Quantifying the Role of Rising Sea Temperatures in the Northward Spread of *Fistularia commersonii* in the Mediterranean Between 2000–2010: A Statistical Analysis Across Lebanon, Turkey, Greece, Italy, France, and Spain

Research Question: How does the rate of sea surface temperature (SST) increase correlate with the invasion speed of *Fistularia commersonii* along the northern Mediterranean route (Lebanon, Turkey, Greece, Italy, France, and Spain) from 2000 to 2010, and what does this reveal about climate-driven marine biodiversity shifts?

Word Count: 3753

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1. Introduction

The Mediterranean Sea has experienced significant changes over the years as invasive non-native species have increased, driven by climate change and human activities. *Fistularia commersonii* (The Bluespotted cornetfish) has become one of these extremely invasive species since its increase in its range in the Mediterranean since its introduction in 2000 and the continuing decades. *Fistularia commersonii* which is originally from the Indo-Pacific made its way into the Mediterranean through the Lessepsian migration and the Suez Canal. Since then, it has spread rapidly all over the Mediterranean; across the eastern, western, and central sectors. Unexpected success in this invasion raises critical environmental and ecological worries that cause its rapid spread.

Invasive species are recognized as one of the leading causes of biodiversity loss, which destroys ecosystems by altering food webs, surpassing native species, and changing ecological balances. Some environmental changes have largely driven the invading of *Fistularia commersonii* and other invasive species in the Mediterranean Sea. One of the primary drivers of its spread is the rising sea surface temperature (SST) which is a direct cause of climate change. Because of climate change, the Mediterranean Sea conditions have become favorable to species like *Fistularia commersonii.* The process of non-native species invading stable populations and surviving in regions where they previously couldn't survive is called tropicalization. Climate change is one of the biggest environmental issues worldwide and one of the biggest environments being affected by it is marine ecosystems. Rising global temperatures have also led to rising sea surface temperatures (SST) which can lead to different oceanic conditions such as different current patterns, salinity levels and ocean acidification and biodiversity distributions. Since climate change is expected to continue altering marine ecosystems, there is an urgent need to study climate-driven marine invasions within an environmental and societal context.

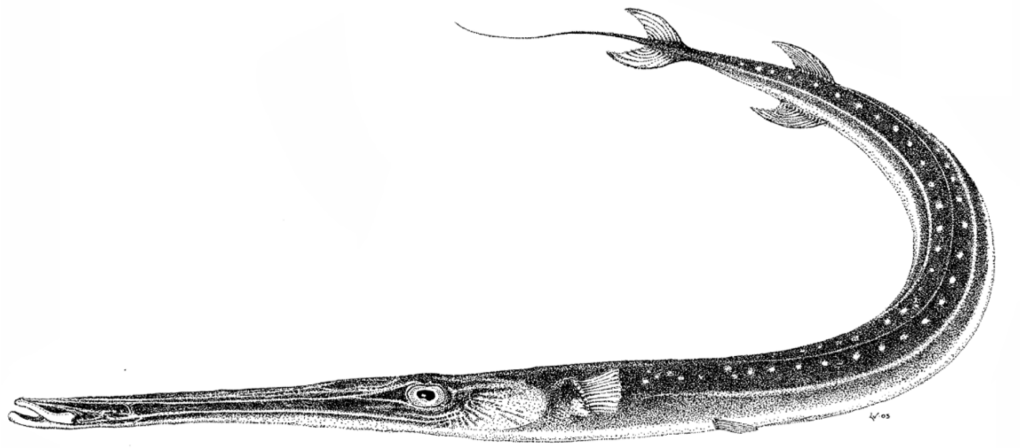
By examining sea surface temperature trends and the species' expansion timeline, this study will assess whether warming waters played a significant role in driving its spread. Because the Mediterranean Sea is going through tropicalization, understanding how climate change influences the rate of *Fistularia commersonii'*s invasion can improve in future predicting models and sustainable strategies to manage future marine invasions. This essay aims to analyze the relationship between climate change and the rate of *F. commersonii* invasion in the Mediterranean from 2000 to 2010.

1.1 Background Information

1.1.1 Biology of the *Fistularia commersonii*

The biometric, biological, and fisheries studies of *F. commersonii* population in the Mediterranean waters are essential to assess the studies of this newly established population. *F. commersonii* is an Indo-Pacific and Red Sea species. This species is a Lessepsian migrant which has spread over the years with a wide geographical distribution. It is a long, slender fish with an average of 107.5 in length. It has a tubular snout which is adapted for ambush predation. Its body has a brownish to olive dorsal side and a white ventral side, with rows of blue markings dots down its back. It has short and flexible spinules on its pectoral fins which makes it a highly efficient predator. It primarily feeds on small fish and crustaceans. Because of this, it basically competes with native Mediterranean predators. Additionally, it has a pelagic larval stage helps it travel through long ocean currents, colonize new territory, and leave habitats that has become unsuitable for them. The species also have a natural reproductive adaptability, which enables them to adjust their spawning periods to align with the Mediterranean's environmental conditions. Because of this, they can expand their population in the new habitats. The species' high fertility has increased their population growth and therefore increased the pressure on native populations. This resulted in a significant biodiversity loss and a change in community dynamics. Because of their fast growth, their ability to adapt easily and the lack of native predators in the Mediterranean the species was able to form a strong population with its biological characteristics, making it one of the worst invasive fish species in the Mediterranean.

Figure 1: *Fistularia commersonii* From the Central Mediterranean (Azurro et al. 2004).



1.1.2 The Lessepsian Migration & Introduction to the Meditarranean

The start of the invading of the *Fistularia commersonii* into the Mediterranean Sea is a result of the Lessepsian Migration which is an event that occurred when the marine species entered the Mediterranean Sea through the Suez Canal. The Suez Canal is an artificial pathway between two marine environments. Initially, most species couldn't pass through the canal because of the hypersaline conditions but over time the salinity levels equalized with the sea water coming from both the Red Sea and the Mediterranean Sea. This increased the number of the foreign species which established populations in the Mediterranean Sea making the species' one of them. *Fistularia commersonii* was first recorded in the Mediterranean in 2000

(The exact beginning of colonization of a particular Lessepsian migrant is difficult to determine. However, in the case of a species with a conspicuous external appearance such as *F. commersonii*, a relatively large and elongated fish, it is very likely that they were discovered a very short time after arrival to the new region.), marking the beginning of its fast invasion across multiple regions. While the introduction of *Fistularia commersonii* is largely attributed to the Lessepsian Migration, rising sea surface temperatures may have played a role in making the Mediterranean more hospitable for tropical species.

1.1.3 Climate Change and Their Role in Fistularia commersonii's Spread

Since the early 1980s, the Mediterranean Sea has been warming at approximately 0.4 °C per decade, (which is faster than the global ocean average) which has contributed to tropicalization. The rising temperatures have removed a thermal barrier preventing the species' survival. This resulted warm water species like the Bluespotted cornetfish from tropical regions to successfully invade temperate ecosystems. Because of the adaptation of the species in the Mediterranean waters, it can now spawn in unfamiliar conditions to their biology. Furthermore, the cold-water native species reproduction has been in a decline because of rising sea temperatures. This reduces competition for the Bluespotted cornetfish and allows it to dominate new habitats.

1.2 Research Question: How does the rate of sea surface temperature (SST) increase correlate with the invasion speed of *Fistularia commersonii* along the northern Mediterranean route (Lebanon, Turkey, Greece, Italy, France, and Spain) from 2000 to 2010, and what does this indicate on climate driven biodiversity shift?

1.3 Hypothesis

1.3.1 Null Hypothesis (H_0)

H_0: The invasion of *Fistularia commersonii* in the Mediterranean Sea has no significant relationship or correlation with rising sea surface temperatures (SST). The species' invasion occurred independently from climate driven temperature changes and any observed changes in species distribution and population dynamics are due to other environmental fluctuations.

1.3.2 Alternative Hypothesis (H_A)

H_A: The invasion of *Fistularia commersonii* in the Mediterranean Sea has a significant relationship and correlation. This suggests that warmer waters had an impact on its spread and facilitated its northward spread, indicating a climate driven expansion pattern.

1.4 Variables

1.4.1 Independent Variable

The independent variable in this study is sea surface temperature changes in each invasion location in years leading up to the species' arrival in the Mediterranean through 2000-2010, measured in °C. By taking regional differences in baseline temperatures in consideration, the study will have a clearer analysis of whether warming trends influenced the species' spread. The data will be collected through satellite data and historical climate records.

1.4.2 Dependent Variable

The primary dependent variable in this study is the invasion timing which is measured by the year *F. commersonii* was first recorded at each location. Additionally, the rate of spread (km per year) is included to quantify how quickly the species expanded across the Mediterranean. This is calculated with the distances between invasion locations and the time intervals between recorded invasions.

1.4.3 Controlled Variables

Table 1: Controlled Variable Table

Controlled Variable	Significance	How to Control
Invasion Route	The invasion route ensures the consistency of the study by analyzing only one pathway of the spread.	Only data from Lebanon, Turkey, Greece, Italy, France, and Spain is used.
Time Period (2000-2010)	By choosing the same time period this range helps in avoiding uncertainty caused by long term changes in SST.	SST and invasion data are only collected for this 10-year period.
Years Used for SST Trends	The time period chosen standardizes temperature trend calculations.	SST trends are calculated based on the three years before invasion at each site.
Definition of Invasion Timing	This ensures comparability of spread rates between locations.	Invasion timing is recorded based on the first official scientific report.

2. Methodology

2.1 Method Development

Selection of the Variables

Before the chosen variables right now, I had decided on different ones which were population density of *F. commersonii* and changes in native fish populations after the invasion. These variables did not work because of the lack of data on specific and precise population numbers and data on fish numbers. After researching more on the fish and what I could analyze on my study, I decided on sea surface temperatures and the rate/time of spread as my variables. There was available and reliable data of the SST's between 2000-2010's of the locations I chose and I could easily find the rate of spread with the help of mapping applications, mostly Google Maps.

Selection of the Countries

While I was researching on the pathways on which *F. commersonii* spread, I came across a map that showed the pathways the species followed in the invasion, dividing them as the north pathway and the south pathway. I chose the north pathway to base my extended essay on due to the fact that there were no reliable/available data of the SST's of the countries in the south pathway. Additionally, the route *F. commersonii* followed in the south pathway had a big range, and determining the exact pathway would conclude in a big uncertainty in calculations.

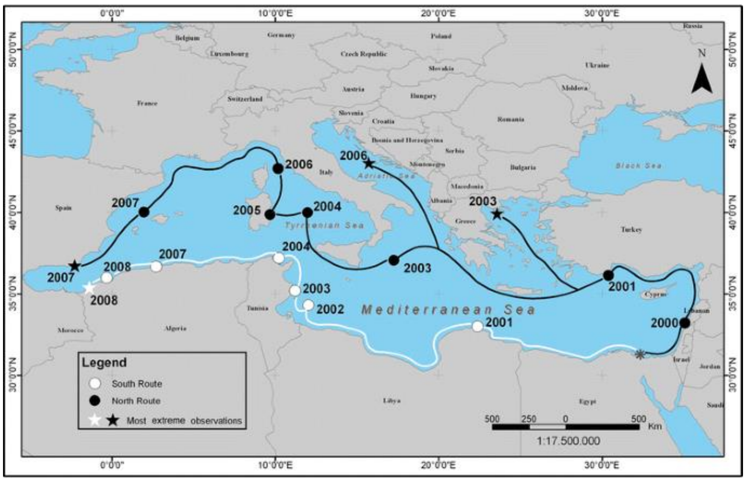
Selection of the Time Frame and Years

The time frame chosen in this study was chosen based on the invasion speed of the species during this time period. The species entered the Mediterranean through the Suez Canal in 2000. This time frame contains a critical phase of the invasion.

Selection of the Species

I chose *Fistularia Commersonii* as the species choice in this study because of a few factors. My main reason in choosing it is because it is the most well documented Lessepsian migrants there are. Anoother reason why I chose this species is because it has had a very fast invasion across the Mediterranean. This factor made the species ideal for a study with a defined time frame. Lastly, because it is a top predator, it makes it easy to study the ecological causes of its invasion.

Figure 2: Centroids of Records (circles) and Most Extreme Observations (stars) of *F. commersonii* in the Mediterranean Sea with a Reconstruction of the Chronology of the Invasion (Azzurro, E., Soto, S., Garofalo, G. et al. 2013)



The map highlights key regions where the species' presence has been recorded. It shows the pathways in the Mediterranean Sea where the species' invasion route is. This study focuses on the north route of the invasion of *F. commersonii*, specifically the coastal regions of the eastern Mediterranean and southern Europe, tracking the species' spread from Lebanon, through Turkey, Greece, Italy (South), France (South), and finally reaching Spain (South). This northward route follows the natural course of marine currents and coastal proximity with *Fistularia commersonii* migrating westward.

2.2 Procedure

1) Identify the locations along the northern pathway of *Fistularia commersonii*'s invasion in the Mediterranean Sea.
2) Gather sea surface temperature data for each invasion by researching satellite datasets or published climate records for the locations from 2000 to 2010 by focusing on the years before and during the invasion.
3) Gather the data of exact year of first establishment for each location.
4) Create a table for each invasion location, its invasion year and sea surface tempreature values to organize the data more clearly.
5) Calculate the sea surface temperature trends by finding the rate of temperature increase for each location before invasion.
6) Determine the distance between chosen locations with an online measuring tool (Google Maps).
7) Use the rate of spread formula to determine the average rate of distance of *F. commersonii.*
8) Use Pearson’s correlation coefficient to check the relationship between SST increase and invasion timing.
9) Determine if the sea surface temperature trends can predict invasion spread rate.
10) Compare the results with other possible influences (ocean currents etc.)

2.3 Evaluation of Ethical Issues and Risks

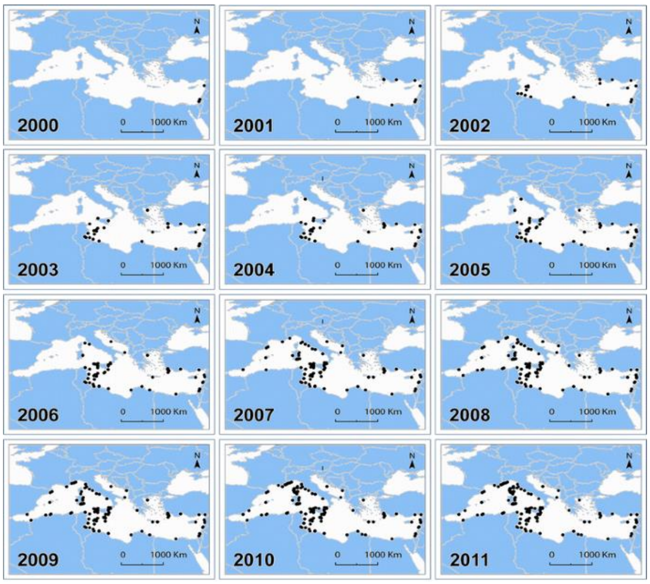
- Since this study relies on documented invasion records and SST levels, the risk of bias in data interpretation must be minimized, so I ensured the data sources are credible to avoid misrepresentation.

- The study assumes that *F. commersonii* was discovered shortly after its arrival. There may be uncertainties in reporting due to delayed scientific documentation. This is recognised as a limitation.
- The study's results are framed in a way that it is not being exaggerated in any form beyond what is supported by reliable data.
- The route from the countries have been calculated by Google Maps, which means there are minimal uncertainties in between the approximated distances of countries.

3. Case Studies and Data Analysis

3.1 Regional Analysis of *F. commersonii* Invasion

Figure 3: Cumulative Occurrences of *F. commersonii* in the Mediterranean Sea from December 2000 to October 2011. (Azzurro, E., Soto, S., Garofalo, G. et al. 2013)



This chronological spread map represents the invasion of the Mediterranean Sea over the 2000-2010 decade. The spread of *F. commersonii* shown in the map highlights the extensive speed of the invasion that started at the Suez Canal. It can be seen that only 3 years after the species first entered the Mediterranean they expanded through the Central Mediterranean. The rapid spread also indicates high adaptability throughout the whole Mediterranean Sea. Its continuous westward movement suggests that climate change and shifting oceanographic conditions could further accelerate its range expansion. After 7 years the species were seen in Western Mediterranean which implicates a sustained dispersal rate possibly facilitated by favorable ocean currents, ecological adaptability, and a lack of natural predators.

Table 3: Average Sea Surface Temperature (SST) (°C) Trends and Invasion Timeline of Fistularia commersonii in the Mediterranean (2000-2010)

Location	Invasion Year	SST 2000	SST 2001	SST 2002	SST 2003	SST 2004	SST 2005	SST 2006	SST 2007	SST 2008	SST 2009	SST 2010	SST Trend (°C/year)
Lebanon	2000	22.4	22.5	22.5	22.6	22.6	22.7	22.7	22.7	22.8	22.8	22.9	+0.05
Turkey	2001	21.3	21.3	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	+0.005
Greece	2003	19.2	19.1	19.0	18.9	18.8	18.7	18.8	18.9	19.0	19.2	19.4	-0.03
Italy	2005	18.5	18.6	18.8	19.0	18.7	18.9	19.1	19.2	18.7	18.9	19.0	+0.05
France	2006	18.8	19.0	19.2	19.5	18.9	19.2	19.3	19.5	19.0	19.2	19.4	+0.06
Spain	2007	19.5	19.8	20.1	19.7	19.5	19.9	20.0	20.3	19.6	20.2	20.4	+0.09

The table shows the average SST data annually for each of the locations under study. (Lebanon, Turkey, Greece, Italy, France, and Spain). from 2000 to 2010, along with the recorded invasion years for *Fistularia commersonii* in each country. The SST trend values indicate how the temperatures have varied annually, with most regions experiencing gradual increases in sea temperature, ranging from +0.005°C/year (Turkey) to +0.09°C/year (Spain).

3.2 Calculations & Rate of Spread

Now, to determine if the species' invasion speed is correlated with the increasing SST's, we need to calculate the speed of the species' spread by determining how far it has traveled between two locations over a given number of years. We already know when the species was first spotted in all the locations. The distance between two locations (this is an approximate distance) is measured along the coastlines (not open sea) to better represent the actual spread of the species in real-world conditions.

The locations chosen for approximation:

<u>Lebanon to Turkey:</u>

Starting Potint: Lebanon's southern coast, around Beirut. It was chosen because it is a common point for marine studies in Lebanon.

End Point: Antalya, located on Turkey's southern coast. It was chosen because of its role as a reference point for marine invasion studies in the eastern Mediterranean.

<u>Turkey to Greece:</u>

Starting Point: Antalya, Turkey's southern coast.

End Point: Athens, Greece. It was chosen because it is a representative coastal location in the central Mediterranean that aligns with the point of invasion and provides a clear pathway for the species' spread from Turkey.

<u>Greece to Italy:</u>

Starting Point: Athens, Greece.

End Point: Sardinia, Italy. It was chosen because it is a geographically important central Mediterranean hub where species often move westward.

Italy to France:

Starting Point: Sardinia, Italy.

End Point: Montpellier, France. It was chosen because of its location along the French Mediterranean coast, acting as a significant entry point for *F. commersonii* into France.

France to Spain:

Starting Point: Montpellier, France

End Point: Almería, Spain. It was chosen because it is part of the western Mediterranean and represents a region where the species made further inroads, a key area for marine species movement between the Mediterranean and the Atlantic.

Here is the rate of spread formula:

$$\text{Rate of Spread (km/year)} = \frac{Distance\ between\ two\ locations\ (km)}{Time\ (years)} \quad \text{(IntMath)}$$

Calculations:

1. Lebanon to Turkey:

- Distance: 350 km
- Years taken: From 2000 to 2001 = 1 year

Rate of Spread (km/year) = $\frac{350\ km}{1\ year}$ = 350 km/year

2. Turkey to Greece

- Distance: 562 km
- Years taken: From 2001 to 2003 = 2 years

  Rate of Spread (km/year) = $\frac{562km}{2\ years}$ = 281 km/year

3. Greece to Italy:

- Distance: 670 km
- Years taken: From 2003 to 2005 = 2 years

  Rate of Spread (km/year) = $\frac{670\ km}{2\ years}$ = 335 km/year

4. Italy to France:

- Distance: 320 km
- Years taken: From 2005 to 2006 = 1 year

  Rate of Spread (km/year) = $\frac{320\ km}{2\ year}$ = 160 km/year

5. France to Spain:

- Distance: 470 km
- Years taken: From 2006 to 2007 = 1 year

  Rate of Spread (km/year) = $\frac{470\ km}{1\ year}$ = 470 km/year

  Average Rate of Spread = $\frac{350\ +\ 281+\ 335\ +\ 160\ +\ 470}{5}$ = $\frac{1{,}596}{5}$ = 319.2 km/year

The rapid dispersal in some regions may suggest favorable environmental conditions. Conversely, slower spread rates may indicate ecological barriers or less suitable temperature conditions. The overall average rate of 319.2 km/year shows that while the species is expanding rapidly, local factors influence the speed at which it reaches new areas.

Now, to determine if there is a correlation between SST trends (°C/year) and spread rates (km/year), it is needed to perform a statistical analysis, which is Pearson’s correlation coefficient (r).

Pearson Correlation Coefficient Formula:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}$$

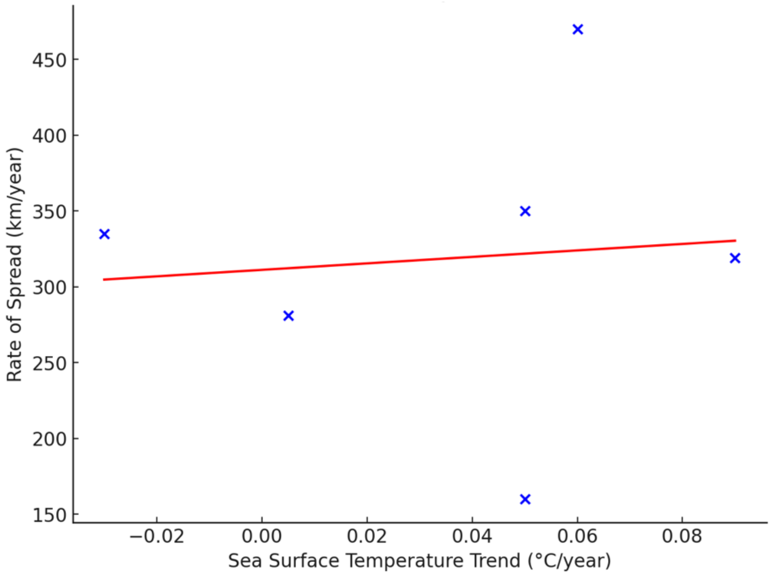
(Newcastle University)

r represents Pearson's correlation coefficient, X represents the SST trend (°C/year), Y represents the spread rate and n represents the number of data points. After we put them in place;

Table 4: Raw Data Table for Pearson' Correlation Coefficient

Location	SST Trend (°C/year)	Spread Rate (km/year)
Lebanon	0.05	350
Turkey	0.005	281
Greece	-0.03	335
Italy	0.05	160
France	0.06	470
Spain	0.09	470

Graph 1: SST Trends vs. Spread Rate of *F. commersonii* (Pearson r = 0.09, p-value = 0.86)



The plot shows the data points, and the red line represents a linear fit, it's nearly flat which reinforces the weak correlation.

Pearson's correlation coefficient (r): ~0.09

p-value: ~0.86

The results of the correlation coefficient suggest a very weak positive correlation (r = 0.09) between SST trends and spread rates. However, the p-value is 0.86 which indicates that this result is not statistically significant. This means that the observed correlation is likely due to random chance rather than an actual connection. SST increases were not a major driver of the species' swift invasion during the study period. This indicates that other factors such as ocean currents, biological adaptability etc. possibly had a bigger role in helping the species' invasion.

4. Discussion

It can be clearly seen that the findings of this study do not support the alternative hypothesis (H_A) which demonstrates that the statistical analysis showed a very weak, non-significant correlation between STT and the invasion speed of *F. commersonii* in the Mediterranean Sea. This means that temperature alone was not a primary driver of the species' westward f invasion from 2000 to 2010. Other historical data and case studies indicate that the invasion of *F. commersonii* could have been influenced by other various environmental factors. The fact that there were little to no natural predators for the species had a possible contribution to its establishment. Furthermore, the species' broad dietary preferences and flexibility in theirhabitat selection may have also improved its ability to thrive in new habitats. Additionally, it can be seen from the chorological maps and other case studies that the species' pace moving westward could be due to favorable ocean currents. While the statistical analysis indicates that STT may not be a direct driver, it is possible that temperature interacts with other factors like altering current patterns or habitat changes which may indirectly influence the species' invasion success. The invasion of the species shows the unpredictability of marina invasions and the complex nature of ecosystem dynamics (many factors such as human-caused habitat changes or species interactions could alter biodiversity). Although there is not a direct correlation between STT and the invasion, the findings still emphasize the need for long-term monitoring and management strategies to mitigate its impact.

4.1 The Risks and Impact Factors

Table 2: Overview of the Risks and Impact Factors

Category	Risk/Impact Factor	Explanation
Environmental Impact	Biodiversity Loss	The species prey on small pelagic and demersal fish, reducing population sizes and altering species composition.
	Trophic Cascades	The species predation on juvenile fish may create cascading effects in the food web.
	Habitat Degradation	*F. commersonii* could alter coastal and shelf habitats, affecting critical environments like seagrass meadows and rocky reefs that support other marine life.
Ecological Impact	Competition with Native Species	They compete with groupers, barracudas, and other piscivores for food resources, potentially reducing their survival chances. [6]
	Altered Predation Pressure	The absence of natural predators in the Mediterranean means *F. commersonii* could have a pressure on smaller fish species.
Climate Change & SST	Sea Surface Temperature Rise	Rising SST due to climate change may accelerate the spread of *F. commersonii.*
	Tropicalization of the Mediterranean	Warming waters in the Mediterranean could lead to the establishment of other tropical species and contribute to a broader shift in marine ecosystems.

5. Implications and Future Considerations (Evaluation)

The findings of this study suggest that the invasion speed of the species in the Mediterranean Sea was not directly driven by SST, however, despite the lack of direct correlation, temperature could still have influenced the invasion indirectly by altering marine ecosystem conditions' factors. Climate change can alter salinity levels, sea temperatures and current patterns which could make the Mediterranean Sea more hospitable to invasive species. For the future studies, adaptive management measures and global collaboration to prevent future ecological disruptions may be required. Additionally, the approximate invasion distances around the coasts of the locations chosen, with *F. commersonii* travelling over 1.400 km westward from the Suez Canal from 2000-2010, could have been an uncertainty factor. For future studies, it can be seen that it is better to work with more specified data. Another important consideration is the limited time frame of the analysis which is between 2000-2010. This time period only demonstrates the initial invasion surge, it may not represent the long term synamics of the species' potential cumulative effects of climate change. Future research consideration on using expanded datasets concluding multiple decades could clarify whether SST plays a more prominent role in the later stages of the invasion. Furthermore, another future consideration on invasive species in marine ecosystems is to acquire monitoring programs that include consistent fishery data collection**,** sighting documentation**,** and DNA barcoding could possibly improve the timely identifications' uncertainty in invasions.

6. Conclusion

The invasion of *Fistularia commersonii* into the Mediterranean Sea indicates a significant ecological shift driven by human activities. Particularly the creation of the Suez Canal which has facilitated Lessepsian migration was the one of the primary causes of the invation. Over the decade between 2000-2010 the species has had a rapid expansion through the regions of the Mediterranean Sea. Despite the weak non-significant correlation between sea surface temperature (SST) and the invasion speed, the species spread rapidly across approximately 1,400 km from 2000 to 2010, likely aided by favorable currents and the absence of natural predators**.** This also demonstrates the remarkable flexibility to adapt to different environmental conditions. While temperature may not have been a direct driver of the invasion, indirect factors influenced by climate change could have influenced the rapid spread of the species. *F. commersonii* since its invasion have had effects on significant disruptions in marine cosystems. These disruptions include changes in the trophic dynamics, competition with native species, and the possibility of a decreasing biodiversity. These effects show a need for long term solutions and management strategies for invasive species. One solution that will have a positive effect is long term and advanced monitoring is needed for new species. Early detection and rapid response (EDRR) of invasive species is much more effective than trying to control a widespread infestation. If it is too late for early action, targeted removal projects like controlled culling could help on reducing the populations of the invasive species. Furthermore, to restore the damaged habitats, habitat restoration projects such as replanting seagrass meadows or preserving coral reefs could support native species resilience and strengthen ecosystem defenses against invasive pressures. Ultimately, the case of *Fistularia commersonii* serves as a critical example of how human-induced environmental changes can drive biological invasions with far-reaching consequences. Regional cooperation among Mediterranean countries will also be critical in formulating united policies to address the larger issue of Lessepsian migration and invasive species management. Moving forward, proactive mitigation efforts and continued scientific investigation will be essential in managing this species and preserving the ecological integrity of the Mediterranean Sea.

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