EXAMINING THE IMPACTS OF CLIMATE CHANGE AND POTENTIAL POLICIES ON INVASIVE LIONFISH

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1. Abstract

Lionfish, *Pterois volitans* and *Pterois miles*, are invasive species of fish from the Indo-Pacific that were introduced in Florida waters in the 1980s and have since spread into the Caribbean and along the Southeastern Coast of the United States.. Without any natural predators, lionfish present a danger to marine ecosystems in the Atlantic—overconsumption of herbivorous fish leads to unchecked algal overgrowth in coral reefs and collapse of higher trophic levels. We investigate how climate change, particularly ocean warming and the shoreward migration of the Gulf Stream, will affect the possible spread of invasive lionfish north along the U.S. East Coast and potentially into the Chesapeake Bay. Applying MAXENT ecological niche modeling (ENM) and a custom Lagrangian adjustment algorithm to account for changing boundary currents, we projected habitat suitability from 2020-2090 under the SSP5-8.5 high-emissions climate scenario. Identifying sea temperature and salinity as the primary predictors of lionfish presence, we conclude that lionfish are likely to establish perennial populations as far north as North Carolina and possibly to the coast of Virginia by 2090. While they are unlikely to establish a permanent population within the comparatively shallow Chesapeake Bay, adjacent offshore and coastal waters will experience a significant increase in habitat suitability.

These predictions establish a timeline that motivates proactive policy initiatives to control lionfish and mitigate damages in Mid-Atlantic waters. We extensively review current aquatic invasive species policies from eight states along the East Coast to determine existing aquatic invasive species policies in comparison to the state's specific lionfish policies, or lack thereof. Our results show commonalities among state policies, such as prohibiting the release of invasive species alive, focusing on population control or eradication, and officially labeling species as invasive to secure management resources. We then created a policy application to act as a guide

to show how a state's current aquatic invasive species policies can be used to assist in lionfish-specific policy creation and implementation. Our results expand the understanding of invasive species distributions in the face of climate change, ensuring our ecological niche modeling results inform proactive, research-based policy decisions for future aquatic species invasions.

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3. Introduction

Invasive species pose substantial ecological and economic harm globally. Impacts from these species can grow over time as their populations spread. As the Earth's climate changes, the range of invasive species can also shift. Understanding how species populations may shift with climate change and the level of policy preparedness across potential future invasion ranges is a critical management need. Here we seek to address this need in the context of lionfish (Pterois volitans and Pterois miles), species that are native to the South Pacific and Indian oceans, which cause significant damage across their nonnative range.

Lionfish are a venomous, striped, saltwater fish that were introduced in Florida waters in the 1980s. They have since spread into the Caribbean and along the Southeastern Coast of the United States. Lionfish are known to disrupt the marine ecosystem in their introduced range by consuming large quantities of small fish and contributing to the destruction of coral reefs. Additionally, they pose risks to divers due to their venomous spines. Without any natural predators, lionfish present a danger to marine ecosystems in the western Atlantic Ocean.

With the climate getting warmer, it is possible that the nonnative range of lionfish could further expand north along the western Atlantic coast, and possibly into the Chesapeake Bay. Climate change is leading to warmer water temperatures, which can foster changes in habitat suitability, as has been seen for other species, e.g. beavers and Pacific cod (Tape et al., 2022; Bigman et al., 2025). In order for resource managers and policy makers to be able to prepare for a future invasion spread, information about potential patterns and timing of spread can support management.

In recent years, there have been efforts to increase lionfish harvesting as a way to manage invasive lionfish populations and promote environmental preservation, while also supporting its use as a food source. However, there is no unified national or regional policy for addressing lionfish invasions. Current management strategies are not enough to counteract the rapid repopulation and maturation rate of lionfish.

To date, the potential range expansion of lionfish with climate change has received only limited attention. Similarly, while there has been extensive analysis of specific management interventions, there has been limited analysis of the preparedness of jurisdictions that are likely to face lionfish invasion in the future. Thus, the aim of this thesis is to quantify the impacts of climate change on lionfish habitability across the Mid-Atlantic and to propose proactive policies for the management of lionfish.

(R1) What future environmental conditions would enable lionfish invasion in the Mid-Atlantic and Chesapeake Bay, and when will these conditions occur?

(R2) What state-specific aquatic invasive species management strategies are currently implemented across U.S. East Coast states, and how do these approaches compare in addressing varying regional vulnerabilities to potential lionfish invasion?

We address these goals through two interconnected approaches. First, we use ecological niche modeling to evaluate habitat requirements for lionfish and estimate lionfish habitat suitability across the Eastern U.S. under current and future climate conditions. Next, we analyze existing policies addressing marine invasion risk across the Eastern U.S., focusing on lionfish management while also drawing on the regions' experiences with other marine and freshwater invaders present in each state. We then assess opportunities for expanding application of existing policies to address the impact of the lionfish invasion.

4. Background

4.1 Lionfish overview

Lionfish, originally from the Indo-Pacific region, are a colorful striped fish that has venomous spines. Their first appearance in the Caribbean coral reefs can be traced back to the 1980s. Their introduction has been attributed to exotic pet owners who, due to the species' unexpected rapid growth and appetite, released lionfish into Florida waters where they became invasive (Selwyn et al., 2017). In general, invasive species have no natural predators in their deposited area, have voracious appetites that out-compete natural species, and can reproduce at faster rates than natural species in similar animal categories. This allows them to cause significant damage in their nonnative range.

4.2 Lionfish invasion: Impacts and Challenges

Invasive species are viewed as one of the biggest unsettling influences to the food web structure of the Caribbean Sea (Arias-González et al., 2011). The invasion of lionfish in Caribbean coral reefs has substantially impacted the biodiversity and ecology of these habitats. The very quick development of lionfish populations poses a significant danger to coral reef food networks in the Caribbean by diminishing the populations of local species through predation. The dramatic density increases and spread of lionfish all through the Caribbean coral reefs, as well as the species' wide variety of fish prey and high predation rates, are trophically affecting Caribbean food networks. Explosive populations of lionfish consume the herbivores that keep the coral reef algae population in check. Following mass die-off events of algae consumers like sea urchins, algal populations have been observed overrunning and completely able to overrun these coral reef systems with cascading effects (Reddick, 2023). Beyond coral reefs, lionfish compete for prey and shelter with native species of groupers and lobster (Morris et al., 2012). This results in a decrease of food for other larger species of fish and the humans that rely on them. In the Bahamas, lionfish predate teleost reef fishes, invertebrates such as crustaceans, and less significantly molluscs. For the most part, large lionfish eat fish, while smaller lionfish eat crustaceans.

Currently, lionfish in the western Atlantic inhabit areas throughout the Caribbean and the Gulf of Mexico, as well as the East Coast of the U.S. through North Carolina. Lionfish sightings have also been documented off the shores of states as far north as New York (Lionfish - NYSDEC, n.d.). In all of these areas, lionfish tend to propagate in aggregate reefs, which are isolated patches of reef about 50 by 50 meters and surrounded by sand and deeper waters, preferring these habitats to shallow water or patch reefs (Biggs & Olden, 2011). However, lionfish show flexibility in their habitat; they can also settle in sea grass beds and shallow reefs if need be. One study of lionfish distribution from 2007 to 2010 concluded that lionfish populations inhabit shallow reefs and grassy areas temporarily before moving to deep water reefs for permanent settlement (Claydon et al., 2012). There is also evidence that lionfish prefer hard-bottom habitats that allow for reef growth over sandy or muddy ocean floors, but again, the species is capable of adapting to various environments that they do not initially prefer (Campbell et al., 2021). Most research on lionfish habitat thus far has been in the preferred habitat in the Caribbean, leaving a gap in research on preferred lionfish habitat in northern areas.

Reproductive habits of lionfish also play a large role in how the species spreads. Lionfish are “r-selected”, meaning that they have early maturity and release large amounts of offspring without parenting (Campbell et al., 2021). Combined with a lack of natural predators, this reproduction strategy allows them to be very successful as an invasive species. Female lionfish can release up to two million eggs per year, which spread through the water column and ocean currents like the Gulf Stream (Morris & Whitfield, 2009). These ocean currents cause the rapid spread of lionfish into deep waters and away from areas that are easy for humans to control. Furthermore, lionfish tend to mate between the months of March and December as warmer temperatures increase their metabolic and reproductive rates, but they are known to reproduce in all months of the year (Fogg et al., 2017). Overall, the reproductive traits of the lionfish cause it to spread rapidly, making it very difficult to control as an invasive species.

4.3 Lionfish Management Strategies and their Efficacy

In general, eradication of invasive species is preferred over naturalization because it is a one-time solution that could completely mitigate any negative effects from the species (Prior et al., 2018). In ideal cases, ecosystems will return to the state they were in before the introduction of these invasive species. However, rapid changes in the biological composition of an ecosystem can have negative effects regardless of whether the eradicated species was invasive. A study by Caut et al. (2007) found that the removal of animal species led to recovery only when there were very few invasive species in the ecosystem. A majority of the ecological damage in the Caribbean can be attributed to the effects of lionfish; should any other invasive competitors be present, they have been largely undetected. However, lionfish are well out of the early invasion stage where eradication is a plausible solution (Giakoumi et al., 2019). Therefore, intensive measures must be taken to suppress the invasive lionfish population and prevent its spread.

There is no unified solution for managing lionfish; instead, each jurisdiction has its own management response, and in some cases, no response at all. Many organizations have tried to remove lionfish manually, but this process is very costly and has limited effectiveness, particularly given the species' rapid rate of reproduction. Nonetheless, most current management methods involve manually harvesting lionfish. Genetic modification, pathogenic/parasitic control, and automated trapping are among other hypothetical control methods currently being researched.

Biological control comes from the use of parasites or disease that can target lionfish in the western Atlantic to cause mortality of the fish. This could give rise to a possible solution to lionfish spread, as lionfish are particularly susceptible to skin ulcers (Cody et al., 2023), but it also presents ethical concerns and potential risks to the environment. Genetic modification is another potential approach to reduce lionfish numbers in the western Atlantic. While genetic modifications are often implemented to benefit organisms, this approach could be applied to reduce the ability of this species to reproduce. For example, inducing gender distortion is an approach that causes offspring to develop as a specific sex but is opposite of the sexual genotype (Compton & Tu, 2022). This means that male-only lionfish could be produced if the gene for sex differentiation was targeted, which would prevent the second generation from reproducing.

Lionfish could also be controlled through automated trapping techniques. Mechanical traps have been explored for killing lionfish (Akpan & Ehrichs, 2016). For example, one robot design includes a spear gun like a human diver. Another zaps lionfish using electrodes. These traps were controlled by a pilot on a boat or on shore using video cameras (Akpan & Ehrichs, 2016). These traps can be successful because lionfish, especially in their invasive range, are generally not scared of other fish and therefore unlikely to flee when approached by robots. While mechanical and biological methods of lionfish control are being considered, they have not been implemented at scale due to potential ethical concerns and high cost.

Recently, the most effective strategy of lionfish management has been through Lionfish Derbies. Lionfish Derbies are hunting competitions to eradicate lionfish, mainly held in Florida, as a way to physically manage lionfish invasions. These derbies are a way to engage the general public in public education as well as create incentives to hunt lionfish for the reward of both a source of food and monetary prizes As of 2025, a recorded 36,333 lionfish have been removed since 2009 via Lionfish Derbies (Reef Environmental Education Foundation [REEF], 2020). Additional efforts to manage lionfish populations include increasing commercial demand for lionfish. These initiatives include promoting lionfish as a culinary delicacy and using lionfish scales and spines to make jewelry. Lionfish Central is a non-profit organization focused on eradicating lionfish from U.S. and Caribbean waters by connecting divers, restaurants, and local organizations through group supports and markets. They provide online recipes using lionfish and have listed 34 unique recipes on their website alone (Lionfish Central, Lionfish Recipes, n.d.). Many more organizations and local home chefs have posted online recipes as well. REEF hosts lionfish jewelry workshops where they provide all jewelry-making materials including the lionfish spines. During the workshop, REEF members also explain the background of the lionfish invasion as well as the biology, impact, and current research findings (Reef Environmental Education Foundation, n.d.).

4.4 Lionfish Habitat and Climate Change

Populations of lionfish have extended in the western Atlantic Ocean and the Mediterranean Sea since they were introduced and have become an invasive species. As such, there is a significant body of research investigating the environmental tolerances of lionfish, particularly in regard to temperature and salinity. This work helps to show the limits of lionfish spread through their invasive range based on climate and environmental features.

The lionfish is a tropical species, so it tends to prefer higher water temperatures. Despite this, the species has a wide temperature tolerance of about 25 degrees Celsius, being able to survive at water temperatures between 13 and 30 degrees Celsius (Dabruzzi et al., 2017). However, they do need a mean winter temperature of 15.3 degrees Celsius or higher to establish a year-round population in an area (Whitfield et al., 2014). On the North Atlantic coast, it has been suggested that the furthest north lionfish are likely to establish a population under current climate conditions is North Carolina (National Oceanic and Atmospheric Administration, 2023).

However, lionfish have shown exceptional resilience at low temperatures and salinities (Dabruzzi et al., 2017; Jud et al., 2014; Schofield et al., 2015).

Other environmental requirements of lionfish, like water salinity, pH, or oxygen content, also may limit their spread. Multiple studies have investigated the salinity requirements of lionfish. The species can survive in water salinity of 10 ppt and above, but dies after twelve days at a salinity 5 ppt or below. This means that lionfish are unlikely to penetrate far into estuaries and other bodies of brackish water, which usually have a salinity of 5 ppt or below (Schofield et al., 2015). Another study found that lionfish are capable of surviving for short periods of time at even 4 ppt salinity, and that they are capable of withstanding major salinity fluctuations (Jud et al., 2011). This indicates that while lionfish are unlikely to have permanent populations deep into estuaries, they can temporarily survive in some estuary systems. There has been at least one instance of lionfish invading an estuary system in Florida (Jud et al., 2011). In this case, lionfish were sighted up to five kilometers from the ocean, and were mostly associated with human construction, like docks and submerged debris.

4.4.a Habitat suitability of the Chesapeake Bay

Current knowledge about lionfish temperature tolerance suggests that the winter temperatures of the Chesapeake Bay are too low for lionfish to survive, with the furthest north established lionfish populations being offshore of North Carolina (Whitfield et al., 2014). Regardless, individual specimens have been sighted as far north as New York in the summer (though it is possible there could be individual releases of Lionfish in the region). Therefore, it seems strange that there have yet to be any lionfish sightings in the Chesapeake Bay. The majority of the Chesapeake is within the salinity tolerance of lionfish, i.e., at or above 10 ppm (Jud et al., 2014; Schofield et al., 2015). Furthermore, lionfish observed in Florida estuaries have been seen enduring such salinity fluctuations. The diet of the lionfish in these estuaries consisted primarily of shrimp, a species of which there is no lack of in the Chesapeake Bay (Jud et al., 2011).

However, as mentioned earlier, winter temperatures pose a major challenge for an established lionfish population. In addition to the shallow depth of the Chesapeake, lionfish would experience average winter water temperatures as low as 3 degrees Celsius (Rome et al., 2005). Lionfish in North Carolina occupy a depth where the winter water temperature averages over 15 degrees Celsius, often at least 20 degrees Celsius. This suggests that for lionfish to overwinter in the Chesapeake, water temperatures would have to rise drastically. Finally, as an estuary, the Chesapeake is exposed to yearly snow melt, which would reduce both the bottom water temperature and salinity, perhaps to temperatures that would be unsuitable for lionfish. However, water temperatures in the Chesapeake Bay are rising at a rate of ~0.2 degrees Celsius per decade (Preston, 2004), and lionfish sightings have continued to occur ever further northward. Therefore, the future lionfish invasion in the Chesapeake Bay is still an important ecological consideration.

A major ecological concern with lionfish is their presence amplifying the potency of algal blooms in the Caribbean (Lesser & Slattery, 2011). The Chesapeake Bay exhibits similar algal phenomena, and by preying on the consumers of these photosynthetic producers, a significant population of lionfish could amplify the intensity of algae blooms in the Chesapeake, which already cause a significant amount of economic damage (Pimental, 2007).

4.5 Ecological Niche Modeling for Projecting Spread of Lionfish

We present ecological niche models (ENMs) as a method to predict the timeline of lionfish habitat expanding northward along the East Coast of the United States. Ecological niche models use climate data, and in our case, climate projections, in tandem with species occurrence data to predict the potential habitat of a species. ENMs are regularly used to determine how the habitat of a species will change over time. Specific knowledge of when and where the lionfish invasion can be expected to spread will allow for proactive measures, which can possibly prevent or reduce the impacts of invasive lionfish.

Although applying ecological niche models in aquatic environments presents unique challenges, as water depth adds a third spatial dimension to habitat possibilities, these models have been used to predict the spread of other aquatic invasive species. Gama et al. (2016) used ecological niche modeling and climate projections to forecast the worldwide distribution of *Corbicula fluminea,* a species of Asian clam. Anthony et al. (2023) created an ecological niche model that draws specifically on publicly collected data to predict the spread of various species of jellyfish. Perrin et al. (2021) also used an ecological niche model to study the potential spread of various invasive fish species in Norwegian lakes over a period of 50 years. Gama et al. and Perrin et al. both included climate projections in their models.

Ecological niche modeling has also been used to predict the spread of invasive lionfish. Evangelista et al. (2016) used an ENM to determine the current suitable habitat for lionfish. The study focused primarily on the eastern coast of North and South America. As ecological niche modeling in aquatic environments was relatively new when this article was published, they used a variety of different training methods to yield predictions. All of their models predicted a potential spread of lionfish into new territory. However, this model did not incorporate any climate projection data, so all results are limited to current climate conditions.

Loya-Cancino et al. (2023) used an ENM to predict the spread of lionfish on a worldwide scale. They also used climate projections based on different RCP scenarios to determine how each scenario would affect potential lionfish habitat. Loya-Cancino et al. also found that the lionfish spread is limited primarily by temperature, and rising ocean temperatures could cause increased lionfish populations in a variety of locations worldwide, including off the banks of western Africa, the Americas, and the Mediterranean Sea. Here we apply a similar analysis using a wider array of environmental variables with a focus on the United States East Coast. In addition, our research will make use of supra-specific units by combining occurrences for *P. miles* and *P. volitans* to improve predictions for the entire Pterois genus, as suggested by Loya-Cancino.

4.6 Policy Analysis and the Development of Preventative Policies

Invasive species management requires policies across federal, state, and local levels because invasive organisms can spread rapidly across state lines which can cause long-term ecological and economic damage. Effective invasive species policies generally play a role in reducing the introduction and spread of invasive species including the regulation of their transport, and public education efforts to maximize the effort to prevent invasive species from establishing into their host environment. At the federal level, policies such as the Lacey Act directly work to restrict the movement of harmful invasive species. The Lacey Act extends the sentiment of reducing harmful movement to any commercial or trade-based action regarding any fish, wildlife, or plant conducted that violates U.S. or Indian tribal law without prior approval (16 U.S.C. §§ 3371-3378). For criminal penalties, the defendant can either be fined up to $20,000 or be imprisoned for up to five years for knowingly violating the Lacey Act. State and local agencies tend to implement more hands-on management strategies, designed to manage invasive species more locally. These policies include monitoring, detection, and removal efforts, often with the help of local anglers and business owners. Together, this multi-level management framework is designed to reduce the likelihood that invasive species enter new environments and to designate management efforts when needed.

Given that lionfish were likely introduced by pet owners, programs that address this introduction pathway are important (Selwyn et al., 2017). For example, the Invasive Species Action Network (ISAN) is a non-profit that works to "promote behavior change that reduces the human-caused spread of invasive species" (About ISAN – StopAIS.org, 2025). ISAN has educational programs aimed at young students to teach the concept of invasive species as well as how they can help. There are also outreach programs, such as the "Don't Let it Loose" program that teaches pet owners to not release their pets in the wild in case of the animal not being able to survive, or the animal surviving and then becoming an invasive species in that environment (Richards, 2024). This program is also supported by the U.S Wildlife & Fish Services. Through federal policy, there is also a requirement to make records of invasive species numbers. There also are programs that aim to harvest lionfish as a way to regulate lionfish population in response to the rapid increase of lionfish. Florida provides some useful examples. Lionfish Derbies held by The Reef Environmental Education Foundation located in the Florida Keys, is a competition where citizens learn about lionfish, compete to net or spear lionfish, and remove as many lionfish as possible (Reef Environmental Education Foundation, n.d.). With community involvement, there can be opportunities for environmental education as well as proactive measures to decrease the population of lionfish. In regards to fishing in Florida, "Lionfish can be harvested year-round with unlimited daily bag limits, and fishing licenses aren't necessary to hunt lionfish with a pole spear or a handheld net" (Talcott, 2023). Additionally, more tourist locations in Florida are being more receptive to hunting lionfish, specifically in Pensacola where people can learn how to hunt lionfish (Ocean Strike Team, 2022).

Understanding the range of existing state-level policies for lionfish and other aquatic invaders is needed to help identify potential proactive policies that states can put in place to reduce the impacts of invasive lionfish or its likelihood of invasion.

5. Methodology

We used the R package "maxnet" (Phillips, 2021, version 0.1.4) to apply ecological niche modeling on public Lionfish sighting datasets. This resulted in a Maximum Entropy (MaxEnt) model that could assess the habitability of lionfish across discrete points across the world's oceans. We then used projected climate data to estimate the change in habitability due to climate change effects. We also surveyed current state-level aquatic invasive species policy, including lionfish-specific policy, across the Eastern United States.

5.1 Ecological Niche Modeling

Ecological niche modeling (ENM) is a method for quantifying the habitat suitability of a given location based on surrounding environmental variables (e.g., temperature, salinity). It accomplishes this by using data about locations where the chosen species are known to be either present or absent, and generating a probabilistic model of species occurrence. As this approach measures occurrence as a function only of local environmental data, these models can also be applied to the predicted values of future environments. Following model generation and refinement, we use future climate projection data from climate scenario SSP5-8.5 to predict habitat suitability in the decades of 2050 and 2090.

5.1.a Species Occurrence Data

For records of current lionfish locations, we considered two online species occurrence databases, GBIF (https://www.gbif.org/) and OBIS (https://obis.org/). GBIF (Global Biodiversity Information Facility) is a comprehensive biodiversity data aggregator for both terrestrial and marine species, whereas OBIS (Ocean Biodiversity Information System) focuses specifically on marine biodiversity data. The primary difference between GBIF and OBIS for modeling purposes is the quality and abundance of data. OBIS sources its occurrence records almost exclusively from published datasets, while GBIF includes data from community sighting reports. Although much of the data between these databases is shared, the more relaxed restrictions on GBIF data mean that it has a greater number of sightings for any given species, which is crucial when attempting to fit a reliable model. A major concern with citizen science aggregators like GBIF is false reports due to species confusion. However, lionfish are quite visually distinct, so we do not expect many false sightings to be reported. Furthermore, our analysis is performed on the genus as a whole, so any misrecordings of *Pterois volitans* as *Pterois miles* or vice versa do not affect our model. Additionally, we used spatial thinning measures to reduce the inherent bias of community sighting records toward populated areas. For these reasons, we ultimately chose GBIF as our lionfish occurrence dataset.

5.1.b Occurrence Data Cleaning

We cleaned the species occurrence data by removing clearly errant points (e.g. reported lionfish locations on land). Then, to reduce collection bias, we used a spatial thinning filter within the R package “spThin”. While there is no standard minimum spacing for spatial thinning, we evaluated thinning distances empirically between 4 km and 150 km within the ENM structure, and 10 km was selected for both *Pterois volitans* and *Pterois miles* due to being the greatest distance that allowed for sufficient sample size. After filtering and cleaning the dataset for ~1700 points, we were left with 257 occurrences of *Pterois volitans* and 103 occurrences of *Pterois miles* (Figure 1). Our data appears to have a bias toward the Mediterranean, Red, and Caribbean seas. We suspect this to be due to lionfish, as an invasive species, attracting more attention in these regions. For our analyses, we combine these to estimate a genus-level model (*Pterois spp.)*. 25% of these points were set aside for model performance assessment, while the remaining 75% (270 points) were used to fit the model.

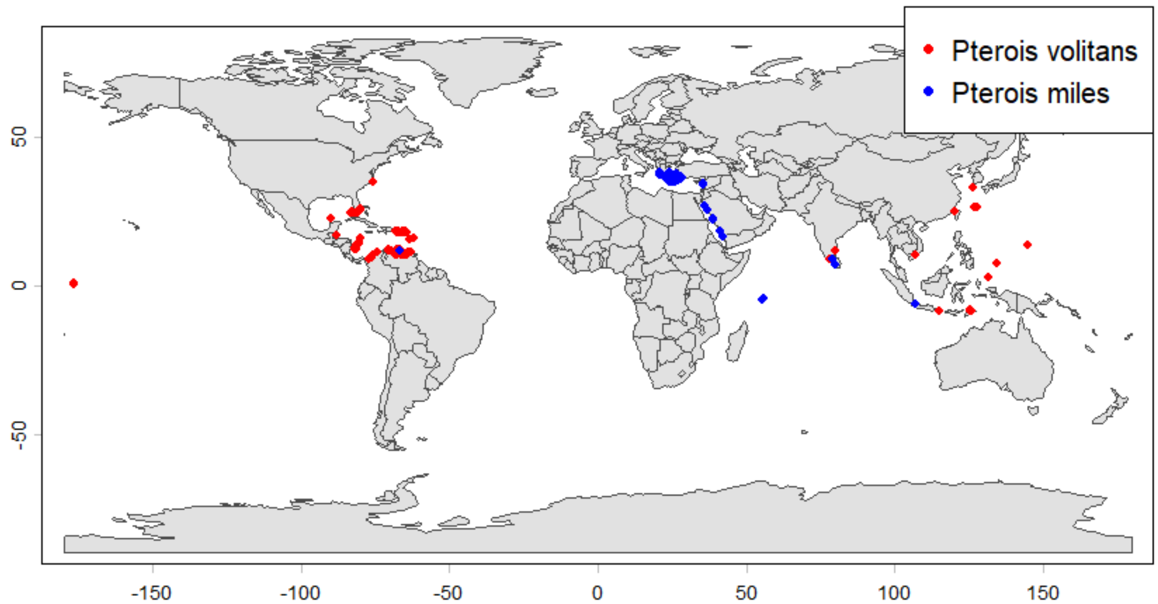

Figure 1. Spatially-thinned occurrence points of the species of interest, Pterois volitans and Pterois miles.

5.1.c Background Data

In addition to occurrence data, our modeling software "maxnet" requires background data points where lionfish are absent. Ideally, these would be points of true absence; locations where lionfish *have not* been sighted. However, information of this nature is not typically recorded. Furthermore, as an invasive species, there is ambiguity as to why lionfish do not appear in certain places. There is a discrepancy on if lionfish are unable to survive there, or if they have not had time to disperse to the location. Instead, we chose to generate our background points by taking a random sample of 360 points (the same number as occurrences) across the ocean between latitudes -10° and 45°.

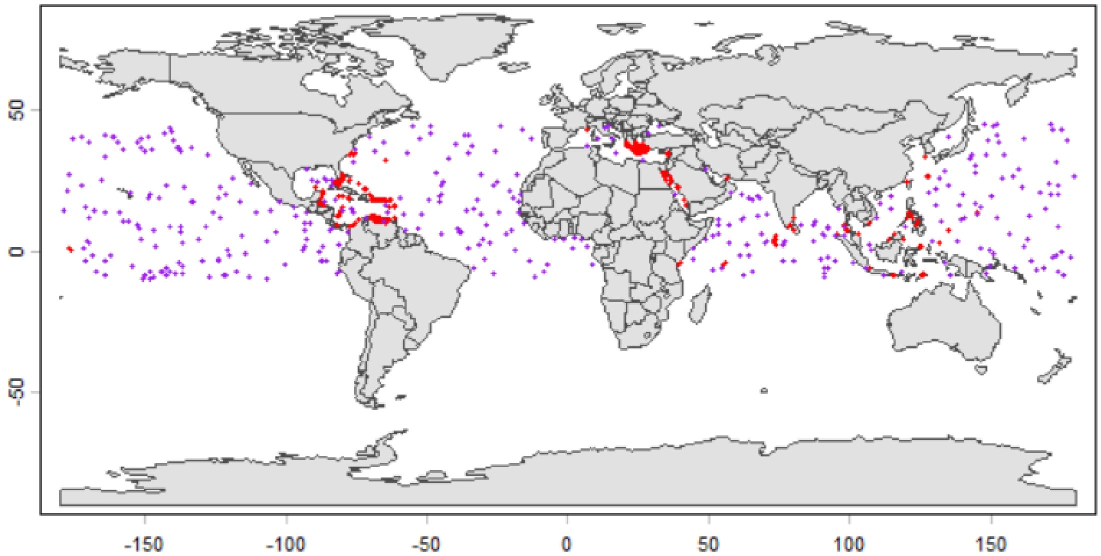

Figure 2. Occurrence data (red) and randomly placed absence data (purple) over the analysis domain of latitudes between -10 and 45 degrees.

5.1.d Environmental Variable Justification

Producing accurate ENM predictions relies on the selection of suitable environmental variables. Selecting environmental variables that directly influence lionfish survivability or capture habitat conditions suitable for lionfish can provide strong insight into their distribution. Our environmental variables are summarized in Table 1 of Section 5.1.f.

The focal environmental variables for our analysis include salinity, dissolved oxygen, pH, and temperature. Temperature is the predictor that we gave the most attention to as research has shown this to be an important constraint (Dabruzzi et al., 2017; Wuenschel et al., 2012). Temperature data can be depth-specific and measured as maximum, minimum, and average temperatures corresponding to each depth. We identified benthic temperature as particularly important due to observations of lionfish population densities increasing with higher mean winter temperatures in Onslow Bay, North Carolina (Whitfield et al., 2014). Additionally, mature lionfish are benthic generalists, commonly found closer to the sea bottom than to the sea surface, further increasing the relevance of bottom temperatures (Gress et al., 2017). Based on this, we have chosen to place an emphasis on the bottom temperature when selecting predictor variables for our ENM models. However, temperature at other depths (e.g., sea surface) may also be important as lionfish occupy all ocean strata, including shallow coastal waters. During their larval and juvenile stages, they spend a large amount of time closer to the surface (Kitchens et al., 2017). To accurately understand lionfish populations at all stages of development, surface and benthic temperatures were initially included as predictors for analysis.

Salinity is defined as the concentration of dissolved salt in saltwater environments, which is an important variable because lionfish, like other marine species, tolerate a specific range of salt concentrations. Experimental studies have shown that even though lionfish have relatively high salinity tolerance, their survival chances decrease significantly at very low salinity of around 5 percent, which suggests that salinity is an important factor in determining habitat suitability for lionfish (Schofield et al., 2015). Moreover, salinity at specific regions gives insight into whether certain predators and prey for lionfish are likely to exist in those regions.

Ocean pH was another environmental variable we included. We hypothesized that variations in pH can affect ecosystem dynamics, including predator and prey availability for lionfish in the studied regions, as well as the quality of the habitat. Lastly, dissolved oxygen was included as an environmental variable because marine species such as lionfish require oxygen for respiratory purposes. Previous studies have shown that lionfish have limited tolerance to exposure to environments with low oxygen concentrations (hypoxic). This suggests a limited ability to occupy reduced oxygen environments in coastal estuaries (Hasenei et al., 2020).

5.1.e Environmental Data Sources

In our initial exploratory analyses, we used environmental data from the Bio-ORACLE v2 dataset (Assis et al., 2018). Bio-ORACLE v2 is a comprehensive global environmental dataset tailored specifically to overcome the historical lack of high-resolution marine data available for bioclimatic modeling (Assis et al., 2018). The dataset provides uniform, high-resolution (5 arcmin, or approximately 9.2 km at the equator) surface and benthic data layers for ecologically relevant variables, including ocean temperature, salinity, and current velocity (Assis et al., 2018). By interpolating climate data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) under various Representative Concentration Pathway (RCP) scenarios, v2 offered the standardized grid system necessary for our predictions (Assis et al., 2018). The availability of these layers in formats explicitly designed for spatial ecology pipelines made it an ideal foundational dataset for training our initial ENM (Assis et al., 2018).

However, upon the release of the Bio-ORACLE v3.0 in 2024, we promptly switched to this dataset as it represented a substantial improvement over its predecessor. Firstly, v3.0 has greater oceanic current resolution, decreasing cell heights from 5 arcminutes to 3. This provides a much more granular image of the Chesapeake Bay and other estuaries. Bio-ORACLE v3 also modernizes marine ecological forecasting by fully incorporating the latest CMIP6 Earth System Models (ESMs) and the updated Shared Socioeconomic Pathway (SSP) narratives, such as the SSP5-8.5 high-emissions scenario utilized in our projections (Assis et al., 2024)[1].

Transitioning the ENM framework from v2 to v3 was simple. We were able to utilize the same core environmental drivers by mapping our scripts to the updated v3 naming conventions and R syntax, while also gaining access to explicit velocity and direction fields (Assis et al.,

[1] Shared Socioeconomic Pathways (SSPs) are standardized climate scenarios that factor in technology, natural resources, policies, economic growth, and demographic changes. SSP5-8.5 used in this study represents a high fossil fuel emissions scenario where global energy, food demand, and greenhouse gas emission continue to increase dramatically with low climate change mitigation (Kriegler et al., 2017). In contrast, Bio-ORACLE v2.0 draws the data from the CMIP5 climate model which uses Representative Concentration Pathways (RCPs). SSP5-8.5 from Bio-ORACLE v3.0 introduces socioeconomic factors when predicting environmental variables.

2024). The transition also provided a significantly expanded suite of biologically meaningful variables, such as dissolved oxygen and pH, which allowed for broader feature selection during model training trials (Assis et al., 2024).

Despite its utility for baseline macroecological modeling, Bio-ORACLE v3 has limitations when simulating highly dynamic ocean currents (Assis et al., 2024). The dataset generates future projections using the “change-factor” method, which downscales expected climate anomalies from coarse ESMs and adds them to high-resolution, present-day observational baselines. While this statistical approach is highly robust for capturing broad thermodynamic shifts like basin-wide warming or acidification, it possesses inherent structural limitations for modeling water movement such as lateral shifting of currents like the Gulf Stream. Specifically, it applies future changes in physical oceanography to a static spatial grid, and therefore cannot reliably reconstruct the dynamic, localized features of Lagrangian transport such as narrow current meanders and physical lateral shifting of boundary currents (Assis et al., 2024; Todd & Ren, 2023).

Consequently, while Bio-ORACLE v3 supplies valuable velocity fields for generalized species distributions, its downscaling methodology begs greater precision regarding future location and trajectory of water currents. To overcome these limitations and accurately project the lionfish invasion along a physically shifting Gulf Stream, we applied supplementary spatial filters and shifting algorithms. In Appendix A, we describe more background on the relationship between climate change and physical oceanography, implications for ENM modeling, and the mathematical framework for the custom adjustment algorithm that we used to improve the oceanic projections. Ultimately, these adjustments resulted in modest adjustments to final suitability values, averaging a <1% correction to occurrence probabilities in the year 2090.

5.1.f Model Variable Selection

When selecting models for estimation, we considered multiple environmental variables that could potentially be physically crucial based on prior ENM studies and background research (Table 1).

Table 1. Summary of selection justification for all environmental variables included in initial ENM analysis, and considered for final ENM trials (using Bio-Oracle V3)

Variable Types	Variable Description	Variable Name	Justification
Salinity	Maximum sea-surface salinity	so_max_surface	Like most marine species, lionfish have a tolerable range of salinities. As the sea surface and benthic salinity are not necessarily coupled, they were considered separate variables for this model. Salinity can also inform what predator/prey species may be present in the areas studied.
	Mean sea-surface salinity	so_mean_surface	
	Minimum sea-surface salinity	so_min_surface	
	Range of sea-surface salinity	so_range_surface	
	Mean seafloor salinity	so_mean_benthic	
	Maximum seafloor salinity	so_max_benthic	
pH	Range of sea-surface pH	ph_range_surface	pH measures the acidity of water bodies. We hypothesized that it affects ecosystem dynamics, such as reef coverage.
Dissolved Oxygen	Range of seafloor dissolved oxygen	o2_range_benthic	Dissolved oxygen is critical for respiratory purposes. Regions exhibiting low oxygen concentration (hypoxic) may limit lionfish suitability.
Temper-ature	Minimum sea-surface temperature	thetao_min_surface	Warmer mean temperatures would suggest greater reproductive ability year-round. While the minimum temperature may provide insight into locations where lionfish would perish if they tried to overwinter.
	Maximum seafloor temperature	thetao_max_benthic	

	Mean seafloor temperature	thetao_mean_benthic	
	Minimum seafloor temperature	thetao_min_benthic	

Through the preliminary research outlined in Section 5.1.d, we selected an initial batch of environmental variables that should be able to describe the physical limits of lionfish habitability. While it could seem desirable to include all of these variables in theENM model to base predictions on as many relevant variables as possible, this approach would include variables that may be highly correlated with each other. Collinearity has been shown to negatively affect model performance when applying said models to novel environments (Feng et al., 2019). As such, our team chose to run models where no two variables share a correlation coefficient of more than 0.75. To this end, we examined pairwise correlation studies between all variables of interest and determined which variables to exclude. For example, bathymetry and bottom pH were both highly correlated with mean benthic temperature (0.89 and 0.81, respectively). As mentioned in Section 5.1.d, our team placed a particular emphasis on the relevance of mean benthic temperature and thus chose to eliminate bathymetry and benthic pH from our list of environmental variables. Given a future opportunity, we would like to examine the effects of including strongly correlated variables in our analysis.

During this variable elimination step, there were several variables that we were unable to rank in terms of importance. When two of these variables shared a high correlation, we chose to run a model with each to assess which would result in a better fit. On average, each model produced by this method had seven variables, some of which had a very weak relationship to lionfish occurrence probability. Figure 3 shows the marginal response curves from one such model run.

Notably, the occurrence probability changes little with mean surface temperature and mean surface pH. This implies that these variables have almost no effect on the results of this particular model. As such, these models were re-run with these less predictive variables removed. The result of this is the 6 variable sets shown in Table 2.

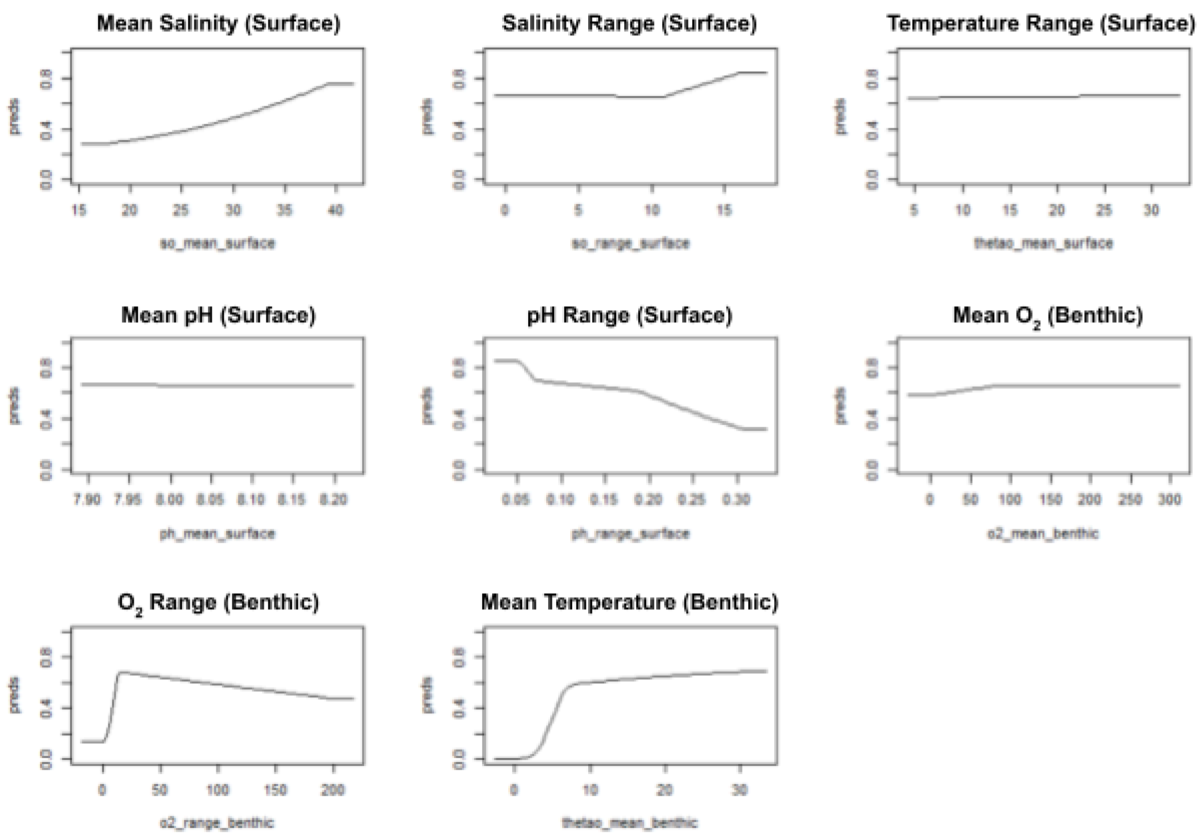

Figure 3. Marginal Response Curves from an 8-variable ENM model. Notably, Surface temperature range and mean surface pH have little marginal effect

Table 2. Variable List for the six selected ENM model trials. Trials were chosen based on suitable correlation results between variables involved.

Variable ID	Description	Model Trials					
		1	2	3	4	5	6
so_max_surface	Max Surface Salinity (ppt)						X
so_mean_surface	Mean Surface Salinity (ppt)		X			X	
so_min_surface	Min Surface Salinity (ppt)						X
so_range_surface	Surface Salinity Range (ppt)	X	X	X	X	X	
so_max_benthic	Max Benthic Salinity (ppt)						X
so_mean_benthic	Mean Benthic Salinity (ppt)	X		X	X		
ph_range_surface	Surface pH Range	X	X	X			
o2_range_benthic	Surface Dissolved O_2 ($mmol/m^3$)	X	X	X	X	X	
thetao_min_surface	Min Surface Temperature (°C)				X	X	X
thetao_max_benthic	Max Benthic Temperature (°C)						X
thetao_mean_benthic	Mean Benthic Temperature (°C)	X	X		X	X	
thetao_min_benthic	Min Benthic Temperature (°C)			X			

5.1.g Model Validation and Projection

MaxEnt (Maximum Entropy), the framework used in this study, relies on two core principles. The first is entropy, which refers to finding the distribution that is the most spread out or uniform in a given region. The second core principle is constraint, which refers to the use of environmental variables to constrain predictions based on where the species has been observed. MaxEnt's results consist of a set of probability distribution functions that relate the likelihood of observing a given species based on the local environmental variables. MaxEnt can generate probability distributions of lionfish habitat suitability across environmental conditions. These can be used to predict or verify current distributions based on current environmental data, or to extrapolate to future distributions, such as for the year 2090, by applying the model to predicted climate data.

We evaluated our suite of models based on classification capacity, the ability of the model to classify locations as inhabitable or uninhabitable to lionfish based on a specific threshold probability. The classification capacity measures we used are precision, accuracy, recall, and F1 score.

Accuracy is the ratio of correct classifications to total classifications. Each location correctly predicted to either be a lionfish habitat or not be a lionfish habitat counts toward a higher accuracy score. *Precision* is the proportion of locations that the model classified as lionfish habitat that are actually lionfish habitat. A high precision score indicates that the model finds few false positives. In contrast, *recall* is the proportion of actual lionfish habitat that the model classifies as lionfish habitat. High recall indicates that the model finds few false negatives. *F1 score* is the harmonic mean of precision and recall, so it accounts for both false positives and false negatives. Each of these metrics is measured on a scale from 0 to 1, where 1 represents a stronger model. For our uses, the most important metrics are the F1 score and precision.

5.2 Policy Framework

5.2.a Study Scope and State Selection

Our policy analysis examined state-specific aquatic invasive species management approaches across eight U.S. East Coast states: New York, New Jersey, Maryland, Virginia, North Carolina, South Carolina, Georgia, and Florida. These states were selected specifically to represent a continuous range geographically along the East Coast of the United States, aiming to include regions with varying marine ecosystems and, most importantly, differing potential exposure to lionfish. This regional focus allowed for inter-state comparison of management strategies relevant to a potential lionfish invasion.

5.2.b Our Definition of "Policy"

For the purposes of our research, policy was defined as any state level invasive species management plan, regulation, or formal strategy that highlights actions that the state can implement to prevent or manage the impacts of invasive species. This included comprehensive invasive species management plans such as Maryland's Invasive Species Management Plan, regulations issued by state wildlife agencies, and state supported programs addressing aquatic invasive species. We identified that these policies typically provide a framework to minimize environmental, ecological, and economic damage caused by invasive species through management efforts.

5.2.c Identification of Aquatic Invasive Species

For each state, two representative aquatic invasive species were selected to contextualize how invasive species are managed at the state level. Species selection was conducted through targeted online searches (e.g. "aquatic invasive species in [state]"), using state government websites, environmental reports, and conservation organization resources. We included aquatic plants and invertebrates in the set of focal species in order to consider broader aquatic invasive species management efforts and examine how each state approaches invasive species spread limitation and cross-state collaboration. Our consideration of species beyond lionfish in our policy examination enabled a more comprehensive analysis of management strategies that could be relevant to lionfish response across the Eastern U.S. and the Chesapeake Bay.

5.2.d Aquatic Invasive Species Policy Search Strategy

For each state, we conducted a systematic review of publicly available materials, including state invasive species management plans, department of natural resources or environmental protection agency publications, state legislation, and official state webpages addressing aquatic invasive species.

We specifically searched for state policies addressing the two representative aquatic invasive species. A state's search was considered exhausted when one of the following conditions was met: a) clear management plans or regulatory approaches for aquatic invasive species were identified, or b) if no detailed plans were found for the state that addressed the focal aquatic invasive species. If the state lacked detailed, targeted plans, they usually deferred to federal invasive species guidelines, such as the Lacey Act, or address invasions through potential local or NGO efforts; however, these were not the focus of our analysis.

5.2.e Lionfish Presence and Lionfish-Specific Policies

Each state was also specifically evaluated for documented lionfish sightings or establishments, as well as the presence or absence of lionfish-specific policies. The identification of lionfish-specific state policies indicated that the state had awareness or specific plans for addressing lionfish management. Unlike general aquatic invasive species state policies, lionfish-specific state policies suggest that the state is using dedicated facilities, targeted interventions, prioritization of the species, or funding to target lionfish specifically. Additionally, since there is no objective or consistent framework on what determines the level of invasiveness, the selection of lionfish to be considered as "invasive" allows the species to receive more awareness on potential management plans and funding.

5.2.f Policy Categorization Framework

To summarize and compare state approaches to management efforts, policy components were categorized into seven management strategy categories. These categories were used in summary tables for a more nuanced analysis:

1. **Illegal to Release Invasive Species Alive:** Prohibits returning captured invasive species to the wild to prevent further spread and population growth. Imposes legal or financial consequences for unlawful release, transport, or introduction.
2. **Illegal to Transport, Sell, or Introduce Without Permit:** Bans unauthorized movement, sale, or introduction of invasive species to reduce human-assisted spread.
3. **Encouraged or Required Reporting of Sightings/Captures:** Requires or promotes public reporting of invasive species observations to help agencies monitor and respond quickly.
4. **Open or Unrestricted Harvest Allowed:** Allows unlimited removal (no size or bag limits) to incentivize population control.
5. **Public Education and Awareness Programs:** Promotes outreach initiatives to inform the public about prevention strategies and responsible practices.
6. **Focus on Eradication or Population Control:** Implements active management strategies aimed at reducing or eliminating established invasive populations.
7. **Specifically Labels Aquatic Species as Invasive:** In order to receive more funding to have specified and monitored management plans for invasive species, those species are thus labeled as invasive to acknowledge the threat to the state's environment.

By comparing different management strategies and policy directions across states we evaluated the extent to which states emphasized prevention, management of present species, and species elimination. We also examined the extent to which states considered lionfish directly in their policies and in relation to presence or absence of lionfish in their waters. These patterns were then used to assess how existing policy frameworks in each state may relate to future responses to a potential lionfish invasion.

5.3 Project Novelty

Our ecological niche model follows up on a recommendation by Loya-Cancino (2023) by combining occurrences for the entire *Pterois* genus. This operates under the assumption of niche conservatism, which suggests that *P. miles* and *P. volitans* are likely to share a similar habitat niche (Peterson, 2011). Combining occurrences allows us to use a larger number of data points, which increases the statistical significance of our results.

Furthermore, our model is the first ecological niche model for lionfish habitat to use Bio-ORACLE v3.0 data. This marine data introduces climate projections of many more data layers than previous versions, including pH and dissolved oxygen, which we use in our ecological niche models. Bio-ORACLE v3.0 also incorporates data from the Sixth Phase of the Coupled Model Intercomparison Project and a wider number of Earth Standard Models than previous versions (Assis et al., 2024). This makes it more accurate and robust than previously available data. Finally, to overcome limitations of global oceanic datasets, we use a custom Lagrangian adjustment algorithm that physically shifts CMPI6 decadal projections shoreward while simultaneously intensifying surface velocity. This dynamic parameterization simulates the AMOC-driven migration of the Gulf Stream to capture moving physical boundary fronts. This transformation towards a dynamic oceanographic simulation contributes a novel framework to the spatial ecology literature regarding climate-driven invasion projections along complex, shifting boundary currents.

As a unique aspect of our project to be more well-rounded with our ecological niche modeling section, we complemented our ENM results with a multi-state policy analysis; we used both components to apply realistic interventions. The addition of a policy section also adds a level of complexity to our interdisciplinary team as a way to approach the lionfish invasion and environmental concerns from a different angle.

6. Results

6.1 Ecological Niche Modeling

A table of the model validation metrics, recall, accuracy, precision, and F1 score for each model fit is below. All of our models performed well on various model validation metrics, with all models scoring at least a recall of 0.97, an accuracy of 0.93, a precision of 0.72, and an F1 score of 0.83.

Table 3: Model performance metrics for the six choices of environmental variables shown in Table 2 (Section 5.1.f). A particular emphasis was placed on Precision, of which model 6 performed best.

Metric	**Model Number**					
	1	2	3	4	5	6
Recall	0.986	0.986	0.986	0.973	0.973	0.973
Accuracy	0.933	0.935	0.935	0.947	0.944	0.954
Precision	0.720	0.727	0.727	0.771	0.763	0.798
F1 Score	0.832	0.837	0.837	0.861	0.855	0.877

Model 6 was identified as the model with the highest precision, meaning that the model showed few false positives. However, these traditional validation metrics, such as precision, accuracy, and F1 score, must be interpreted with caution in the context of presence-only Species Distribution Models (SDMs). Because true absence data is rarely available for marine invaders like the lionfish, our models rely on background points (pseudo-absences) rather than confirmed true negatives. Consequently, the definitions of "false positives" and "true negatives" are mathematical approximations rather than observed ecological realities, which can artificially inflate metric scores or misrepresent actual predictive performance. Furthermore, while methodological adjustments like spatial filtering are often employed to mitigate sampling bias in presence-only datasets, recent literature demonstrates that such spatial thinning techniques may not substantially improve these model evaluation outcomes (Ten Caten & Dallas, 2023). Interestingly, despite each model sharing similar values for all of the evaluation metrics, the models reported substantially different suitability values when they were applied to a novel region like the Chesapeake bay. Suitability values occasionally varied as much as 50 % in the shallow portions of the Chesapeake. This suggests that there is a great amount of uncertainty in our results. Although we were not able to perform an in depth uncertainty analysis for this project, future analysis should compare values from multiple similar models to create a distribution of suitability values.

Looking at the Marginal Response Curves for model 6 (Figure 4), it appears that lionfish suitability increases with max surface salinity, flattening out at around 35 ppt. This is consistent with previous literature on lionfish, suggesting that lionfish are capable of surviving at low salinities but prefer an average oceanic salinity of 35 ppt (Schofield et al., 2015; Jud et al., 2011). Similarly, lionfish suitability increases with temperature, with some suitability in temperatures between 5 and 30 degrees Celsius, with a strong preference for higher temperatures. Our findings were again consistent with prior literature on lionfish temperature preferences (Dabruzzi et al., 2017).

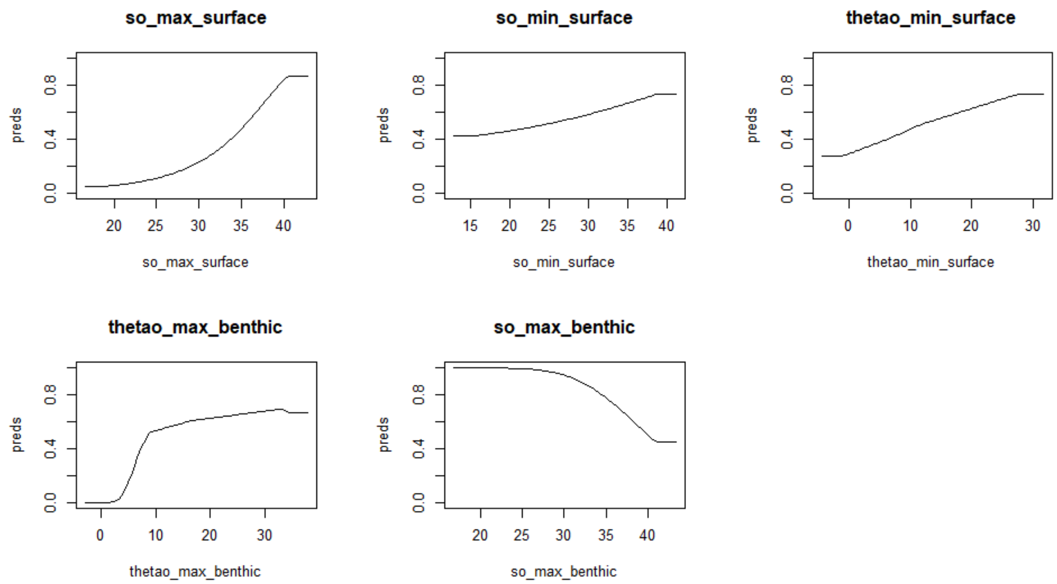

Figure 4. Marginal Response Curves for model 6 which showed the best precision among the candidate models and used with the following variables: maximum surface salinity, minimum surface salinity minimum surface temperature, maximum benthic temperature, maximum benthic salinity.

Our results indicate that the Chesapeake Bay is likely to remain unsuitable u for long-term lionfish populations, even by 2090. Specific suitability values from model 6 for six sample points, ranging from deeper into the Chesapeake Bay to coastal waters outside the bay, are shown in Table 4. In Figure 5, these points are highlighted in red, with the northernmost being Point 1 and the southernmost being Point 6. The first three locations, which are within the Chesapeake Bay, increase in suitability by no more than 20%. Since lionfish currently have little presence in the Chesapeake Bay, these findings support that they are unlikely to establish one. Furthermore, total suitability values for points 1-3 in 2090 do not exceed 0.12, which is not enough evidence to suggest the ability to support a suitable habitat. The other models have similar results, with all models except for Model 1 also having suitability values for 2090 lower than 0.15 within the bay. Model 1, however, shows suitability values up to 0.3.

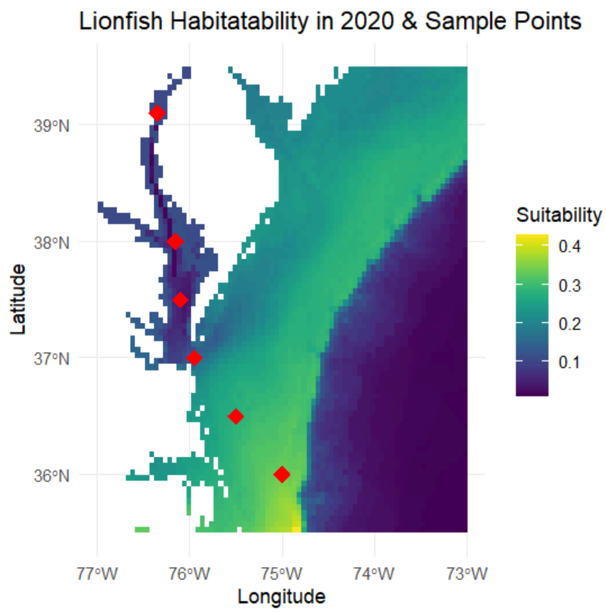

Figure 5: The current suitability for lionfish in the Chesapeake Bay and coastal waters near Maryland, Delaware, and Virginia, as predicted by model 6.

Table 4: Change in suitability for lionfish between 2020 and 2090 at each of the six points shown in Figure 5 (labeled from north to south).

Point	**Suitability (2020)**	**Suitability (2090)**	**Change in suitability**	**% Change in suitability**
1	0.10435	0.11652	0.012171	11.66%
2	0.10422	0.11330	0.009084	8.71%
3	0.03336	0.03935	0.005988	17.95%
4	0.16928	0.21180	0.042519	26.70%
5	0.27975	0.34189	0.062133	22.21%
6	0.33736	0.40098	0.063618	18.89%

Outside of the Chesapeake Bay, a much larger area along the Maryland shoreline has higher predicted suitabilities for lionfish. The three southernmost points in the table above have greater relative changes in suitability and higher suitability overall in 2090. These results are supported by the other five models, which also report suitability up to 0.5 in coastal waters in locations 4-6.

By the year 2090, the Florida, Georgia, and South Carolina coasts are predicted to have high suitability for lionfish. Meanwhile, the northern limits of New York and New Jersey were found to be unfit for lionfish even under the worst-case climate scenario SSP5-8.5. Maryland, Virginia, and North Carolina coastal waters have a moderate chance of supporting lionfish populations. All states that were sampled showed a significantly amplified lionfish habitability in 2090 compared to 2020. Specific suitabilities for five sampled locations along the East Coast of the United States are shown in Table 5. While southern states are more likely to be suitable habitats for lionfish, northern states have much larger increases in suitability.

Table 5: Suitability values for lionfish in each of five near-shore locations off the East Coast of the U.S, based on predictions from Model 6. Suitability values were based on modern day (2020) environmental values and Bio-Oracle 3 projections for the decade of 2090.

Latitude, Longitude	Approx. Location	Suitability (2020)	Suitability (2090)	% Change
40.52, -72.72	Long Island, NY	0.19016	0.23213	22.07%
37.27, -75.40	Virginia Beach, VA	0.20307	0.25763	26.87%
35.36, -75.315	Outer Banks, NC	0.33648	0.40868	21.45%
33.38, -78.57	Myrtle Beach, SC	0.48795	0.56753	16.31%
31.17, -80.51	Brunswick, GA	0.55143	0.62966	14.19%

The maps in Figure 6 show the suitability across the southern half of the East Coast in 2020, 2050, and 2090 for comparison. While the possible habitat for lionfish does not change significantly, suitability increases in many areas near Florida, South Carolina, and Georgia, so these areas are likely to have increases in lionfish population by 2090. Also, water slightly further from the shoreline is much more likely to be suitable for lionfish populations.

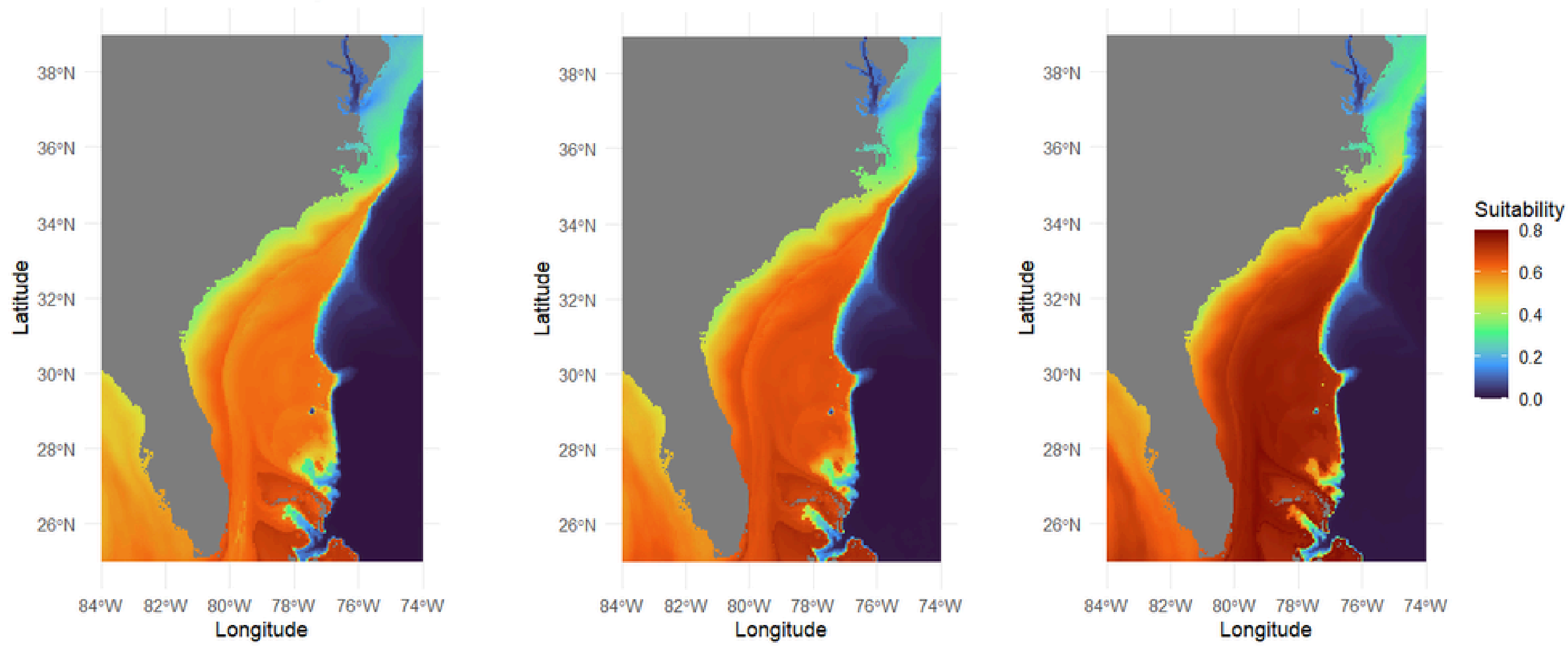

Figure 6: Three maps showing suitability for lionfish along the East Coast, (from left to right) in 2020 and projections to 2050 and 2090 based on the predictions generated by Model 6.

6.2 Policy

Below, we summarize the aquatic invasive species policies as well as lionfish-specific policies for each state along the East Coast in our policy analysis. Findings are also summarized in tables 6 and 7.

New York

In New York, the two representative aquatic invasive species are the Shore Crab (*Carcinus maena*s), native to the western Pacific, and the Round Goby (*Neogobius melanostomus*), native to the Black and Caspian Seas. Shore Crabs mainly consume invertebrates (e.g., blue mussels, snails, barnacles) and algae. Shore crabs also compete with native species for food and shelter. For example, research from Long Island, NY, suggests that shore crabs outcompete native, black-fingered mud crabs. The shore crab is a prohibited species under New York State Invasive Species Regulation 6 NYCRR Part 575. According to this regulation, prohibited species cannot be possessed with the intention to sell, import, purchase, transport or introduce.

The Round Goby outcompetes and reduces native fish populations. They increase the mercury content of sports fish and act as a carrier for viral hemorrhagic septicemia (VHS), a serious, fatal fish disease. Round gobies increase mercury levels in aquatic ecosystems by acting as a link between contaminated invasive mussels and larger predators. They eat zebra mussels, which absorb and store heavy metals, and then are eaten by sport fish, which pass the mercury up the food chain, increasing its concentration (NY Department of Environmental Conservation, n.d.). The Rapid Response Plan is an early intervention strategy that uses surveys to monitor the round goby population size and location south of Champlain Canal Lock C-1.

Although lionfish are rarely spotted in New York, they are a regulated species under New York State Invasive Species Regulation 6 NYCRR Part 575. Regulated species cannot be knowingly introduced in a free-living state or introduced by means that one should have known would lead to such an introduction, although such species shall be legal to possess, sell, buy, propagate, and transport. Additionally, the state guidance clearly supports public education and awareness programs, as it encourages people to learn how to identify lionfish and understand how to prevent their spread by cleaning, draining, and drying equipment. It also reflects a focus on eradication or population control, since individuals who find a lionfish are instructed not to release it alive and to dispose of the specimen (NY Department of Environmental Conservation, n.d.). Additionally, the instructions to report sightings through email or iMapInvasives match policies that encourage or require reporting of sightings or captures, which helps agencies monitor and respond to invasive populations.

New Jersey

In New Jersey, the two representative aquatic invasive species are the Flathead Catfish (*Pylodictis olivaris*), native to the Mississippi River, and the Green Sunfish (*Lepomis cyanellus*), native to the Great Lakes. Flathead catfish are considered invasive in New Jersey because they out-compete other recreational and native fish. Flathead catfish are considered an "emerging invasive freshwater species", meaning that they are found within 100 miles of New Jersey border/border waters. The New Jersey Fish Code statute N.J.A.C. 7:25-6.1(g) prohibits the possession or release of live potentially dangerous animals including fish.

Green Sunfish are considered an aggressive species that over consumes native species as well as taking up a lot of the water space. Green Sunfish are considered to be a "Widespread" invasive species meaning it is an invasive species that occurs in abundance within New Jersey.

This label encourages a management goal of local control in the waters of New Jersey, and is given the highest priority of population management.

Similar to New York, New Jersey has not had frequent sightings of lionfish, however, they are currently categorized as a "buffer" species, meaning that the state of New Jersey has recognized the potential for an invasion even though there have been no significant sightings of lionfish in the area. According to Statute N.J.A.C. 7:25-6.2, since lionfish are considered to be a designated "Potentially Dangerous Species", which can be defined as "any exotic mammals, birds, reptiles or amphibians or nongame species which, in the opinion of the Division, is capable of inflicting serious or fatal injuries or which has the potential to become an agricultural pest or a menace to the public health or indigenous wildlife populations (N.J.A.C 7:25)". A specific restriction of "Potentially Dangerous Species" is that a person with a pet shop or animal distribution permit cannot possess a "Potentially Dangerous Species", which means that lionfish cannot be sold commercially.

Maryland

In Maryland, the two representative aquatic invasive species are the Blue Catfish (*Ictalurus furcatus*), native to the Mississippi River, and the Northern Snakehead (*Channa argus*), native to Eastern Asia.

Blue Catfish are apex predators that outcompete native fish species for food and directly prey on them which is disrupting the Chesapeake Bay food web and aquatic ecosystem. In response, Maryland has implemented policies to prioritize active removal and commercial usage. For example, the USDA, in partnership with the Maryland Department of Agriculture, recently launched a one-year pilot program using Section 32 funds to purchase up to $2 million worth of Chesapeake Bay blue catfish (USDA, 2025). This initiative aims to support regional seafood processors, reduce invasive catfish populations in the bay, and distribute seafood to families in need through food banks and other food distributors. Other notable state-level policies include the promotion of blue catfish sales at retail stores, encouragement of angler harvest while discouraging catch-and-release, a ban on transporting live blue catfish between bodies of water, and the development of new commercial markets. Examples include the Mitigation Action and Watermen Support Act (MAWS Act) of 2025, which proposes to create a new market for blue catfish to be used in pet food (Congress.gov, 2025).

The Northern Snakehead poses a similar ecological threat, with the potential to outcompete and prey upon popular sportfish species, including bass and native shad (Eroh & Liebich, 2022). This endangers recreational fisheries throughout the Chesapeake Bay region as well as the local ecosystem. Snakeheads are also particularly difficult to control due to their ability to spawn multiple times per season (Eroh & Liebich, 2022). At the federal level, the species is listed as “injurious” under the Lacey Act, making it illegal to possess or transport live individuals (FWS.gov, 2025). Maryland’s management goals for Northern Snakehead focus on preventing transport to new watersheds and limiting the spread within the Chesapeake Bay watershed. Similar to blue catfish, the state emphasizes angler harvesting as a cost-effective population control strategy.

With respect to lionfish, there have been few sightings in Maryland, however, the species has not yet established a stable population. Lionfish are classified as a Red Alert Species in Maryland’s Aquatic Nuisance Species (ANS) Management Plan, indicating that lionfish are high-priority, non-native aquatic organisms not yet established in local waters but posing severe ecological or economic threats. This plan aims to prevent spread, detect new invasions, and control existing populations through research, outreach, and public participation. Maryland encourages public reporting of sightings and allows for special permits for removal in protected areas.

Virginia

In Virginia, the two representative aquatic invasive species are Zebra Mussel (*Dreissena polymorpha*) and Rusty Crayfish (*Faxonius rusticus*). Zebra mussels are native to the Caspian, Black and Azov seas of Eastern Europe. This species was first discovered in the U.S. in Lake Saint Clair, Michigan in 1988 and is believed to have been introduced in 1986 through ballast water discharge from ocean-going ships. Zebra mussels remove the food base upon which many of our native fish and freshwater invertebrates are dependent. Due to their ability to rapidly colonize any hard surface, zebra mussels also pose a significant risk to many bottom-dwelling species, including the rare and endangered freshwater mussel populations.Virginia's policy for zebra mussels prohibits knowingly introducing them into state waters without a permit and requires boaters to practice "Clean, Drain, Dry" to prevent their spread (*Zebra Mussel*, 2021). When cleaning, you should remove all aquatic plants, animals, or mud from your boat. When draining, you should remove all water from your boat. When drying, let all your equipment dry completely, preferably for five days. The state also mandates education programs and has specific reporting requirements if zebra mussels are detected.

Rusty crayfish (*Faxonius rusticus*) is native to Ohio, Indiana, Kentucky, and northern Tennessee, but was first found in Virginia in 2011, probably having been used by anglers for bait and sold in the pet and biological supply industries. Rusty crayfish outcompete native crayfish for food and territory, are voracious fish egg-eaters, and reduce aquatic plant abundance and species diversity, which impacts the habitat for other crayfish and fish species (*Rusty Crayfish,* n.d.). They are associated with population declines of game fish such as bluegill and bass, along with game and non-game other fish species. Rusty Crayfish is considered a nonindigenous aquatic nuisance species. It is unlawful to take, possess, transport, import, sell, or offer for sale within the Commonwealth any nonindigenous aquatic nuisance species except as authorized by law or regulation (*4VAC15-20-210*).

Currently there are rare sightings of lionfish without an established population, however, there is a general invasive species statute in Virginia called the Nonindigenous Aquatic Nuisance Species Act (§ 29.1-571). This law defines and prohibits the introduction of nonindigenous aquatic nuisance species into Virginia's waters, which are species that threaten native ecosystems or water use (*§ 29.1-571*). Additionally, Virginia has a state plan called the "State Invasive Species Management Plan" to implement strategic actions for invasive species, including prevention, early detection, and control, involving various state agencies and public stakeholders.

North Carolina

In North Carolina, the two representative aquatic invasive species are Hydrilla (*Hydrilla verticillata*) and Alabama Bass (*Micropterus henshalli*). Monoecious hydrilla is native to Korea and India. Monoecious hydrilla is considered invasive due to its aggressive nature, it grows in massive amounts that disrupt fish populations as well as become a hazard for water sports, (*NC DEQ*, 2023). North Carolina recognizes hydrilla as a noxious aquatic weed. It is illegal to culture, transport, and sell this plant.

Alabama Bass are originally from Alabama and Georgia, but are now invasive in North Carolina and Virginia. Alabama Bass are considered invasive because they out-compete and replace native largemouth bass. They also interbreed with native smallmouth and spotted bass which could eventually eliminate all native bass. Since most of the invasion originates from anglers stocking Alabama Bass, it is illegal to move or stock fish into public waters without a stocking permit obtained from the North Carolina Wildlife Resources Commission. This includes live well releases into waters different from where the fish were caught, (*Invasive Bass Species Spreads from western NC to Coastal Region*, 2025).

North Carolina has had a few counts of lionfish sightings since 2000, (*Lionfish Alert | NC DEQ*, 2023). In 2023, Lionfish have recently been added into North Carolina's bill in the "General Assembly Of North Carolina Session 2023" Senate Bill 834: "For the Control and Prevention of Invasive Species", which specifically labels lionfish as an invasive species. This means that there can now be state-wide open seasons on lionfish as well as distribution of funds for lionfish management in the Invasive Species Management Fund. This fund allocates state revenue for management of the species, public education, and establishment of a Rapid Response Team to the invasive species. Additionally, there is no established bag limit or size limit for lionfish which aligns with the policy approach of open and unrestricted harvest of this species. Furthermore, by encouraging divers and fishermen to share informational flyers and spread awareness about the hazards of lionfish, the policy supports public education and awareness programs. This outreach helps inform the public about the risks associated with the species' venomous spines and how to safely respond to encounters. The recommendation to report lionfish catches to NOAA through email or phone aligns with policies that encourage or require reporting of sightings or captures, which helps researchers and managers track the spread of the species (North Carolina Department of Environmental Quality, n.d.).

South Carolina

In South Carolina, the two representative aquatic invasive species are Snakehead (*Channa argus*) and Walking Catfish (*Clarias batrachus*). Snakehead fish are native to China, Southern Siberia, and North Korea, but are currently invasive to states along the East Coast including Virginia and Maryland. Snakeheads are considered invasive because they rapidly multiply which creates a competition with the native species for habitats and resources which outcompete and prey upon popular sportfish species, including bass and native shad (Eroh & Liebich, 2022). Additionally, the snakehead can travel on land from different bodies of water which makes their invasion wide-spread and adaptable to any environment. In South Carolina, there is a “hunt-to-kill” initiative where any snakehead that is caught needs to be exterminated and not released back into the water. Additionally, people who have caught and killed the snakehead need to report it to the South Carolina Department of Natural Resources.

Walking Catfish are native to Southeastern Asia from Eastern India to Borneo (Lee et al., 1980; Talwar & Jhingran, 1991; Kottelat et al., 1993). Walking catfish are invasive due to their adaptable nature being able to travel small distances between bodies of water where they will overpopulate those areas to snuff out native species. In South Carolina, the intentional release of walking catfish, or any type of invasive species including lionfish, is subject to a fine of $500 or imprisonment.

In South Carolina, the outreach efforts for lionfish encourage anglers to spread awareness about lionfish and the risks from their venomous spines, supporting public education and awareness programs. In addition, instructions to report hook-and-line catches of lionfish by email or phone align with policies that encourage reporting of sightings or captures of lionfish (South Carolina Department of Natural Resources, 2019). Lionfish are also listed as a non-indigenous species, which is under the category of invasive species, according to the South Carolina Department of Natural Resources.

Georgia

In Georgia, the two representative aquatic invasive species are the Asian Swamp Eel (*Monopterus albus*) and the Asian Tiger Shrimp (*Penaeus monodon*). Asian swamp eels are native to Southeast Asia but are currently invasive to U.S. states such as Georgia, Hawaii, New Jersey, and Florida. They were first discovered at spring-fed impoundments at the Chattahoochee Nature Center in Georgia (Greco, 2025). Asian swamp eels are considered invasive in their nonnative range because they can breathe air, move over land, and resist desiccation. This allows them to thrive in various habitats while also acting as novel predators that disrupt the food chain by consuming native wildlife (Greco, 2025). The main guidance regarding Asian swamp eels is to report them to the Georgia DNR if encountered and to never release them into waterways.

Asian tiger shrimp are native to the Indo-Pacific region, including parts of Africa, Asia, and Australia. Asian tiger shrimp are an invasive species found along the southeast U.S. coast and the Gulf of Mexico, from North Carolina to Texas (NOAA, n.d.). Asian tiger shrimp are considered invasive because they compete for food and habitat with native shrimp, are aggressive predators of smaller crustaceans, carry diseases like White Spot Syndrome Virus that can infect and kill native populations, and can damage infrastructure like water conservancy projects (PBS.org, 2013). We found no specific Georgia state regulations for Asian tiger shrimp and although there has been a recent uptick in species sightings, scientists have still classified this species as “not established” (NOAA, n.d.).

The guidance from the Georgia Department of Natural Resources in Georgia regarding lionfish aligns with several invasive species policy approaches. By identifying lionfish as a Priority 1(a) species and describing the risks posed by aquatic nuisance species, the policy clearly labels the species as invasive (Georgia Aquatic Nuisance Species Plan, 2009). Additionally, the recommendations to report non-native species through regional offices such as the GA WRD Fisheries Office, or online systems support policies that encourage reporting of sightings or captures. Guidance such as removing non-native species when caught and avoiding relocation or release into new water bodies reflects a focus on eradication or population control and implies that releasing invasive species is discouraged. Finally, outreach efforts like the “Stop Aquatic Hitchhikers” campaign demonstrate strong public education and awareness programs aimed at preventing further spread (Georgia Department of Natural Resources Division, n.d.).

Florida

In Florida, the two representative aquatic invasive species are the Clown Knifefish (*Chitala ornata*) and Blue Tilapia (*Oreochromis aureus*). The Clown Knifefish is native to Indochina, but has been found in South Florida starting in the 1990s. It is established in Palm Beach and possibly Broward counties, Florida, so it has been identified as an invasive species to Florida. Clown Knifefish are large, nocturnal predators that consume a variety of prey, including native fish species (Kreuger, 2018). In new environments, they reproduce successfully and establish large populations, which can overwhelm the local ecosystem. By preying on native species and competing for resources, clown knifefish can decrease the abundance of other fish and disrupt the natural balance of the aquatic community. In Florida, they are classified as an invasive species and have no bag limits, closed seasons, or minimum size limits, meaning they can be harvested year-round without restriction. It is illegal to release them alive into Florida's waters, so they must be kept, eaten, or used as bait (Kreuger, 2018).

Blue Tilapia were introduced into Florida in the 1960s and can be found extensively in tropical/sub-tropical regions of the U.S., Central and South America, Africa, and Eurasia. However, their native range is typically represented in parts of Africa and the Middle East (Odum, 2019). Blue Tilapia may compete with native species for food as they feed on algae, plant material, and bottom-dwelling invertebrates (D'Imperio, 2024). They have been known to compete with native fish for spawning sites, and their high reproductive success can lead to dense populations which may crowd native fish out of waterways. Most species of tilapia are either restricted or prohibited in Florida meaning it is generally illegal to possess, transport, or sell them alive without special permits. Blue tilapia, *Oreochromis aureus*, Nile tilapia, *O. niloticus*, and hybrids of the two species *may* be possessed, transported and cultured without a special permit (D'Imperio, 2024).

Florida has been considered as "Ground Zero" for the lionfish invasion in the western Atlantic Ocean where lionfish are prominently known as invasive. The state has a "hunt to kill" initiative. In particular, Florida has removed the requirement to possess a recreational saltwater fishing license when harvesting lionfish with approved or lionfish-specific gear. To prevent additional release of lionfish, state regulations have been put into effect to prohibit the importation, breeding, and possession of lionfish eggs or larvae. The Florida Fish and Wildlife Commission has created a permitting system to allow for harvest of invasive lionfish in ecologically sensitive or protected areas and areas where harvest presents a public safety concern (i.e. near fishing piers and jetties), within certain limitations. Additionally, Florida emphasizes lionfish removal tournaments such as organized derbies with incentives like monetary prizes and resource-based incentives which are supported by the Florida Fish and Wildlife Conservation Commission and the Reef Environmental Education Foundation (Lionfish Summit, 2018). These approaches demonstrate a clear focus on eradication or population control as they actively incentivize large-scale removal efforts for lionfish. These initiatives also support public education and awareness programs, as the derbies act as a medium to engage the community and raise awareness about the ecological threat posed by lionfish. Additional efforts include promoting commercial use such as selling lionfish fillets in Whole Foods (Lionfish Summit, 2018).

6.2.a State Analysis

Table 6: Invasive Aquatic Species by State

State	Species	Location (Current/Native Range)	Why Harmful/ Invasive	State Policies/ Programs	Policy Patterns Utilized Among the Researched Species
New York	Shore Crab[1]	Coastal NY / Native to western Pacific	Outcompetes native mud crabs; consumes invertebrates; reduces biodiversity	Prohibited species under Part 575; cannot be sold, imported, or transported	Illegal to Transport, Sell, or Introduce Without Permit, Focus on Eradication or Population Control, Specifically labels aquatic species as an invasive, Public Education and Awareness Programs, Encouraged or Required Reporting of Sightings/Captures
	Round Goby[2]	Hudson River & Great Lakes / Native to Black & Caspian Seas	Outcompetes native fish; increases mercury in sportfish; carries fatal fish disease VHS	Rapid Response Plan for monitoring and containment south of Champlain Canal	
	Lionfish (Presence)[3]	Not officially established, but there have been frequent sightings in the past two years. These sightings have both occurred in warmer seasons.	—	Regulated species under Part 575; cannot be introduced but can be possessed, sold, or transported	
New Jersey	Flathead Catfish[4]	NJ border waters / Native to Mississippi River region	Competes with native and sport fish; invasive freshwater predator	Possession or release of live fish prohibited (N.J.A.C.	Illegal to Release Invasive Species Alive, Focus on

				7:25-6.1(g)), Classified as an “Emerging Invasive Freshwater Species”	Eradication or Population Control Specifically labels aquatic species as an invasive, Illegal to Transport, Sell, or Introduce Without Permit
	Green Sunfish[5]	Statewide / Native to Great Lakes	Aggressive; displaces native fish; dominates habitats	Managed for local control; classified as 'Widespread Invasive'	
	Lionfish (Presence)[6]	First observed in 2003.	—	Classified as 'Buffer Species'; added to NJ Fish Code under 'Potentially Dangerous Species'	
Maryland	Blue Catfish[7]	Chesapeake Bay (MD & VA) / Native to Mississippi, Missouri, Ohio, and Rio Grande river basins	Competes with and preys on other fish; apex predator disrupting food web	USDA & MD Dept. of Agriculture pilot ($2M) removal program; ban on transporting live catfish; encourage harvest and processing (MAWS Act of 2025) research;	Illegal to Transport, Sell, or Introduce Without Permit, Specifically labels aquatic species as an invasive, Focus on Eradication or Population Control, Encouraged or Required Reporting of Sightings/Captures
	Northern Snakehead[8]	Chesapeake Bay watershed & Potomac River / Native to Eastern Asia (China, Russia, Korea)	Outcompetes and preys on native sportfish; spawns multiple times a season	MD encourages angler harvesting; aims to prevent transport and limit spread	

	Lionfish (Presence)[9]	Not Established	—	Red Alert Species; MD ANS Plan for prevention, detection, and control; public reporting, derbies, awareness campaigns; special permits for removal in protected areas	
Virginia	Zebra Mussel[10]	Statewide / Native to Caspian & Black Seas	Outcompetes native mussels; clogs pipes; depletes food base	Prohibits introduction; 'Clean, Drain, Dry' rule; education & reporting requirements	Encouraged or Required Reporting of Sightings/Captures, Public Education and Awareness Programs, Specifically labels aquatic species as an invasive, Illegal to Transport, Sell, or Introduce Without Permit, Focus on Eradication or Population Control
	Rusty Crayfish[11]	Statewide / Native to Midwest (OH, IN, KY, TN)	Outcompetes native crayfish; destroys aquatic plants; reduces fish habitats	This species is labeled as “nonindigenous aquatic nuisance species” which makes it illegal to possess, transport, or sell unauthorized	
	Lionfish (Presence)[12]	Observed in 2013, specifically in the Virginia Beach city area.	—	Covered under Nonindigenous Aquatic Nuisance Species Act; prohibits introduction; robust	

				management plan	
North Carolina	Hydrilla[13]	NC, SC, FL / Native to Korea & India	Forms dense mats; disrupts fish populations; hinders recreation	Listed as noxious weed; illegal to culture, transport, or sell	Illegal to Release Invasive Species Alive, Illegal to Transport, Sell, or Introduce Without Permit, Specifically labels aquatic species as an invasive, Open or Unrestricted Harvest Allowed, Public Education and Awareness Programs, Encouraged or Required Reporting of Sightings/Captures
	Alabama Bass[14]	NC & VA / Native to Alabama & Georgia	Outcompetes and hybridizes with native bass; reduces genetic diversity	Illegal to move/stock fish without NCWRC stocking permit	
	Lionfish (Presence)[15]	First observed in early 2000, breeding in large numbers reported in 2022	—	Newly classified as invasive; allows open season and funding for management	
South Carolina	Snakehead[16]	Statewide / Native to China, Siberia, Korea	Rapidly multiplies; competes with native fish; survives on land	Hunt-to-kill rule; must be killed and reported to SCDNR	Illegal to Release Invasive Species Alive, Encouraged or Required Reporting of Sightings/Captures, Public Education and Awareness Programs
	Walking Catfish[17]	Statewide / Native to Southeast Asia	Moves between waters; overpopulates new habitats; displaces natives	Illegal release = $500 fine or imprisonment	
	Lionfish (Presence)[18]	First sightings in early 2000's	—	Illegal release = $500 fine or imprisonment ; reporting of sightings are encouraged to	

				SCDNR and NOAA	
Georgia	Asian Swamp Eel[19]	Chattahoochee Nature Center / Native to Southeast Asia	Breathes air, moves on land, preys on native wildlife	Must be reported to GA DNR; never release into waterways	Illegal to Release Invasive Species Alive, Encouraged or Required Reporting of Sightings/Captures, Specifically labels aquatic species as an invasive, Public Education and Awareness Programs, Eradication or Population Control
	Asian Tiger Shrimp[20]	Southeast Coast (NC–TX) / Native to Indo-Pacific	Competes with native shrimp; carries diseases; damages infrastructure	No specific GA regulations; defers to federal/regional plans	
	Lionfish (Presence)[21]	Since 1992, adult lionfish now inhabit locations at Gray's Reef National Marine Sanctuary off the Georgia coast.	—	Identifying lionfish as a Priority 1(a) species; "Stop Aquatic Hitchhikers" campaign, strong public education and awareness programs; discourages the release of invasive aquatic species	
Florida	Clown Knifefish[22]	South Florida (Palm Beach, Broward) / Native to Indochina	Large predator; preys on native fish; disrupts ecosystem balance	No bag/size limits; may be harvested year-round; illegal to release alive	Specifically labels aquatic species as an invasive, Illegal to Release Invasive Species Alive, Open or Unrestricted Harvest Allowed, Illegal to Transport,
	Blue Tilapia[23]	Florida (introduced 1960s) / Native to Africa and Middle East	Competes for food and spawning sites; reproduces rapidly; crowds native fish	Blue/Nile tilapia & hybrids can be possessed and cultured without permit	

	Lionfish (Presence)[24]	Broward County, Florida in 1985, negative effects started in 2011	—	No license or bag limits; rebreathers allowed; bans import/breeding; FWC permits for sensitive area harvest; hunt to kill	Sell, or Introduce Without Permit, Focus on Eradication or Population Control, Public Education and Awareness Programs

Data are from:
[1] Shore Crab - Department of Environmental Conservation (n.d.).
[2] Bills and Perry (2023), Round Goby - Department of Environmental Conservation (n.d.).
[3] Invasive Species Partners - NYSDEC (n.d.)
[4] NJDEP - Department of Environmental Protection (2026).
[5] NJDEP - Department of Environmental Protection (2026).
[6] Lionfish Central (2019), Department of Environmental Protection (2009).
[7] Pasko (2016), Maryland Division of State Documents (2019), Virginia Law (2023), U.S. Department of Agriculture (USDA), (2025).
[8] Pasko (2016), Eroh and Liebich (2022), U.S. Fish and Wildlife Service[a].
[9] Pasko (2016), Presidential Documents (2016).
[10] Zebra Mussels (*Dreissena polymorpha*), (2026), Zebra Mussel, (2021).
[11] Rusty Crayfish, (2026).
[12] Virginia Invasive Species Advisory Committee (2018).
[13] Hydrilla (Hydrilla verticillata), (n.d.).
[14] North Carolina Wildlife (ncwildlife), (2025).
[15] Lionfish Alert | NC DEQ (2023), Michelson (2022).
[16] South Carolina Department of Natural Resources (SCDNR), (2019).
[17] South Carolina Aquatic Invasive Plants and Animals (n.d.).
[18] South Carolina Aquarium (2024).
[19] Greco (2025).
[20] PBS (2013), US Department of Commerce (n.d.).
[21] Scott (2019), Hall (2013).
[22] Krueger (2018).
[23] Odum (2019), D'Imperio (2024).
[24] U.S. Fish and Wildlife Service (2023).

Table 7: Policy Patterns and Strategic Themes for State Aquatic Invasive Species

Policy Area	Description	States Utilizing Policy: Representative AIS	States Utilizing Policy: Lionfish Specific
Illegal to Release Invasive Species Alive	Most states prohibit the release of invasive fish, plants, or invertebrates back into waterways	New Jersey, North Carolina, South Carolina, Georgia, Florida (5)	Florida (1)

	once captured. States can impose monetary fines or legal penalties for intentionally releasing or transporting invasive species.[1]		
Encouraged or Required Reporting of Sightings/Captures	States require or strongly encourage the public to report sightings of invasive species to wildlife or natural resources agencies.[2]	Virginia, South Carolina, Georgia (3)	New York, Maryland, North Carolina, South Carolina, Georgia (5)
Open or Unrestricted Harvest Allowed	Many states allow or encourage unlimited harvesting of invasive species to help control populations (no size or bag limits).[3]	Florida (1)	North Carolina, Florida (2)
Illegal to Transport, Sell, or Introduce Without Permit	Strict bans on moving, selling, or introducing invasive species into state waters without proper authorization.[4]	New York, Maryland, Virginia, North Carolina (4)	New Jersey, Virginia, Florida (3)
Public Education and Awareness Programs	States promote awareness campaigns and education for boaters, anglers, and the public to prevent spread.[5]	Virginia (1)	North Carolina, South Carolina, Georgia, Florida (4)
Focus on Eradication or Population Control	Most states have programs or policies aimed at reducing or eradicating existing invasive populations through removal or control measures.[6]	New York, New Jersey, Maryland, Virginia (4)	New York, Maryland, Virginia, Georgia, Florida (5)
Specifically Labels Aquatic Species as Invasive	In order to receive more funding to have specified and monitored management plans for invasive species, those species are thus labeled	New York, New Jersey, Maryland, Virginia, North Carolina, South Carolina, Florida (7)	New York, New Jersey, Maryland, North Carolina, Georgia, Florida (6)

	as invasive to acknowledge the threat to the state's environment.[7]		

Data from:
[1] Richards (2024).
[2] Department of the Interior Departmental Manual (n.d.).
[3] Simberloff (2020).
[4] U.S. Fish and Wildlife Service (n.d.[a]).
[5] Richards (2023).
[6] National Invasive Species Information Center (n.d.).
[7] Department of the Interior Departmental Manual (n.d.).

Across the states shown, there are several similarities in representative AIS policies. The most consistently used strategies across states include banning the release of the invasive species alive and specifically labeling the AIS as invasive. Both of these policy patterns appear in a majority of the states analyzed, indicating a shared priority of clearly defining invasive threats so management efforts are more specific and further spread is prevented.

When focusing specifically on lionfish related policies, there is a slight shift in emphasis. The most widely adopted strategies include encouraging or requiring reporting of sightings/captures, focusing on eradication or population control, and explicitly labeling lionfish as an invasive species all of which are implemented across a majority of the researched states, This reflects a recognition of lionfish as a high priority invasive threat and leverages outreach and community input as a tool to manage lionfish populations.

Some other notable findings include that open or unrestricted harvest is used more frequently for lionfish than for the representative AIS, but is only applied in a limited number of states. This finding may be due, in part, to the fact that states handle fishing regulations (e.g. bag limits) in different ways. For example, the Maryland Department of Natural Resources clearly identifies three specific AIS without any bag limits, namely blue catfish, flathead catfish, and snakehead. South Carolina Department of Natural Resources, on the other hand, notes that there are no bag limits for freshwater non-game fish species unless specifically restricted. It also specifically lists several saltwater fish with bag limits and some with no regulations. A commonality that is shown in all of the studied Atlantic states is that most regions, including North Carolina, Virginia, and Georgia, either explicitly permit an unlimited harvest or do not provide any specific bag limits in the case of invasive species while at the same time encouraging people to hunt them to reduce their effects on the environment (Nongame Fish, 2015).

As such, the absence of a policy indicating no bag limits for a species does not necessarily indicate restricted harvest. Instead, the default policy may be unrestricted harvest. Similarly, policies prohibiting transport, sale, or introduction without permit are less consistently applied to lionfish in comparison to the representative AIS. Lastly, while banning the release of invasive species alive is common in the representative AIS policy patterns, it is rarely mentioned in lionfish-specific regulations, suggesting that states may rely more on removal incentives and reporting rather than strict release prohibitions for lionfish. Alternatively, any lionfish specific policies may be further implied in more general AIS policies that are not specifically targeting these species.

Overall, while representative AIS policy patterns emphasize regulation and prevention, lionfish-specific strategies place greater emphasis on active removal, monitoring, and public engagement.

7. Discussion

7.1 Implications of Ecological Niche Modeling

We found the combination of the following five environmental variables to be the most effective at predicting the occurrence of lionfish: maximum surface salinity, minimum surface salinity, maximum benthic salinity, minimum surface temperature, and maximum benthic temperature. However, since all of our final candidate models showed relatively similar performance characteristics, we believe that any of the variables listed in table 2 can be used to reasonably predict the habitat suitability of lionfish.

The ENM results suggest that climate change will likely advance lionfish populations further northward along the East Coast of the U.S., but likely no further than North Carolina waters by 2090. These results agree with those of Loya-Cancino et al. (2023) and Grieve et al. (2016), both of whom concluded that lionfish populations will be limited to North Carolina by 2100. In addition, the likelihood of lionfish establishing a population in the Chesapeake Bay is low.

Interestingly, the suitability for lionfish in the Chesapeake Bay is somewhat analogous to the suitability for lionfish along the Black Sea coast (both hover between 0.09 and 0.11 depending on the model). Both bodies of water currently have no credible reports of lionfish sightings and are known for significantly lower salinity content compared to their surrounding regions. However, the waters in the Black Sea seemed to show much more consistent increases in habitability, averaging ~30%. As the Black Sea was not the focus of this research, no further exploration was done into this. However, if significant numbers of lionfish sightings begin appearing in the Black Sea, this could act as a bellwether signaling a potential lionfish invasion into the Chesapeake Bay.

The model results indicate that lionfish suitability is generally higher in offshore waters compared to nearshore coastal regions. This finding provides important implications for detecting and managing lionfish populations. Since people are less likely to sample and be active in water further from the coastline, lionfish populations may be able to establish and expand with limited awareness and monitoring, which may lead to underestimating the lionfish population. As such, accurate ENM prediction models that identify high-suitability regions for lionfish could be valuable for guiding targeted monitoring efforts. Dedicated equipment could then be deployed for early detection and monitoring of lionfish in those predicted high-suitability regions.

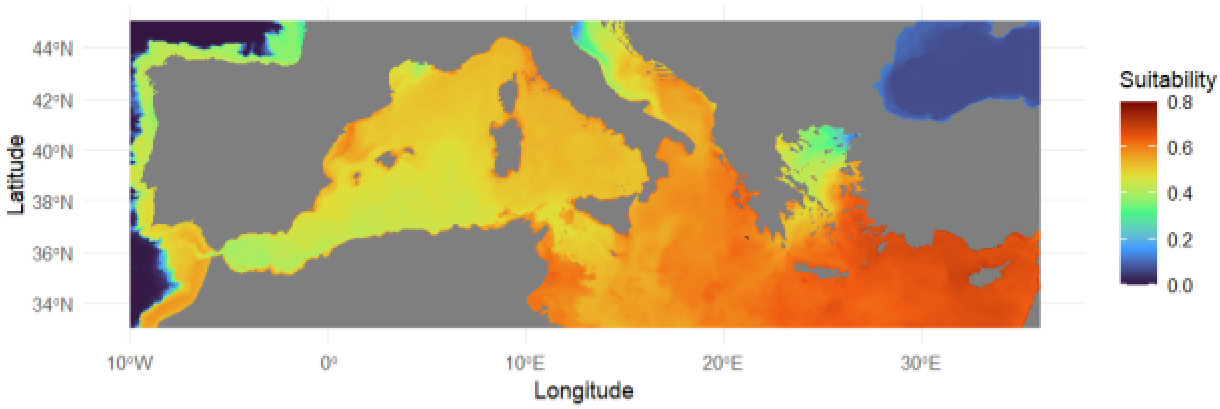

Figure 7. Lionfish habitability in the Mediterranean for 2020.

There is some variation in results from different models. All six of our models had the same general trends of increased predicted suitability over time, higher suitability further from the coast, suitability decreasing in northern regions, and low suitability inside the Chesapeake Bay. Models 1 and 2 in particular predicted a larger increase in suitability in most locations by 2090 than model 6. As such, there is still uncertainty about all of our predictions.

7.2 Policy Discussion

In our policy analysis, we found that most states used policies that are based on preventative management of species as a way to facilitate the state's public education on aquatic invasive species in an active manner. Examples of preventative management policy strategies include "Encouraged or Required Reporting of Sightings/Captures" and "Illegal to Transport, Sell, or Introduce Without Permit". By having these preventative management action items, states can engage in aquatic invasive species management that can continue to preserve the state's aquatic ecosystem from introducing any new invasive species. In contrast, the least used general aquatic invasive species policy strategies are more directly focused on the community. These general aquatic invasive species policies include "Open or Unrestricted Harvest Allowed" and "Public Education and Awareness Programs". These policy strategies are more direct in which they actively, and specifically, target aquatic invasive species while using the public to engage in managing the species. Usually, these direct policies are utilized if there is an active and ongoing invasion that requires immediate management. Note, that Florida is an example of using these types of policies specifically for lionfish, and Virginia uses these policies specifically for zebra mussels. From the general aquatic invasive species policy strategies, Virginia is the state that uses the majority of these strategies, using five out of the seven policy strategies. In contrast, we found that South Carolina and Georgia have the lowest number of specific aquatic invasive species policy strategies. This is not to say South Carolina and Georgia do not strictly enforce the management of aquatic invasive species, but it is more likely that these two states refer back to federal laws or other institutions instead of using more state authority.

In terms of lionfish-specific policies, it is understood that lionfish have generally inhabited waters around Florida, with rare sightings in northern states. Likewise, Florida has the majority of aquatic invasive species policies aimed at the management of invasive lionfish. Following Florida, New York and North Carolina are next with having the second majority of implementing lionfish-specific policy strategies. Since North Carolina recently added lionfish to the status of "invasive", it thus follows that lionfish have more focus on management as well as management funding from the state government. Out of all eight states that were analyzed, the majority of states implemented the policy strategy of labeling lionfish as an invasive species in the state's legislature. By merely labeling a species as "invasive", the state acknowledges the increased level of danger from the introduction of the species which makes its management more feasible within the state. Specifically, the newly termed invasive species may begin to receive management funding with general aquatic invasive species policies as well as possible management teams and initiatives to use direct methods if the invasive species is spreading rapidly to call for that type of direct action. Based on our analysis we can consider how each of the different policy components observed for aquatic invaders across the East Coast can be applied specifically to lionfish.

During the policy statewide analysis, we found that a majority of states defer to state-level natural resources or agriculture agencies for aquatic invasive species policies. For example, agencies like the Georgia Department of Natural Resources and the New York State Department of Environmental Conservation play central roles in invasive species management efforts specifically through measures like listing the species as invasive, transport restrictions, and public education initiatives to name a few. However, there are notable exceptions in states facing a more heightened invasion such as the lionfish invasion in Florida. The Reef Environmental Education Foundation (REEF) is a non-profit organization based in Key Largo, Florida that has taken a leading role in managing the lionfish invasion, reflecting the need for additional "task force" like programs to inform further specific policy recommendations. REEF works directly with the community to provide services like lionfish collecting and handling workshops, lionfish jewelry workshops, lionfish derbies, and more lionfish resources (Invasive Species Program | Reef Environmental Education Foundation, n.d.). This contrasts with the state departments which take on a more generalized approach to AIS management strategies. Additionally, states may prioritize federal level legislations such as the Mitigation Action and

Watermen Support Act of 2025. This act illustrates how the state of Maryland worked together with Congress to address the ecological and economic impacts of blue catfish by supporting commercial harvesting efforts. Furthermore, the US Fish and Wildlife Service has worked with states dealing with the snakehead fish invasion by implementing policies to control the population spread of this species. These examples highlight how state and federal agencies work together to address the environmental challenges of AIS invasions and how multiple agencies can operate within the same state to implement complementary management strategies.

7.3 Policy Application

Recognizing that there is an existing suite of different types of policies that states have applied to various aquatic invaders in their purview, it is worth highlighting how each of these could be applied specifically to lionfish to demonstrate how states could leverage their existing approaches. Such approaches could be useful, particularly if lionfish were to expand their range northward. We outline application of state policies to lionfish below, as well as in Table 8.

Table 8: Policy Application

Policy Area	Description	Application to Lionfish
Illegal to Release Invasive Species Alive	Most states prohibit the release of invasive fish, plants, or invertebrates back into waterways once captured.	If lionfish are captured, it will be prohibited to release lionfish back into the wild.
Encouraged or Required Reporting of Sightings/Captures	States require or strongly encourage the public to report sightings of invasive species to wildlife or natural resources agencies.	It is encouraged and/or required for the public to report lionfish sightings to wildlife or natural resources agencies
Open or Unrestricted Harvest Allowed	Many states allow or encourage unlimited harvesting of invasive species to help control populations (no size or bag limits). Specific species regulations are highly variable	There is unlimited harvesting of lionfish to help control populations with no size or bag limits.

	across states.	
Illegal to Transport, Sell, or Introduce Without Permit	Strict bans on moving, selling, or introducing invasive species into state waters without proper authorization.	Strict bans on moving, selling, or introducing lionfish into state waters.
Public Education and Awareness Programs	States promote awareness campaigns and education for boaters, anglers, and the public to prevent spread.	States promote awareness campaigns and education about lionfish to boaters, anglers, and the public.
Focus on Eradication or Population Control	Most states have programs or policies aimed at reducing or eradicating existing invasive populations through removal or control measures.	There will be programs or policies aimed at reducing or eradicating existing lionfish populations.
Specifically labels aquatic species as invasive	In order to receive more funding to have specified and monitored management plans for invasive species, those species are thus labeled as invasive to acknowledge the threat to the state's environment.	Lionfish are specifically labeled as an invasive species.

Illegal to Release Invasive Species Alive

The main cause as to how lionfish initially spread is from the release of pet lionfish into Florida waters. Although it is unclear if exotic pet owners still participate in this act, defining the release of lionfish specifically in state policy further exemplifies how quickly lionfish can spread. Specifying lionfish into state policy also puts more attention on the actions of pet owners to take more responsibility not just to care for an animal, but to take responsibility for the surrounding environment.

Encouraged or Required Reporting of Sightings/Captures

Currently, there is encouraged reporting of sightings of lionfish per NOAA's recommendation. However, with a required reporting of sightings, this not only aids in tracking the movements of lionfish across the East Coast, but these sightings also help anglers know where to hunt lionfish and assist the management of the lionfish population.

Open or Unrestricted Harvest Allowed

This state policy is mainly found in Florida where the greatest lionfish invasion population is, and lionfish have no bag limit or limited season for hunting. There are also private corporations who host “Lionfish Derbies” where it is a competitive event to see which angler can hunt the most lionfish. This strategy has been shown to be fairly effective to the extent of which experts such as Steve Gittings from NOAA, suggest that this strategy alone has been contributing to the decrease in lionfish populations. By having an unrestricted harvest of lionfish named in state policies, even in states with rare sightings of lionfish, there would be a more consistent form of management, as well as this being a possible preventative measure against a lionfish invasion.

Illegal to Transport, Sell, or Introduce Without Permit

Under the Lacey Act, lionfish are included in the federal statute where it is illegal to transport, sell, or introduce. Although this is a federal statute, it is still important to make a note of this in state policy as a way to unify state policies about specific aquatic invasive species such as lionfish.

Public Education and Awareness Programs

Currently, there are private lionfish awareness programs that are already in place, in particular, the Lionfish Extermination Corp which is based in Florida and is popular on social media. Although these private organizations are spreading awareness of lionfish, making this awareness more public will help in making education about aquatic invasive species more accessible to those who do not have access to learn about private organizations. This also helps anglers know how to handle and hunt lionfish as well as tourists in the case of lionfish being dangerous to swim around.

Specifically Labels Aquatic Species as Invasive

According to experts, most funding and creation of state programs around aquatic invasive species management are due to the labeling of a species as "invasive". In most states, there is a hierarchy of species based on their level of "invasiveness" or "dangerousness". By specifically labeling lionfish as an aquatic invasive species, this would put more of a spotlight on managing lionfish populations instead of solely relying on federal programs and funds.

7.4 Interpretation of ENM Results and How this Affects AIS State Policy

Examination of habitat suitability for lionfish along the East Coast by 2090 provides important context for our state-level policy analysis. Our results show that New York is more likely to support lionfish by 2090 than it is currently, but suitability remains low overall. Similarly, the Chesapeake Bay, which spans from Maryland to Virginia, exhibits increased, but still low, suitability by 2090. There also is a small increase in the likelihood of suitable lionfish habitat in North Carolina along the Outer Banks by 2090. South Carolina also shows a small increase in likelihood to support lionfish,with a moderately high suitability for lionfish by 2090 that increases with distance from the coast. In Georgia, the change in suitability by 2090 is very small, but overall suitability is high.

We found in the policy analysis of the East Coast states, that direct policies for species were less common if an invasive species is not an immediate threat to the livelihood of the state's aquatic ecosystem. Based on this, it seems like New York, Maryland, and Virginia,are unlikely to update or further enforce new lionfish policies because there is not an immediate predicted threat from lionfish. However, the more southern states along the East Coast like North Carolina, South Carolina, and Georgia, may opt to expand lionfish specific policy strategies because there is a higher likelihood that lionfish will expand their populations in these states. These specific policy strategies can include the preventative strategies like "Illegal to Release Invasive Species Alive" and "Illegal to Transport, Sell, or Introduce Without Permit" strategies, as well as the main direct strategy of "Open or Unrestricted Harvest Allowed". These states could apply many of the same policies that are already present for other aquatic invaders, but applied to include lionfish in particular, as illustrated in Table 8.

7.5 Project Limitations and Future Directions

While our projections offer valuable insights into potential range expansions, several additional limitations warrant consideration in future work. First, our models primarily rely on abiotic environmental constraints (temperature and salinity) and do not account for biotic interactions, such as prey availability, native predation, or competition, which could further restrict lionfish establishment. Second, predicting distributions decades into the future inherently assumes niche conservatism—the idea that the lionfish will not biologically adapt to colder thermal tolerances over time. Finally, while our environmental data adjustments improved the representation of broader oceanographic shifts, near-shore estuarine dynamics in regions like the Chesapeake Bay involve highly complex, localized hydrography that global models may still under-resolve. Future analyses should incorporate higher-resolution regional hydrodynamic models and dynamic biotic variables to reduce these uncertainties and provide a more comprehensive assessment of invasion potential.

Another limitation of our ecological niche modeling is the inherent bias in the lionfish occurrence data that we used. As GBIF data is primarily from coral reef surveys and human observations from iNaturalist, it contains a strong bias towards coral reefs, coastlines, and shallow waters where divers and researchers are likely to spot lionfish (Global Biodiversity

Information Facility, 2024). As such, the true distribution of lionfish is not readily apparent, as lionfish may be more prevalent in deep waters and noncoastal water that are not often surveyed. A careful method of removing this coastline bias, or accounting for this bias when training an ecological niche model, may result in more accurate characterization of potentially suitable lionfish habitat.

We also could explore alternative databases that provide more detailed species occurrence data, such as the OBIS-SEAMAP database. As of 2009, OBIS-SEAMAP already possessed more than 2.2 million observations coming from over 230 datasets, with exponential growth in size (Halpin et al., 2009). Another major advantage of OBIS-SEAMAP is that it includes sampling effort information, which could provide insights on which areas were searched but with no species observed (Halpin et al., 2009). This feature could be a potential alternative to our randomly generated species absence data. Moreover, the newer version of OBIS-SEAMAP2.0 provides even more functionalities. It includes possible support of new data types such as acoustic location data, interactive photo-ID data, advanced telemetry data, and integration with ecological models (Halpin et al., 2009).

There are other techniques in ecological niche modeling that could be used to build upon the results and methodology of this thesis. For example, many environmental variables are highly correlated with each other. This can cause overfitting, since much of the data is duplicated when variables are highly correlated. As such, we suggest performing principal component analysis (PCA) on environmental variables. PCA has the capacity to reduce overfitting by capturing correlation in separate variables. Furthermore, our shifted ocean data has many uses beyond ecological niche modeling for lionfish. We recommend using this data to model the projected habitat suitability for other reef-dwelling species.

Finally, we also suggest that future work should model the uncertainty of our ecological niche modeling results. Uncertainty in ENMs can derive from the data, the model training, and the model validation (Warren et al., 2025). As the final aim is to use niche modeling to inform policy decisions, understanding the uncertainty of our results is very important and careful consideration is needed for using these types of analyses for specific management decisions.

With respect to our policy analysis, the original goal for the policy sub-team was to develop a regional invasive lionfish policy across the East Coast in the case that lionfish migrate north due to climate change. Ecological niche modeling results, however, indicate only limited range expansion north in the near future, such that there is not an urgent need to have an intentional regional lionfish policy. Therefore, we do not suggest a tangible plan or product to be created and integrated into society. Another goal of the policy sub-team was to possibly align a policy strategy to the ENM results. For example, if lionfish had a high chance of suitability to live in the Chesapeake Bay in 2030-2040, the policy team had intended to draft a piece of legislation for Maryland that could be adopted to help mitigate the effects of lionfish invasion on the bay's ecosystem and economy. However, lionfish invasion in the Chesapeake Bay seems unlikely. Based on these outcomes, we instead developed the policy application table (table 8) to provide a more generalized roadmap in the case of a future invasion.

Following the policy application table, the policy strategies among the states may be utilized as a set of action items for states that have emerging aquatic invasive species. The applications of existing strategies allows for a systematic approach toward invasive species management while taking into account different nuances in the invasive species. For example, some invasive species can be hunted for sport like Blue Catfish, whereas other species like Zebra

Mussel cannot be consumed and must be disposed of, such that these two different species require different arrangements of the policy strategy "Open or Unrestricted Harvest Allowed".

Also, before considering any type of policy application to lionfish, labeling the species as "invasive" can be very beneficial. The acknowledgement of lionfish as an aquatic invasive species opens the door to preventative measures and proactive management in which lionfish receive more attention and funding. Just by this policy strategy alone of "Specifically labels aquatic species as invasive," lionfish and other invasive species have made the step to be involved in aquatic invasive species state policy, and have the potential to be further managed to meet the state's needs.

Our findings emphasize the need for adaptive and forward-looking management strategies to address the growing threat of invasive lionfish under climate change. While ecological niche modeling suggests that the Chesapeake Bay remains unlikely to support permanent lionfish populations, increasing habitat suitability in nearby coastal waters indicates a rising regional risk that warrants proactive intervention. To guide these responses, it could be useful to apply the Resist–Accept–Direct (RAD) framework, which is a decision-making framework developed to respond to ecosystem transformations driven by climate change and other stressors. The resist step focuses on maintaining or restoring ecosystems to their current or historical conditions (Climate Adaptation Science Centers, 2023). In the context of lionfish, this supports strong preventative policies in regions like the Chesapeake Bay, where establishment of a lionfish population in the near future is still unlikely. Strategies such as expanding public education campaigns that align with teaching what lionfish are and how they are invasive. The accept step recognizes that some ecological changes are unavoidable or impractical to prevent, allowing ecosystems to shift (Climate Adaptation Science Centers, 2023). In areas where lionfish are already widespread or highly likely to expand particularly in southern coastal waters management should prioritize mitigation rather than eradication. This includes continued harvesting efforts including more support and incentives for Lionfish Derbies. The direct step involves actively shaping ecosystem change toward a desired future condition (Climate Adaptation Science Centers, 2023). For lionfish management, this includes investing in multi-state policy efforts for a regional lionfish policy. The RAD framework considers a broader range of strategies rather than focusing solely on resistance. Applying this framework to lionfish policy enables region-specific responses that reflect ecological realities, feasibility, and long-term goals.

By pairing ecological niche modeling with the creation of aquatic invasive species policy, this sets a standard where proactive policy is supported by predictive research instead of enacting policy in response to an issue. Using ENM research to support proactive policy decisions as opposed to only using responsive policy based on given information provides more context to the issue at hand of invasive lionfish as well as keeping the policy up to date on lionfish activity. Overall, research-based policy is a more responsible and active way to approach an aquatic invasive species that can also be administered to other forms of environmental policy.

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Appendix A. Physical Oceanography and Climate Change

Anthropogenic climate change is fundamentally altering the physical oceanography of the global ocean, primarily through surface warming and increased stratification. Numerical modeling reveals that ocean surface warming significantly intensifies upper-layer currents across approximately 77% of the global ocean (Peng et al., 2022). This acceleration increases the mean kinetic energy in the upper 200 meters of the ocean by roughly 21% (Peng et al., 2022). This acceleration is predominantly driven by increased density stratification rather than wind stress; enhanced stratification strengthens vertical shear and accelerates surface currents while causing a corresponding deceleration at depth (Peng et al., 2022). These types of physical disruptions have been observed in the North Atlantic as increased Arctic freshwater export alters salinity and stratification, and these changes can then drive ecological regime shifts and biogeographic expansions of boreal plankton species (Greene et al., 2008).

Real-world ocean behavior frequently deviates from simplified theoretical expectations of climate-driven current intensification. For instance, observational data from the Agulhas Current reveals that warming-driven changes in wind systems have not increased the current's total volume transport (Beal & Elipot, 2016). Instead, the current has widened over time due to wind energy driving increased turbulence and eddy formation rather than enhancing the mean flow itself (Beal & Elipot, 2016). Similarly, in the southwest South Atlantic Ocean, the Brazil Current has intensified and shifted poleward due to the widening of the Hadley cell, creating a significant ocean warming hotspot that is actively shifting the distribution of commercially important marine species (Franco et al., 2020). These non-linear dynamics and boundary effects highlight the immense complexity of forecasting marine ecosystems under changing hydrodynamic conditions.

In the North Atlantic, the Atlantic Meridional Overturning Circulation (AMOC) plays a pivotal role in global heat transport and the oceanic current physics of the region. However, it is projected to undergo significant weakening (Schleussner et al., 2014). Probabilistic assessments under the high-emissions RCP8.5 scenario project a median AMOC decline of 38% by the end of the century (Schleussner et al., 2014). The slowing of this deep-water circulation alters the separation of western boundary currents, leading to profound physical changes in the Gulf Stream. Over the past two decades, autonomous observations have documented a noticeable lateral shift of the Gulf Stream toward its cooler, shoreward side at a rate of approximately 6 kilometers per decade (Todd & Ren, 2023). This lateral movement coincides with intense surface warming rates of 0.05 to 0.07 degrees Celsius per year and a vertical deepening of the current structure (Todd & Ren, 2023). Long-term monitoring from commercial vessels corroborates these trends, identifying a northward shift of the Gulf Stream's path by approximately 50 kilometers since the early 1990s, alongside intense upper-layer warming extending down to 750 meters (Andres, 2020).

In addition to the Gulf Stream, the Labrador Current is a critical driver of thermal regimes along the Mid-Atlantic Bight, directly influencing the coastal and estuarine temperatures of the Chesapeake Bay. This cold, southward-flowing boundary current typically acts as a thermal buffer along the continental shelf. However, under progressive climate change, increased freshwater export from Arctic melting is fundamentally altering the subpolar gyre, leading to a projected weakening and northward retreat of the Labrador Current (Claret et al., 2018; Saba et al., 2016). When this "cold water faucet" retreats, it allows warm, highly saline Gulf Stream waters to intrude onto the continental shelf, exacerbating marine heatwaves and driving accelerated warming anomalies along the Mid-Atlantic coast (Pershing et al., 2015). While these dynamics are ecologically critical for near-shore habitats like the Chesapeake Bay, modeling them poses severe technical challenges. Unlike the Gulf Stream, where uniform spatial shifts can roughly approximate offshore boundary current relaxation, the Labrador Current's influence is mediated by highly complex, localized interactions involving shallow shelf bathymetry, mesoscale eddies, and estuarine outflow. Consequently, there is currently insufficient high-resolution predictability to reliably construct a post-processing spatial adjustment algorithm for the Labrador Current without executing full, computationally intensive hydrodynamic re-modeling.

Despite these well-documented shifts, representing these large-scale spatial patterns accurately remains a significant challenge for modern climate models. Evaluations of large ensembles of climate models reveal systematic discrepancies between modeled predictions and observed trends, suggesting that models may poorly represent ocean-atmosphere dynamics or underestimate natural multi-decadal variability (Wills et al., 2022). While advanced deep learning approaches—such as neural networks predicting surface currents from satellite variables or the OceanNet framework mitigating autoregressive errors—are demonstrating success at forecasting mesoscale ocean currents and eddy shedding at reduced cost compared to numerical models (Sinha & Abernathey, 2021; Chattopadhyay et al., 2024), these high-resolution dynamic forecasts are not typically integrated into long-term global climate datasets used for ecology.

For marine macroecology, Bio-ORACLE v3.0 represents a substantial upgrade over its predecessors by delivering fine-resolution decadal climatologies derived from CMIP6 Earth System Models under Shared Socioeconomic Pathway (SSP) scenarios (Assis et al., 2024). This multi-model ensemble provides a robust baseline product for correlative ecological niche modeling by computing interpolated anomalies at the native resolution and adding them to high-resolution present-day baselines. This technique is known as the change-factor or delta method (Assis et al., 2024). However, while the change-factor method is suitable for representing broad, forced changes in mean atmospheric and thermodynamic fields, it has structural limitations for simulating movement (Assis et al., 2024). Because the downscaling process simply adds an anomaly field to a stationary grid, it inherently captures large-scale circulation changes but cannot reconstruct the dynamic features of Lagrangian transport, such as eddy shedding, narrow current meanders, and lateral shifts (Assis et al., 2024). Therefore, while Bio-ORACLE v3 supplies essential velocity and thermodynamic fields, it remains insufficient when an ecological research question depends on where and when water travels (Assis et al., 2024). To accurately project future biological range expansions in highly dynamic boundary currents like the Gulf Stream, applying supplementary spatial shifting algorithms to correct for these unmodeled oceanic circulation changes is a necessary methodological intervention (Assis et al., 2024).

Our modeling framework places Sea Surface Temperature (SST) and surface current velocity among the primary environmental drivers of lionfish invasion potential. While the AMOC is a three-dimensional system involving deep-water formation, the ecological relevance of the lionfish invasion is largely confined to the upper ocean mixed layer. Lionfish disperse during a pelagic larval phase lasting 20 to 35 days, during which they are passively transported by surface currents (Ahrenholz & Morris, 2010). Furthermore, their survival in an expanding northern range is strictly limited by minimum winter isotherms, specifically a 10 degrees Celsius lethal limit (Kimball et al., 2004). This biological constraint is imposed almost exclusively by surface thermodynamics rather than benthic conditions on the shallow continental shelf. Oceanographically, the Gulf Stream is a surface-intensified western boundary current, and

Global Climate Models (GCMs) consistently project that the strongest warming signals and velocity shifts will occur in the upper 200 meters due to enhanced thermal stratification, which decouples the surface flow from the slowing deep-water return flow (Peng et al., 2022).

When parameterizing these projections, a critical distinction must be made between the volume transport of the AMOC and the spatial trajectory of the Gulf Stream Extension. While the aggregate AMOC is projected to weaken by 34% to 45% under the SSP5-8.5 scenario (Weijer et al., 2020), this weakening reduces the Coriolis-driven separation of the current from the coast (Saba et al., 2016). Consequently, the slowing deep circulation paradoxically results in a shoreward migration and surface intensification of the Gulf Stream in the northwest Atlantic (Todd & Ren, 2023; Andres, 2020). Because standard GCM outputs often fail to resolve the sharp gradients of this boundary current (Saba et al., 2016)—resulting in a warm bias offshore and a cold bias onshore—a custom Lagrangian adjustment algorithm was developed for this Species Distribution Model (ENM). This algorithm physically shifts the current's path and corrects its velocity rather than relying on uniform, basin-wide warming artifacts.

The algorithm applies a post-processing transformation to Bio-ORACLE v3 SSP5-8.5 projections (Assis et al., 2024) to simulate structural changes in the northwest Atlantic. To capture the relaxation of the Gulf Stream's separation from the continental shelf (Saba et al., 2016), a systematic coordinate transformation is applied to both scalar and vector fields. The Lagrangian displacement is defined by the equation:

$Raster_{adj}(x, y) = Raster_{raw}(x - \Delta x,\ y - \Delta y)$ where $\Delta x = \ - 0.5°$ represents a westward/shoreward shift, and $\Delta y = \ + 0.5°$ represents a northward shift. This displacement of approximately 50 to 70 kilometers, represented by the 0.5 degree shifts in the above equation and based on the projections by Andres (2020) and Todd & Ren (2023), effectively pushes the warm, high-velocity core of the Gulf Stream onto the continental shelf and slope (Andres, 2020; Todd & Ren, 2023). This method preserves the internal physics of the current, including its width, meanders, and thermal gradients, while correcting its geographic location to match high-resolution projected anomalies.

Handling the directional data of these currents presented a significant technical challenge, as Bio-ORACLE v3 provides current data in terms of magnitude (speed) and direction (degrees). Initial attempts to process direction as a scalar variable failed due to the circular nature of angular data, where the arithmetic mean of 359° and 1° erroneously reverses the current to 180°. To preserve the physical integrity of the flow during the shift, the algorithm utilizes a decomposition-shift-recomposition workflow (Emery & Thomson, 2014). Raw speed (S) and direction (θ) are first converted into Cartesian velocity components (u, v) using the formulas: $u = S \cdot sin(\theta)$ and $v = S \cdot cos(\theta)$.

The Lagrangian shift is then applied independently to the u and v rasters. Following this spatial shift, the algorithm accounts for surface intensification. Despite the overall AMOC slowdown, surface Mean Kinetic Energy (MKE) and Eddy Kinetic Energy (EKE) are projected to increase by approximately 21% in the Gulf Stream region due to increased thermal stratification (Peng et al., 2022). This energy increase is parameterized as a velocity multiplier, calculated as $|V|_{adj} = |V|_{raw} \times 1.10$. This 10% increase in velocity magnitude corresponds to a 21% increase in kinetic energy, aligning with theoretical consensus without requiring computationally expensive hydrodynamic re-modeling (Peng et al., 2022). Finally, the adjusted components are recombined into a scalar surface speed variable for the model using the formula $Speed_{final} = \sqrt{(u'_{shifted})^2 + (v'_{shifted})^2}$. This ensures that the directionality of the flow is implicitly shifted along with its magnitude, maintaining the correct vector physics required for larval transport simulation. To avoid instantaneous climate change, the algorithm applies a linear time-step interpolation across decadal time slices from the 2030s to 2090s. The adjustments are defined as a function of time t, relative to a 2020 baseline and a 2100 target, where progress is calculated as $Progress(t) = \frac{t-2020}{2100-2020}$. The shift distance D and velocity multiplier M for any given decade are subsequently scaled by this progress metric using the equations $D(t) = D_{max} \times Progress(t)$ and $M(t) = 1.0 + (0.10 \cdot Progress(t))$.

This temporal scaling ensures a smooth, continuous migration of the Gulf Stream front, allowing the ENM to project a biologically realistic rate of range expansion for the lionfish. Furthermore, the algorithm deliberately avoids applying latitude-dependent velocity gradients to prevent artificially accelerating the subpolar gyre, which contradicts the established “Warming Hole” phenomenon driven by the North Atlantic Dipole. Finally, the shifted layers are not subjected to Gaussian smoothing or noise reduction filters. Because lionfish are an opportunistic species that utilize mesoscale eddies for transport, smoothing the data would artificially homogenize these high-velocity features.

While this methodology provides a pragmatic spatial adjustment for Ecological Niche Modeling, it is crucial to acknowledge the immense uncertainty surrounding future projections of the AMOC and Gulf Stream. Recent literature highlights drastically conflicting trajectories for these hydrographic systems: some observational constraints imply that future AMOC weakening will be extremely limited (Bonan et al., 2025), whereas other advanced models suggest a tangible probability of an AMOC collapse onset before the end of the twenty-first century (Dijkstra & van Westen, 2026). Furthermore, abrupt Gulf Stream path changes have been identified not just as a symptom, but as a potential precursor to an AMOC collapse (van Westen & Dijkstra, 2026). Given these profound uncertainties, simulating exact future oceanographic states is a monumental challenge. Because the primary focus of this project lies in spatial ecology and environmental policy, we recognize the inherent limitations of applying post-processing kinematic shifts to complex boundary currents. Developing true predictive oceanography requires executing formal numerical modeling frameworks, which typically fall under the purview of dedicated Atmospheric and Oceanic Science (AOSC) methodologies. However, within the scope of this ecological assessment, attempting to parameterize the Gulf Stream's documented shoreward influence provides an important improvement over relying solely on static, unadjusted climate projections.