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Invasive Lionfish in Atlantic Reef Ecosystems: A Bibliometric Review of Contemporary Research and the Vulnerability of Certain Prey Species.

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Abstract

Invasive lionfish (&apos&aposPterois volitans&apos&apos and &apos&aposPterois miles&apos&apos) have become a significant threat to Atlantic marine ecosystems, outcompeting native species through rapid reproduction and predation. This bibliometric study of contemporary research examines the growing research interest in lionfish since their introduction to the Atlantic in the late 20th century through an analysis of academic publications from 1980 to 2020 comparing lionfish studies with research on seven different Atlantic grouper species (Epinephelinae), which served as controls due to their shared ecological trophic level. While lionfish-focused research has steadily increased, statistical analysis (paired t-tests) showed no significant difference in publication rates compared to grouper studies. Additionally, an analysis of five observational studies on lionfish stomach contents revealed a preference for small, schooling, pelagic fish, such as grunts (Haemulidae), particularly those active during twilight hours. Lionfish consume prey at alarming rates in Atlantic reef ecosystems, uhindered by the biotic factors of native predators or parasites. Their diet overlaps with native mesopredators, including the economically valuable groupers, further threatening these species by depleting juvenile populations and monopolizing resources.The findings highlight lionfish as a growing ecological and economic concern for Atlantic marine ecosystems. Their unprecedented proliferation underscores the urgent need for targeted interventions to mitigate their impact on biodiversity and support the resilience of native marine communities.

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Keywords: Pterois volitans, Pterois miles, mesopredator, Western Atlantic, stomach content, invasive

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Invasive species pose an ever-increasing threat to the stability of marine ecosystems worldwide. Warming temperatures and increased carbon dioxide absorption from the atmosphere have been associated with strong changes in wind speed and decreased pH levels as they create changes in the environment that allow for new species to establish a foothold in foreign environments. By allowing invasive species to survive in foreign environments, humans enable them to outcompete native species for resources. (Hoegh-Guldberg 2010) In a controlled experiment, just a three-degree Celsius increase in temperature, caused an observed increase in the populations of invasive species. Conversely, the experiment revealed an observed decrease in native populations. (Sorte et. al, 2010) The Atlantic coast is a hotbed for biodiversity with a temperate climate of roughly 18 degrees Celsius (NCEI 2023).One particularly large marine ecosystem in the Atlantic is the Florida Keys National Marine Sanctuary which houses roughly 6000 native marine species includes fish, marine mammals, sea urchins, coral reef species, and shrimp. (Office of National Marine Sanctuaries, 2011) Further north, off the shore of North Carolina, the Atlantic White Marlin, *Tetrapterus albida*, a species of marlin that can grow to be roughly 3 meters long, hunt for mackerel and squid. However, the Atlantic Ocean's mild temperature leaves its ecosystems vulnerable to invasion. *Pterois volitans*, a species of lionfish endemic to the Indo-Pacific, was first spotted near Dania Beach on Florida's Atlantic coast in 1985 where they have since proliferated at a rapid rate. In addition, another pair of lionfish were spotted by recreational divers in North Carolina in 2000 where they had managed to

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spread further north independently of the Floridian invasion (*Florida Fish And Wildlife Conservation Commission*). While there is little difference between them, there are technically two species of lionfish invading the Atlantic coast, *P. volitans* and *P. miles*.: *P. volitans* have one more dorsal and fin ray than *P. miles*. (Morris 2009) Besides their slight taxonomic differences, Research specialist David W. Freshwater from the University of North Carolina identified through mitochondria analysis that there was enough genetic variety between the two to claim that they were two different species (Freshwater, 2009). Furthermore, the two species inhabit different areas of the Pacific Ocean with *P. volitans* in the Western and Central Pacific Ocean as well as Western Australia (Morris 2009). However, the differences between the two species have little bearing on the threat they pose to native Atlantic marine species. According to the United States Geological Survey's Nonindigenous Aquatic Species information database, lionfish have been reported along the Atlantic coast from Pennsylvania to Rio de Janeiro (NAS). One major reason why lionfish have been able to spread so rapidly is their lack of predators. In their natural habitats, lionfish are under constant predation by large groupers, moray eels, certain shark species, and even people. As a result, they evolved to release many eggs, and often: every four days, a female lionfish releases two egg sacks filled with 15,000 eggs each. In addition, female lionfish breed all year. One female lionfish alone can release close to two million eggs in just a year (Coles 2018). However, as a non-native species, lionfish in the Atlantic are unaffected by native parasites and avoided by native predators because of their vibrant colors and venomous spines (Hixon 2016). In addition to their strange appearances, lionfish target their prey with an equally foreign hunting method: lionfish are able to shoot jets of water toward their prey, disorienting prey fish and driving them into the mouth of the lionfish (Del Río 2023). However, as evidenced by studying the hunting habits of invasive lionfish in the Atlantic, invasive lionfish use this tactic of firing water at prey significantly less in the Atlantic because native fish species are completely oblivious to the threat that the lionfish pose. As a result, invasive lionfish in the Atlantic have been recorded to eat larger amounts daily than their Indo-Pacific counterparts as they continue to hunt with the same voracity but without the limitations set by their natural habitats (Cure 2012). As a generalist and opportunistic hunters, lionfish have evolved to eat whatever they can. Nevertheless, even lionfish have a preferred prey. In the Indo-Pacific, lionfish hunt by just above the sea floor and stalking prey from below. As such, lionfish who employ the same stalking technique in the reef ecosystems of the Atlantic coast prefer to target fish species inhabiting the pelagic zone of the coast. Furthermore, as crepuscular predators, lionfish are more likely to target prey species that are most active in the evening. Along with these criteria, research has revealed that the fish species most vulnerable to lionfish predation are small, schooling, pelagic, and active in the evening (Green 2014). In coastal North Carolina, a family of fish species that matches these criteria, Grunts, or *Haemulidae*, make up almost half of the gut contents of invasive lionfish, an indication that grunt populations are subject to lionfish predation at higher rates than other preyed-upon marine species such as lobsters, goatfish, and parrotfish (Chappell 2016). While there is evidence that native mesopredators like groupers are able to deter invasive lionfish from feeding on native reef fish, there is also evidence that adolescent lionfish prey on juvenile groupers (Ellis 2016). In summary, invasive lionfish have overfed and reproduced at a rapid rate, stealing resources from other mesopredators and threatening the stability of Atlantic ecosystems along the United States coast. Because of the naturally warmer waters of the Indo-Pacific, lionfish are not able to survive ocean temperatures under 10 degrees Celsius, limiting their expansion in the Atlantic to the southeast US continental shelf (Kimball 2004). Nevertheless, the invasion of marine ecosystems by foreign lionfish, even within the US continental shelf, is devastating for both native marine populations and coastal people. Their proliferation in Atlantic ecosystems is unhindered to the extent that, without human intervention, the largest limiting factor for lionfish population growth is competition for resources with other lionfish (Benkwitt 2013). With coral reefs as far as Brazil affected by the wave of fast-reproducing lionfish, fish species like the Grouper family, or *Epinephelus*, and Snappers, or *Lutjanus*, both of whom play important roles in the economy of the human populations in the region, are at risk of being outcompeted for resources (Morris 2012). Therefore, this study sets out to answer the question of how research interest in invasive lionfish has increased since the first report of lionfish in the Western Atlantic in the late 1990s and how, in general, their rapid growth has spurred research on their impact on specific native prey species. Furthermore, this study seeks to understand why certain prey species populations are more vulnerable to predation than others.

Methodology

I measured the growth of the field of study regarding invasive lionfish by conducting a bibliometric analysis of the available academic body of research on lionfish, *Pterois volitans,* and *Pterois miles*, from 1980 to 2020. I split the 40-year time period into 8 periods of 5 years each, exclusive to the starting year and inclusive of the ending year. For example, the second period of time I recorded data for was 1986 to 1990. Over each 5-year-period I sampled the number of newly published academic papers relevant to *Pterois volitans* and *Pterois miles* respectively.

Furthermore, I compared the rate of research on lionfish to that of other common mesopredators found in the Atlantic Ocean. In both cases, Google Scholar was used with the species' binomial nomenclature (*e.g.*, "*Pterois volitans*", "*Epinephelus morio*"), limited to review articles with included citations which excluded ambiguous and non-scientific entries. Moreover, the Mendeley Citation Tool was used to remove duplicates among the remaining studies. The term "mesopredator" refers to mid-sized predators that not only prey on other but are preyed upon by the apex predators of their ecosystem. I used 7 different species of Groupers, marine fish mesopredators of the *Epinephelinae* subfamily of the Serranidae family, as controls for the rate of research. The control represented by the grouper species contribute to gathering an accurate representation of how the invasive nature of lionfish in the Atlantic has specifically spurred the publication of new academic research. Not only are Groupers indigenous to the regions in which lionfish have invaded, they also share many commonalities with them. The rate of research regarding the different grouper species represents the expected rates of research for mid-sized marine mesopredators. The seven Grouper species that had their rates of research sampled include the Atlantic Goliath grouper (*Epinephelus itajara*), Black grouper (*Mycteroperca bonaci*)*,* Gag grouper (*Mycteroperca microlepis*)*,* Red grouper (*Epinephelus morio*)*,* Scamp grouper (*Mycteroperca phenax*)*,* Yellowfin grouper (*Mycteroperca venenosa*)*,* and the Nassau Grouper (*Epinephelus striatus*). Notably, the Nassau Grouper is considered critically endangered under the Endangered Species Act of 1973.

Using the mean average of the number of new academic papers published through Google Scholar regarding each grouper species, I calculated a mean dataset representative of all seven grouper species across the 8 5-year-periods and used this new dataset as the expected values to produce a faux-residual graph of the rate of research for the two lionfish species. In addition, to show the statistical significance of the upward trend in lionfish research, I conducted multiple paired t-tests comparing each of the 7 species of grouper to both *P. miles* and *P. volitans* at a 95% significance level.

Moreover, when attempting to find what makes certain Atlantic prey species more vulnerable to lionfish predation than others, I conducted an in-depth analysis of 5 different observational studies of the stomach contents of invasive lionfish in the Atlantic. The academic papers used were sourced through Google Scholar with the control search phrase "lionfish predation rates" combined with different marine regions along the Atlantic coast. As coastal reef ecosystems tend to have the most biodiversity, lionfish not only have a greater opportunity to proliferate than they would in open water, but the lionfish are more likely to encounter prey that are particularly vulnerable to lionfish predation. Therefore, the marine regions I combined with the control search phrase were all coastal ecosystems in the Atlantic. The marine regions used in our analysis came from S.R. Floeter's *Atlantic Reef Fish Biogeography and Evolution* which splits the vast Atlantic ocean into regions (*e.g.*, "Northwestern Atlantic (NWA)", "Southwestern Atlantic (SWA)"), with each 'province' further splitting into areas designated by the nearby country. These areas such as "Bahama" or "Southern Carribean" were variable phrases combined with the search phrase. To increase the probability of finding academic sources relevant to both the specified area and invasive lionfish, I narrowed the scope of the research to the Western Atlantic, the part of the Atlantic Ocean where the ocean meets the coastline of North and South America. After entering in a complete search phrase, I used a pool of the first five pages of search results to find the relevant academic papers. I narrowed the academic papers to further research from the list of 5 pages through a series of steps. The first step was to remove any papers that did not mention the searched-for area, an area inside one of the relevant areas, or lionfish predation in the title. Further, based on the abstract or title, reviews of literature were removed in the second step. In the third step, in order to be able to compare one research paper to another, I limited the pool of research papers to strictly research papers that studied the stomach contents of invasive lionfish in their relevant area and named a specific marine species as the most preyed upon (Figure 1).

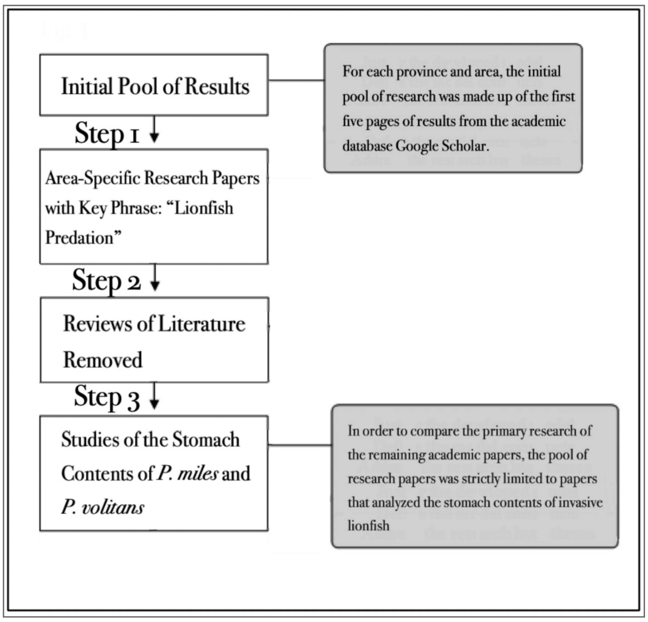

Figure 1: Steps 1 through 3 of narrowing research pools. Detailed in the methodology, steps 1-3 took a pool of 50 academic publications (10 publications per page * 5 pages per search) to one research paper per area.

The "most preyed upon" species was not the species that made up the most stomach mass but the frequency of prey appearing in the stomach. The slight but important distinction is demonstrated in the 2018 research paper *Feeding Ecology of Invasive Lionfish in the Temperate and Tropical Western Atlantic* where shrimp make up 29.5% of the frequency of predation but only represent 6% of the stomach mass (Peake et al. 2018). After the third step, I read the remaining research papers fully and determined which marine species, based on the findings of the research paper, were the most preyed upon by invasive lionfish (Table 1).

Province	Area	Most Preyed Upon Fish Species	Relative Frequency as Prey in their Respective Stomach Analyses
Northwestern Atlantic (NWA)	North Carolina	Grunts (*Haemulidae*)	42%
Northwestern Atlantic (NWA)	Bermuda	Bluehead Wrass (*Thalassoma bifasciatum*)	3.40%
Northwestern Atlantic (NWA)	Bahama (Eastern Carribean)	Masked Goby (*Coryphopterus hyalinus/personatus*)	48%
Temperate and Tropical Western Atlantic	N/A	Red Night Shrimp (*Cinetorhynchus manningi*)	3.60%
Southwestern Atlantic (SWA)	Mexican Carribean	Mechanical Shrimp (*Cinetorhynchus rigens*)	23.95%

Table 1: A table of research papers that met the criteria of steps 1 through 3. Adjacent to them are the relevant provinces, areas, the citation index of the research paper, and the most-preyed upon species according to lionfish stomach contents in that area.

Results

An analysis of the increasing rate at which new research papers are published with lionfish as the focus help demonstrate the growing research interest in the actions of lionfish in the Atlantic. Data on the number of papers published was recorded from 1980 to 2020. While the number of published articles regarding lionfish grew with an upward trend, the number of new articles published on the seven grouper species stagnated as time passed (Figure 2).

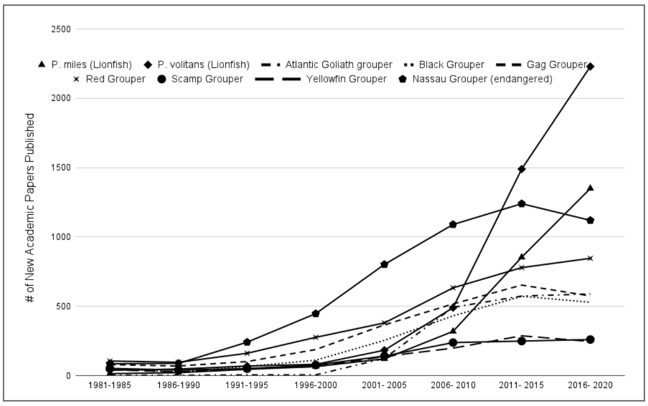

Figure 2: The increasing rate of new academic papers published yearly. The number of new articles published in four-year periods regarding the two invasive lionfish species compared to number of new articles published in the same periods on seven different species of grouper (*Epinephelinae*).

Moreover, as shown by the high rates of research interest in both *P. volitans* and *P. miles*, the only two lionfish species to invade the Atlantic, the threat that invasive lionfish pose to the environment is one of the main drivers in the observed spike in interest (Figure 3).

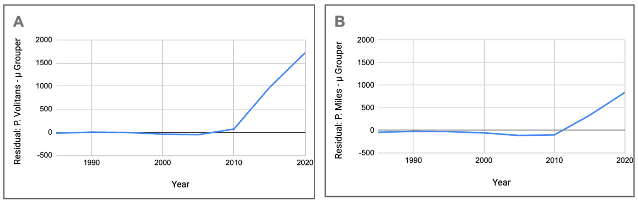

Figure 3: Faux-residuals created from rates of research of lionfish - rates of research of μ grouper. (A) the rate of research relevant to P. volitans compared to the μ average research rate for groupers. (B) the rate of research relevant to P. miles compared to the μ average research rate for groupers.

However, according to the paired t-tests of *P. volitans* and *P. miles* in comparison to the average marine mesopredator, as represented by the aforementioned species of grouper, the rate of growth of academic research on lionfish is not statistically significant at a 95% confidence interval ($p<0.05$). In the case of *P. volitans*, the p-values resulting from the paired t-tests ranged from 0.14 when compared to the Atlantic Goliath Grouper, *Epinephelus itajara*, to 0.76 when compared to the endangered Nassau Grouper, *Epinephelus striatus* (df=7). Similarly, p-values from the paired t-tests between groupers and *P. miles* ranged from 0.80 to 0.0433 (df=7) (Table 3).

P-value	**Atlantic Goliath grouper**	**Black Grouper**	**Gag Grouper**	**Red Grouper**	**Scamp Grouper**	**Yellowfin Grouper**	**Nassau Grouper**
P. volitans	0.1407	0.1988	0.29	0.43	0.1408	0.1333	0.7674
P. miles	0.2579	0.4355	0.8031	0.52	0.1953	0.1788	0.0433
T-value							
P. volitans	1.661	1.4194	1.13	0.833	1.6605	1.6983	0.3076
P. miles	1.2316	0.827	0.259	0.6662	1.4318	1.4942	2.4633
Standard Error							
P. volitans	213.195	227.918	229.427	202.887	265.125	263.054	197.113
P. miles	100.887	113.207	116.327	91.374	146.931	145.149	117.932
DF for all: 7							

Table 3: A table of P-values and T-values resulting from paired t-tests between *P. volitans* and *P. miles* against each selected Grouper species.

As for the vulnerability of certain prey species, the results of our selective criteria for research papers were five observational studies, all of which studied invasive lionfish in the western Atlantic, with an emphasis on mapping the stomach contents of the wild invasive pests. Across the 5 studies, the average number of citations across the five papers was 60.8±54.1 (N=5) (Table 1). Furthermore, the plurality of prey fish in the stomach contents of invasive lionfish across the western Atlantic demonstrates that lionfish have a preference from fish over shrimps and mollusks (Table 2).

Region	**Area**	**Academic Papers Used**	**Most Preyed Upon Fish Species**	**Date of Publication**	**Citation Index**
Northwestern Atlantic (NWA)	North Carolina	Patterns of Predation of Native Reef Fish by Invasive Indo-Pacific Lionfish in the Western Atlantic: Evidence of Selectivity by a Generalist Predator.	Grunts (*Haemulidae*)	2016	19
Northwestern Atlantic (NWA)	Bermuda	Diet of invasive lionfish (Pterois volitans and P. miles) in Bermuda	Bluehead Wrass (*Thalassoma bifasciatum*)	2016	49
Northwestern Atlantic (NWA)	Bahama (Eastern Carribean)	Predation rates of Indo-Pacific lionfish on Bahamian coral reefs	Masked Goby (*Coryphopterus hyalinus/personatus*)	2010	165
	Temperate and Tropical Western Atlantic*	Feeding ecology of invasive lionfish (Pterois volitans and Pterois miles) in the temperate and tropical western Atlantic	Red Night Shrimp (*Cinetorhynchus manningi*)	2017	53
Southwestern Atlantic (SWA)	Mexican Carribean	Spatio-temporal variation in the diet composition of red lionfish, Pterois volitans, in the Mexican Caribbean: Insights into the ecological effect of the alien invasion	Mechanical Shrimp (*Cinetorhynchus rigens*)	2016	18

Table 2: a list of the most preyed upon species according to the 5 research papers that met the research criteria (see table 1) and the class of preyed upon species as well as relative frequency and the mean average of values that shows a preference for Vertebrate over Crustacea.

Discussion

Although the first lionfish in the Atlantic was sighted in 1985, research interest in the then-newly established invasive species was practically nonexistent until the lionfish population had spread into North American waters by 2000 when the first lionfish was spotted off of the coast of North Carolina. Ever since, research interest in *Pterois volitans* and *Pterois miles* has been growing rapidly at an exponential rate. However, because of initial lackluster concern during the first two decades since the first lionfish sighting in the Atlantic Ocean at Dania beach Florida, research interest in invasive lionfish is not yet statistically significant, indicating that a larger investment into the research and prevention of invasive lionfish is necessary. Moreover, the wide variety in p-values and t-values is likely to be swayed heavily by the research interests of the scientific community and conservation status of the individual grouper species (Table 3). For example, the critically endangered Nassau Grouper, *Epinephelus striatus*, had the lowest p-values in comparison to invasive lionfish among all the tested Grouper species. Meanwhile, the common Red Grouper, *Epinephelus morio*, had the highest P-values among all the Grouper species (Table 3). Contemporary research does not show statistical significance, likely because invasive lionfish have only begun to become a prevalent issue in the past two decades. However, as evidenced by the growth of research regarding both lionfish species compared to stagnating rates of research among grouper species, research interest will continue to grow as the environmental threat of invasive lionfish propels *P. miles* and *P. volitans* into public awareness. Even now, as research steadily interest grows, invasive lionfish are becoming an increasingly prevalent issue in the Carribean and the Mediterranean where warming ocean temperatures have expanded the predicted regions of invasion for lionfish populations (Mitchell 2024). In the Alacranes Reef system near the Gulf of Mexico, invasive lionfish have replaced sharks as the apex predator, negatively impacting the populations of multiple small reef fish in the area (Arias-González 2011). Since the earliest analysis of lionfish in the Atlantic Ocean, the consensus that lionfish pose a threat to the stability of marine ecosystems and the fear of proliferation has stayed consistent, albeit without the hope that lionfish settlement and reproduction would be hindered by abiotic and biotic factors (Whitfield 2002). Due to high fecundity and an abundance of prey, invasive lionfish are predicted to be able to expand from a northern limit of Cape Hatteras in North Carolina to the Carribean sea in the southern hemisphere, only limited by ocean temperature; lionfish are able to tolerate temperatures between 10 and 16.1 degrees Celsius. (Kimball 2004). Furthermore, *Pterois miles* and *Pterois volitans* lack both the predators and competition to face the natural abiotic and biotic controls found in their native habitats in the Indian and Pacific oceans respectively (Kulbicki 2012).

To answer the question of why certain prey species are more vulnerable to lionfish predation than others, my research supports the conclusion set by contemporary research: lionfish are generalist predators with natural preferences for certain prey species. Across all of the areas of the Western Atlantic studied, my research showed that the prey that consistently made up the largest percentages of lionfish stomach contents were prey species most abundant in the region, demonstrating the generalist diet of *P. miles* and *P. volitans*. On top of preying on the most common prey available, lionfish are willing to consume a wide range of prey; the stomach contents of 8125 invasive lionfish all across Atlantic reef ecosystems reveals that lionfish in these areas hunted prey from 167 distinct species from 78 families and 108 genera (Peake 2018). However, as shown by the stomach contents of invasive lionfish found in North Carolina, wildlife proportion does not always directly correlate to predation frequency. In North Carolina, fish of the family *Scaridae* (parrotfishes) were disproportionately preyed upon 67 times more than the researchers had expected (Chappel 2016). In addition, analysis of *Pterois volitans* and *Pterois miles*' native prey species in the Indo-Pacific Ocean reveal that lionfish prefer to hunt small, nocturnal fish that exhibit schooling behaviors (Green 2014). One consequence of such targeting of certain prey risks driving keystone species to extinction and putting the entire reef ecosystem at risk. Parrotfishes, of the family *Scaridae*, for example, play key roles in maintaining healthy coral reef ecosystems (Cramer 2017).

In combination with the naivete of Atlantic prey species to the invasive lionfish, certain prey species are more vulnerable to predation than others. In their natural habitats, lionfish hunt by blowing a jet of water out of their mouths to confuse their prey. However, in Atlantic reef ecosystems, the invasive lionfish relied on their blowing techniques three times less than they do in their native habitats, demonstrating that the decreased wariness of prey species enabled lionfish populations to capture prey without a reliance on the hunting techniques used in their native indo-pacific habitats. (Cure 2012).

Moreover, the research interest in the two lionfish species is not equal. From 2015 to 2020, the number of new research papers published about *P. miles* was only 60% of the number of new articles about *P. volitans*, implying that *P. volitans* is more prolific, less detectable, or a larger cause for concern than *P. miles.*

While the findings presented provide valuable insight into the ecological impact of *Pterois volitans* and *Pterois miles* on Atlantic reef ecosystems and the scientific body's response to it, several limitations must be addressed as well. First, the reliance on stomach content analysis, while informative, is inherently constrained by sample variability and potential biases in prey identification, which may overlook less recognizable prey species or those digested more rapidly. Additionally, while my research suggests that *P. volitans* may pose a greater ecological threat than *P. miles*, the disparity in publication rates could reflect differences in research focus rather than actual biological significance. Publication rates are an effective means of measuring scientific interest in a species but fails to capture the nuance of the species' ecological impact, it's interactions with other species, and namely preexisting conservation status irrelevant to lionfish. Furthermore, the role of abiotic factors such as temperature and salinity, as well as potential adaptation in native predator or prey behaviors, remains underexplored and may significantly influence the long-term trajectory of lionfish invasions. Moreover, an undeniable limitation of relying solely on publication rates on Google Scholar introduces selection bias as relevant studies may not be available on Google Scholar.

Most importantly, with time, a more consistent trend for the rate of new academic articles published regarding lionfish will appear. Future research addressing these gaps will be critical in developing a comprehensive understanding of the scope of the lionfishes' ecological impact.

Compared to the threat posed by lionfish, contemporary research is disproportionately behind and must catch up to address the rapidly evolving ecological crisis. Despite their ability to proliferate across vast regions of the Atlantic and Caribbean, research rates on invasive lionfish underplay the scale of their environmental impact. The potential for lionfish to fundamentally alter reef ecosystems calls for accelerated efforts to understand their behavior, ecological interactions, and population control strategies.

One particularly relevant implication is the capacity of invasive lionfish to hunt certain prey species to near extinction. Of the 23 fish species driven to extinction since the 1500's, invasive marine species have been responsible for 11 of them (Clavero 2005). The disproportionate predation on keystone species, such as parrotfishes of the family *Scaridae*, demonstrates the lionfish's ability to destabilize entire reef ecosystems. Parrotfishes, critical for maintaining coral health through their grazing behaviors, are at risk due to their disproportionate representation in lionfish diets, as observed in North Carolina and elsewhere. The extinction or significant decline of such species would compromise reef resilience, reducing biodiversity and hindering the natural recovery of coral systems already under stress from climate change and human activities.

Given the threat P volitans and P miles pose against the ecosystems of the Atlantic Ocean, there is an urgent need for research to shift from documenting lionfish impacts to developing and implementing effective population control strategies. Contemporary population control strategies for invasive lionfish in the Atlantic Ocean primarily focus on targeted removals through spearfishing and organized culling events. Spearfishing using scuba diving and pole spears is often the most efficient method for removing lionfish (Candelmo et al., 2022). These removal efforts conducted on a regular basis have shown to be effective in reducing lionfish densities in specific areas (de León et al., 2013). Organized removal events, such as lionfish tournaments, have also demonstrated success in dramatically lowering local lionfish populations while simultaneously raising public awareness about the invasive species (Harris et al., 2022). However, complete eradication is likely unfeasible due to the species' high reproductive rate and widespread distribution (Johnston and Purkis, 2015). Instead, management efforts aim to suppress lionfish populations to levels that minimize their ecological impact, particularly in ecologically sensitive areas and marine protected zones (Morris, 2012). Understanding the prey preferences, reproductive cycles, and potential biotic and abiotic controls of P. volitans and P. miles in the Atlantic and in the Indo-Pacific is essential to inform management practices. Without immediate and sustained scientific attention, the ecological balance of countless Atlantic reef ecosystems may irreversibly tip, leaving behind degraded systems unable to support their once-rich biodiversity.

References

1. Hoegh-Guldberg, Ove, and John F. Bruno. "The Impact of Climate Change on the World's Marine Ecosystems." *Science* , vol. 328, no. 5985, 2010, pp. 1523–1528. JSTOR, http://www.jstor.org/stable/40656421.

2. Sorte, Cascade J., et al. "Ocean Warming Increases Threat of Invasive Species in a Marine Fouling Community." *Ecology*, vol. 91, no. 8, Aug. 2010, pp. 2198–2204. https://doi.org/10.1890/10-0238.1.

3. "NCEI Coastal Water Temperature Guide – All Coastal Regions Table." *National Centers for Environmental Information (NCEI)*, www.ncei.noaa.gov/access/coastal-water-temperature-guide/all_table.html.

4. Office of National Marine Sanctuaries. *Florida Keys National Marine Sanctuary Condition Report 2011.* U.S. Department of Commerce, NOAA, 2011.

5. "Lionfish – Pterois volitans." *Florida Fish and Wildlife Conservation Commission*, https://myfwc.com/wildlifehabitats/profiles/saltwater/lionfish/.

6. Morris, James A., and Paula E. Whitfield. *Biology, Ecology, Control and Management of the Invasive Indo-Pacific Lionfish: An Updated Integrated Assessment.* NOAA, 2009, https://coastalscience.noaa.gov/data_reports/biology-ecology-control-and-management-of-the-invasive-indo-pacific-lionfish-an-updated-integrated-assessment/.

7. Freshwater, D. Wilson, et al. "Molecular Evidence That the Lionfishes *Pterois miles* and *Pterois volitans* Are Distinct Species." *Journal of the North Carolina Academy of Science*, vol. 125, no. 2, 2009, pp. 39–46. JSTOR, http://www.jstor.org/stable/24336413.

8. Coles, Nigel. "Lionfish Reproduction." *Lionfish Hunting*, 29 Oct. 2018, https://lionfish-hunting.com/lionfish-reproduction/.

9. Hixon, Mark A., et al. "Lionfish: A Major Marine Invasion." *Marine Ecology Progress Series*, vol. 558, 25 Oct. 2016, pp. 161–165. https://doi.org/10.3354/meps11909.

10. Del Río, Laura, et al. *Peer Review #2 of "Biology and Ecology of the Lionfish Pterois volitans/Pterois miles as Invasive Alien Species: A Review (v0.2)."* 25 July 2023, https://doi.org/10.7287/peerj.15728v0.2/reviews/2.

11. Cure, Katherine, et al. "Comparative Behavior of Red Lionfish *Pterois volitans* on Native Pacific versus Invaded Atlantic Coral Reefs." *Marine Ecology Progress Series*, vol. 467, 25 Oct. 2012, pp. 181–192. https://doi.org/10.3354/meps09942.

12. Green, Stephanie J., and Isabelle M. Côté. "Trait-Based Diet Selection: Prey Behaviour and Morphology Predict Vulnerability to Predation in Reef Fish Communities." *Journal of Animal Ecology*, vol. 83, no. 6, 25 June 2014, pp. 1451–1460. https://doi.org/10.1111/1365-2656.12250.

13. Chappell, Ben F., and Kevin G. Smith. "Patterns of Predation of Native Reef Fish by Invasive Indo-Pacific Lionfish in the Western Atlantic: Evidence of Selectivity by a Generalist Predator." *Global Ecology and Conservation*, vol. 8, Oct. 2016, pp. 18–23. https://doi.org/10.1016/j.gecco.2016.08.002.

14. Ellis, R. D., and M. E. Faletti. "Native Grouper Indirectly Ameliorates the Negative Effects of Invasive Lionfish." *Marine Ecology Progress Series*, vol. 558, 25 Oct. 2016, pp. 267–279. https://doi.org/10.3354/meps11808.

15. Kimball, M. E., et al. "Thermal Tolerance and Potential Distribution of Invasive Lionfish (*Pterois volitans/miles* Complex) on the East Coast of the United States." *Marine Ecology Progress Series*, vol. 283, 2004, pp. 269–278. https://doi.org/10.3354/meps283269.

16. Benkwitt, Cassandra E. "Density-Dependent Growth in Invasive Lionfish (*Pterois volitans*)." *PLoS ONE*, vol. 8, no. 6, 25 June 2013. https://doi.org/10.1371/journal.pone.0066995.

17. Morris, James A. *Invasive Lionfish: A Guide to Control and Management.* Gulf and Caribbean Fisheries Institute, 2012.

18. Peake, Jonathan, et al. "Feeding Ecology of Invasive Lionfish (*Pterois volitans* and *Pterois miles*) in the Temperate and Tropical Western Atlantic." *Biological Invasions*, vol. 20, no. 9, 11 Apr. 2018, pp. 2567–2597. https://doi.org/10.1007/s10530-018-1720-5.

19. Mitchell, Emma, and Victoria Dominguez Almela. "Modelling the Rise of Invasive Lionfish in the Mediterranean." *Marine Biology*, vol. 172, no. 1, 16 Dec. 2024. https://doi.org/10.1007/s00227-024-04580-6.

20. Eddy, C., et al. "Diet of Invasive Lionfish (*Pterois volitans* and *P. miles*) in Bermuda." *Marine Ecology Progress Series*, vol. 558, 25 Oct. 2016, pp. 193–206. https://doi.org/10.3354/meps11838.

21. Côté, Isabelle M., and Alena Maljkovic. "Predation Rates of Indo-Pacific Lionfish on Bahamian Coral Reefs." *Marine Ecology Progress Series*, vol. 404, 8 Apr. 2010, pp. 219–225. https://doi.org/10.3354/meps08458.

22. Arredondo-Chávez, A. T., et al. "Spatio-Temporal Variation in the Diet Composition of Red Lionfish, *Pterois volitans* (Actinopterygii: Scorpaeniformes: Scorpaenidae), in the Mexican Caribbean: Insights into the Ecological Effect of the Alien Invasion." *Acta Ichthyologica et Piscatoria*, vol. 46, no. 3, 30 Sept. 2016, pp. 182–200. https://doi.org/10.3750/aip2016.46.3.03.

23. Arias-González, Jesús Ernesto, et al. "Predicted Impact of the Invasive Lionfish *Pterois volitans* on the Food Web of a Caribbean Coral Reef." *Environmental Research*, vol. 111, no. 7, Oct. 2011, pp. 917–925. https://doi.org/10.1016/j.envres.2011.07.008.

24. Whitfield, Paula E., et al. "Biological Invasion of the Indo-Pacific Lionfish *Pterois volitans* along the Atlantic Coast of North America." *Marine Ecology Progress Series*, vol. 235, 2002, pp. 289–297. https://doi.org/10.3354/meps235289.

25. Kulbicki, Michel, et al. "Distributions of Indo-Pacific Lionfishes *Pterois* spp. in Their Native Ranges: Implications for the Atlantic Invasion." *Marine Ecology Progress Series*, vol. 446, 2 Feb. 2012, pp. 189–205. https://doi.org/10.3354/meps09442.

26. Cramer, Katie L., et al. "Prehistorical and Historical Declines in Caribbean Coral Reef Accretion Rates Driven by Loss of Parrotfish." *Nature Communications*, vol. 8, no. 1, 23 Jan. 2017. https://doi.org/10.1038/ncomms14160.

27. Clavero, Miguel, and Emili García-Berthou. "Invasive Species Are a Leading Cause of Animal Extinctions." *Trends in Ecology & Evolution*, vol. 20, no. 3, Mar. 2005, pp. 110–110. https://doi.org/10.1016/j.tree.2005.01.003.

28. Candelmo, Allison C., et al. "Lessons from the Western

Atlantic Lionfish Invasion to Inform Management in the Mediterranean." *Frontiers in Marine Science*, vol. 9, 2022. https://doi.org/10.3389/fmars.2022.845196.

29. De León, Ramon, et al. "Effectiveness of Lionfish Removal Efforts in the Southern Caribbean." *Endangered Species Research*, vol. 22, no. 2, 2013, pp. 175–182. https://doi.org/10.3354/esr00542.
30. Harris, Holden J., et al. "A New Study Outlines the Do's and Don'ts of Managing Invasive Lionfish." *University of Florida Institute of Food and Agricultural Sciences*, 24 May 2022, https://blogs.ifas.ufl.edu/news/2022/05/24/a-new-study-outlines-the-dos-and-donts-of-managing-invasive-lionfish/.
31. Johnston, Matthew W., and Sam J. Purkis. "A Coordinated and Sustained International Strategy Is Required to Turn the Tide on the Atlantic Lionfish Invasion." *Marine Ecology Progress Series*, vol. 533, 2015, pp. 219–235. https://doi.org/10.3354/meps11399.