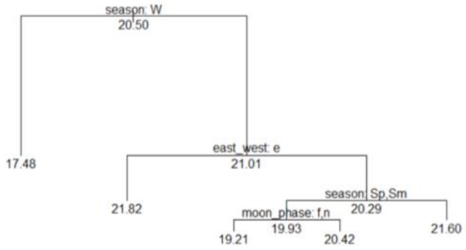
Caranx melampygus



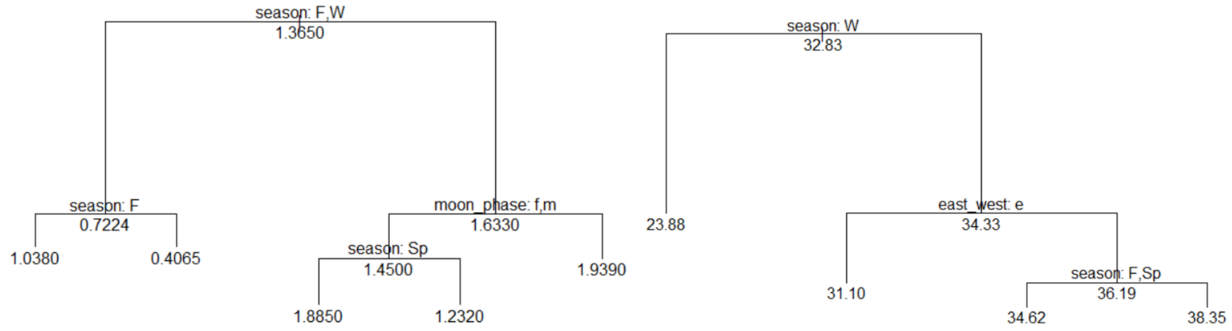


Naso lituratus

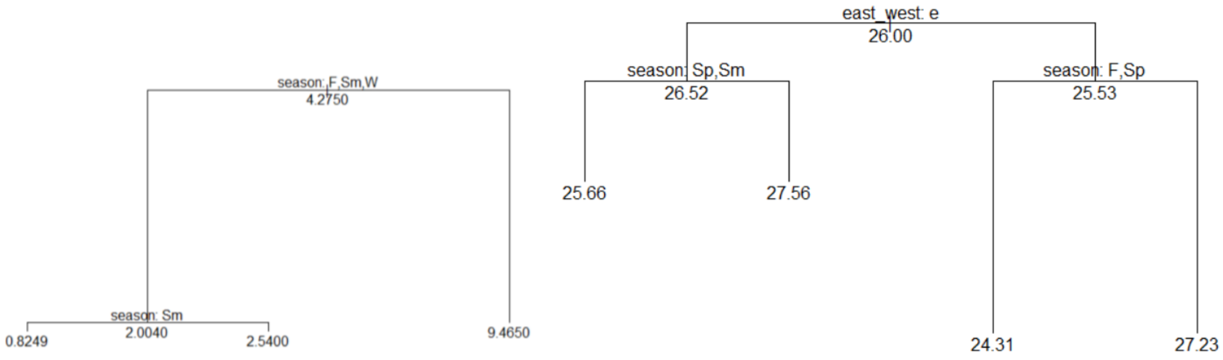




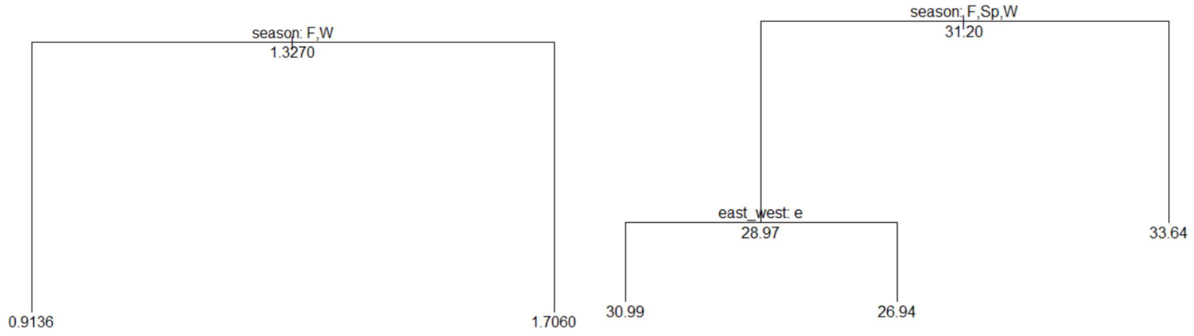
Chlorurus microrhinos



Lethrinus rubrioperculatus



Kyphosus cinerascens



Size structure across moon, seasons, and geographical regions

	L_{min}	L_{max}	Avg daily kg
MOON			
Mid	9.0	46.0	7.6
Full	8.0	52.7	8.5
New	12.3	48.9	8.8
SEASON			
Winter	10.4	39.0	2.7
Spring	15.0	55.0	5.6
Summer	10.1	47.2	12.7
Fall	8.0	49.0	6.9
REGION			
NE	9.0	48.4	7.9
NW	9.0	44.8	5.5
SE	11.0	52.5	6.8
SW	10.8	36.4	5.4

Table S1a. Minimum size (cm), maximum size, and average daily biomass across the different moon phases, seasons, and geographic regions within the spearfishing sector.

	L_{min}	L_{max}	Avg daily kg
MOON			
Mid	12.1	39.7	20.2
Full	15.3	36.5	9.3
New	12.0	41.6	21.0
SEASON			
Winter	12.8	33.6	23.4
Spring	12.0	37.1	11.9
Summer	12.8	44.0	24.4
Fall	13.6	33.5	13.1
REGION			
NE	14.1	39.5	7.5
NW	12.0	39.0	15.7
SE	14.0	43.3	-
SW	12.8	39.5	19.0

Table S1b. Minimum size (cm), maximum size, and average daily biomass across the different moon phases, seasons, and geographic regions within the bottom fishing sector. Only one southeast event was recorded within this sector throughout the one-year period and therefore could not compute average daily landings.

TO THE OFFICE OF GRADUATE STUDIES

The members of this committee approve the thesis of Leilani Sablan, presented on July 25, 2023.

Dr. Peter Houk, Chair

Dr. Brett Taylor, Member

Dr. Frank Camacho, Member

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Dr. T Todd Jones, Member

ACCEPTED:

Director of Graduate Studies

Date