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Climate resilience in aquaculture: A cluster analysis of Chinese coastal regional production and farming practices in the face of climatic shifts 2017–2021

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Abstract: This study conducts a comprehensive analysis of the aquaculture industry across 11 coastal regions in eastern China from 2017 to 2021 to assess their adaptability and resilience in the face of climate change. Cluster analysis was employed to examine regional variations in aquaculture adaptation by analyzing data on annual average temperatures, annual extreme high/low temperatures, annual average relative humidity, annual sunshine duration, and total yearly precipitation alongside various aquaculture practices. The findings reveal that southern regions, such as Fujian and Guangdong, demonstrate higher adaptability and resilience due to their stable subtropical climates and advanced aquaculture technologies. In contrast, northern regions like Liaoning and Shandong, characterized by more significant climatic fluctuations, exhibit varying degrees of cluster changes, indicating a continuous need to adjust aquaculture strategies to cope with climatic challenges. Additionally, the study explores the specific impacts of climate change on species selection, disease management, and water resource utilization in aquaculture, emphasizing the importance of developing region-specific strategies. Based on these insights, several strategic recommendations are proposed, including promoting species diversification, enhancing disease monitoring and control, improving water quality management techniques, and urging governmental support for policies and technical guidance to enhance the climate resilience and sustainability of the aquaculture sector. These strategies and recommendations aim to assist the aquaculture industry in addressing future climate challenges and fostering long-term sustainable development.

Keywords: aquaculture resilience; climate change adaptation; regional variability; sustainable aquaculture practices

1. Introduction

The escalation of climate change represents a defining challenge of the 21st century, profoundly affecting global ecosystems and various human activities (Mann and Gleick, 2015) Among the sectors experiencing acute impact is aquaculture, which plays a crucial role in global food security (Béné et al., 2016). This industry, inherently intertwined with environmental conditions, is confronting unparalleled challenges as the severity of the climate crisis intensifies (Baer and Singer, 2016). Climate change manifests as a tangible and immediate reality rather than a distant threat, characterized by increased global temperatures, altered precipitation patterns, rising sea levels, and more frequent and severe weather events (Tanner and Horn-Phathanothai, 2014). These climatic shifts pose complex, multifaceted challenges for the aquaculture sector, influencing water quality, disease prevalence, and the overall ecological balance that is vital for aquaculture productivity (Oyebola and Olatunde, 2019).

In this global context, China's role in aquaculture is pivotal (Xie et al., 2013). As the world's leading aquaculture producer, China accounts for approximately 60% of global aquaculture production, significantly influencing global trends with its practices, challenges, and responses to climate change (Reid et al., 2019). The vast scale and diversity of China's aquaculture are evident as it spans from densely populated coastal regions to remote inland areas, covering over 2 million hectares of aquaculture farms, which amplifies its vulnerability to climatic variations (Szuwalski et al., 2020).

China's aquaculture sector has experienced remarkable growth, with an annual increase of about 5%–8% in production over the past decade, propelled by technological advancements, supportive government policies, and increasing domestic and international demand (Yu and Liu, 2022; General Fisheries Commission for the Mediterranean, 2009). This rapid expansion, however, has been accompanied by significant environmental repercussions (Cavicchioli et al., 2019; Hishamunda and Subasinghe, 2003). For instance, the coastal provinces, which contribute over 70% of the country's marine products, face the brunt of escalating climate change impacts, including rising sea temperatures, increased frequency of extreme weather events, and sea-level rise (Ding et al., 2021). These factors, coupled with environmental degradation, pose a dual threat to the sustainability of Chinese aquaculture, challenging the industry's resilience and adaptive capacity (Lam et al., 2020).

The sector faces manifold challenges, including pollution from the overuse of feeds and chemicals, habitat destruction, and the depletion of natural fisheries (Desai and Radhakrishnan, 2003). These challenges are further exacerbated by both direct and indirect impacts of climate change, placing the Chinese aquaculture industry at a critical juncture where sustainable practices are becoming increasingly vital (Boyd et al., 2020).

In China, the repercussions of climate change on aquaculture manifest in both direct and indirect forms (General Fisheries Commission for the Mediterranean, 2009). Direct impacts are seen in changes to water temperature affecting species' metabolism and growth rates, as well as sea-level rise posing threats to coastal aquaculture infrastructure (Bricknell et al., 2020). Indirect impacts, such as altered rainfall patterns and increased extreme weather events, can cause flooding or droughts, disrupting operations and supply chains (Ghadge et al., 2019).

These impacts vary across different regions, leading to questions about why certain areas and aquaculture methods are more susceptible to climate change than others (Callaway et al., 2012). This variation underscores the need for detailed, region-specific analysis to understand the varying degrees of vulnerability and resilience within China's diverse aquaculture landscape (Peng et al., 2024).

Recent studies have shown a significant increase in the frequency, duration and overall intensity of oceanic heat waves surrounding Chinese waters since 1982 (Yuan and Chinese Academy of Sciences, 2023), and these extreme weather events have exacerbated the impacts of climate change on marine systems, leading to coral bleaching as well as significant losses to fisheries and aquaculture (Johnson et al., 2020). At the same time, changes in the physical and chemical environment of the oceans, such as increased temperatures and enhanced stratification, have led to significant changes in fish communities, as evidenced by a reduction in body size and an increase in the number of warm-water species (Wang et al., 2023). Seas around China are experiencing hypoxia and acidification, which pose a threat to the survival and reproduction of marine organisms, especially benthic organisms (Shi and Li, 2023). In addition, studies of nutrient concentrations in Chinese rivers between 1980 and 2018 show that total nitrogen pollution has increased over this period and is now considered a serious pollution problem in most areas (Zhang et al., 2023). Human activities and climate change are expected to have a significant impact on river nutrient salt concentrations in the future, especially in the Yellow, Huai and Hai Rivers (Li et al., 2023).

Despite the importance of understanding the impacts of climate change on aquaculture, current research often lacks the depth and specificity needed to address China's complex and varied aquaculture systems. There is a tendency in existing studies to generalize or oversimplify these impacts, overlooking the intricate interaction between local environmental conditions, specific farming practices, and socio-economic factors (Greenspan et al., 2017). This research gap impedes the development of effective strategies for adaptation and mitigation.

This study hypothesizes that the adaptability and resilience of aquaculture practices to climate change in China display significant regional disparities. Our research aims to dissect these disparities by examining the intricate relationship between regional aquaculture production, specific farming methodologies, and the multifaceted dimensions of climate change. Through a critical and comprehensive analysis, this study endeavors to answer key questions about differential vulnerabilities and adaptive capacities, aiming to provide vital insights for developing policies and practices that enhance the resilience of China's aquaculture sector in an ever-evolving climate landscape. Based on these premises, we are at the following research hypothesis:

Hypothesis (H1): The aquaculture industry in 11 coastal regions in China exhibits significant regional differences in adaptability and resilience to climate change. These differences can be identified through cluster analysis based on combinations of annual average temperature, annual extreme maximum/minimum temperatures, annual average relative humidity, annual sunshine hours, annual precipitation, and various aquaculture practices.

Hypothesis (H2): Within these regions, there are specific areas where the aquaculture environment shows unfavorable characteristics in response to climate change, leading to low efficiency and limited productivity. These unfavorable characteristics are likely related to specific combinations of regional climatic factors and aquaculture methods.

2. Materials and methods

2.1. Ward hierarchical clustering

Ward Hierarchical Clustering is a statistical method used to group data points into clusters based on their similarities (Murtagh and Legendre, 2014). Unlike other clustering methods, Ward's method minimizes the total within-cluster variance (Ward, 2016). At each step, the pair of clusters with the minimum between-cluster distance are merged (Kimes et al., 2017). This approach is particularly effective in identifying distinct, homogenous clusters within a heterogeneous dataset (Randriamihamison et al., 2020). Standardization of data by column was conducted before clustering to ensure uniformity of scale across different variables. This step is crucial in a dataset like ours, where variables differ in units and magnitude, to prevent skewed influence by any single variable.

Ward's method was chosen for several key reasons: 1) Suitability for diverse data (Posner et al., 1990): Our dataset's complexity, containing both climatic and aquacultural variables, necessitated a method capable of discerning subtle patterns within the data. Ward's method excels in this aspect. 2) Focus on homogeneity (Posner et al., 1990): The objective of our study was to identify clusters with high internal similarity. Ward's method is apt for this purpose as it minimizes within-cluster variance, thus enhancing the reliability of the cluster formation. 3) Robustness to outliers (Campello et al., 2015): Given the potential for outliers in aquacultural data, Ward's method offers the necessary robustness, ensuring our analysis is reflective of general trends rather than being biased by anomalies. 4) Standardization needs (Schaffer and Green, 1996): The different scales of the variables in our dataset necessitated standardization to allow equal contribution of each variable to the analysis. Our study employs Ward Hierarchical Clustering to discern patterns in climatic and aquacultural data across China's coastal regions, thereby addressing Hypothesis 1 (H1). This method is well-established in various research domains for its efficacy in identifying and grouping multivariate data based on similarity. Similar methodologies have been applied in environmental science and agriculture, where they have been used to analyze evolutionary adaptations to changing conditions. For example, Bouroncle et al. (2017) utilized cluster analysis to map the adaptive capacity and vulnerability of smallholder agricultural livelihoods in Central America, focusing on the potential impact of climate change on crop suitability and municipal adaptive strategies. Additionally, Gori Maia et al. (2017) investigated the impacts of climate conditions on agricultural production in the Brazilian Sertão, assessing how adaptive strategies might alleviate these effects. Their study combined climate and production data to evaluate the effectiveness of different strategies for small farmers, enhancing resilience against climate change. By adopting this method, our research aligns with these studies but innovates by applying it to the specific context of aquaculture, focusing on regional adaptability and resilience to climate change. This application is crucial for identifying specific regional challenges and successes in aquaculture, informing tailored strategies for sustainable development. We interpret the temporal stability of regions within clusters as indicative of consistent climatic conditions and potentially successful adaptation strategies, whereas shifts between clusters suggest significant climatic changes necessitating adaptive responses in aquaculture practices. To further validate these interpretations and address Hypothesis 2 (H2), we integrate case studies highlighting specific regional adaptations, thereby linking quantitative cluster analysis with qualitative insights into the industry's resilience and productivity challenges. Acknowledging the limitations of cluster analysis in isolating the effects of adaptation strategies, we propose complementing our findings with additional analytical approaches, such as time-series or econometric analysis, to draw more definitive conclusions about the aquaculture industry's adaptability and resilience to climate change.

2.2. Data set and variables

This paper investigates the aquaculture industry across 11 regions in mainland China: Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi, and Hainan (**Figure 1**). The selection of these regions is strategic due to their significant roles in China's aquaculture industry, both in terms of production volume and innovative practices. Collectively, these regions contribute to a substantial portion of China's total aquaculture output, embodying diverse aquaculture systems ranging from inland freshwater farming to coastal mariculture. For example, Shandong and Guangdong are among the top producers of seafood in China, contributing significantly to the country's aquaculture with their advanced mariculture and shellfish farming (Xu et al., 2022).

The diversity across these regions manifests in their varied geographic and climatic conditions, which range from the temperate zones in the north, such as in Liaoning and Hebei, to the tropical climates in the south, exemplified by regions like Guangdong and Hainan. This variation significantly influences their respective aquaculture practices and climate adaptation strategies, reflecting the distinct environmental challenges and opportunities each region faces. This geographical span allows for a wide range of aquaculture species and methods, from the cold-water species in Liaoning (Mugwanya et al., 2022) to the tropical species in Hainan (Edwards, 2015). The diversity is characterized by variables such as temperature ranges, precipitation patterns, and the type of aquaculture systems prevalent in each region (Heino et al., 2009) (e.g., pond aquaculture in inland areas, cage culture in coastal waters, and polyculture systems in the deltas (Gasalla et al., 2017)).

The choice of these regions allows us to examine the impacts of climate change on aquaculture in a comprehensive manner. For instance, the northern regions, with their temperate climate, face challenges like seasonal temperature variations affecting species (Weitzman and Filgueira, 2019), while the southern, tropical regions face issues such as sea-level rise and increased frequency of extreme weather events affecting shrimp and tilapia farming (Jiang, 2017).

Moreover, the prominence of these regions in aquaculture production reflects a variety in scale and farming methods, providing insights into the sector's adaptive capacities (Wang et al., 2020). For example, the extensive use of technology and modern aquaculture practices in Zhejiang and Jiangsu showcases advanced adaptive strategies such as automated feeding systems and integrated multi-trophic aquaculture, which may serve as models for other regions facing similar climatic challenges (Audigier et al., 2014; Hellberg and Chu, 2015).

By analyzing the aquaculture practices across these diverse climatic and geographic regions, we can better understand the industry's overall resilience and adaptability to climate change. This comprehensive approach, facilitated by cluster analysis, enables us to identify and compare the different adaptation strategies employed, thereby supporting our hypotheses concerning regional adaptability and resilience to climate change in China's aquaculture sector.

It's important to note that while these regions are pivotal in understanding the climate resilience of China's major aquacultural areas, the focus on coastal regions might limit insights into the challenges and adaptations in inland and lesser-known aquaculture regions of the country. The study employed a comprehensive dataset, encompassing both climatic and aquacultural parameters across various regions in China. Key indicators in this dataset included annual average temperature, extreme maximum and minimum temperatures, annual average relative humidity, annual sunshine hours, and annual precipitation. Additionally, the dataset detailed the areas dedicated to different aquaculture practices such as pond aquaculture, general net cage aquaculture, deep water net cage aquaculture, raft aquaculture, cage aquaculture, bottom seeding aquaculture, and factory aquaculture. Each type of aquaculture area was quantified to assess its prevalence and distribution across the regions studied, reflecting the diversity of aquaculture systems tailored to the local environmental conditions (**Table 1**). The choice of variables for our cluster analysis, including temperature, precipitation, relative humidity, and sunshine hours, was driven by their direct and indirect influence on aquaculture. Temperature and precipitation are crucial as they directly affect the physiological conditions of aquatic species and the aquatic environment. Meanwhile, variables like relative humidity and sunshine hours were included to capture the broader climatic conditions that influence aquaculture ecosystems, affecting everything from water quality to the prevalence of pathogens (Zhao et al., 2021). The data was collected over 5 years, enabling an analysis of temporal trends. Due to limitations in data acquisition, the study only covers aquaculture and fisherfolk engaged in aquaculture production in China. The statistical software deployed for this study was SAS JMP Pro16.

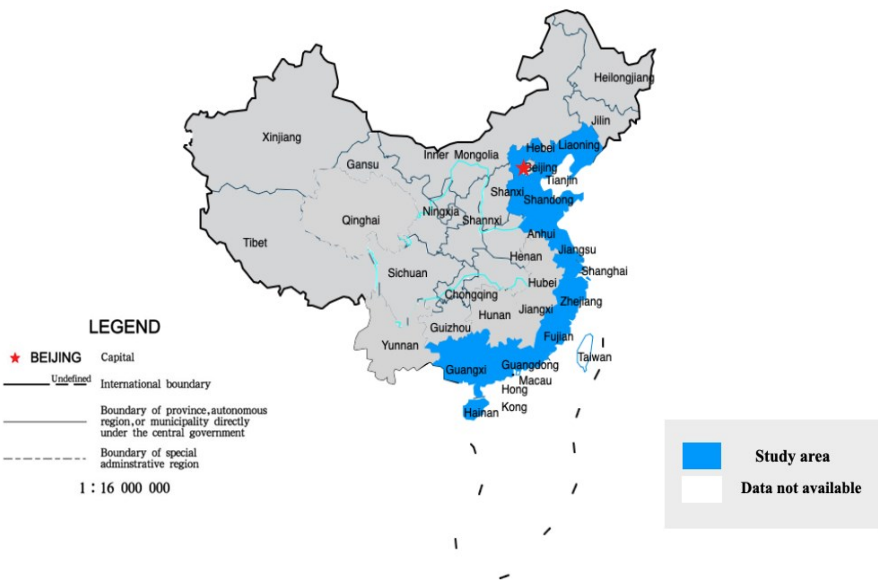


Figure 1. Studied Chinese coastal regions (China Map Publishing House, National Basic Geographic Information Center, 2024).

Table 1. Variable definition.

Variable	Description	Meaning and potential impact in aquaculture
AAT	Annual average temperature	Represents the mean temperature over a year, crucial for determining the overall climatic suitability for various aquaculture species. Warmer temperatures might accelerate growth, but also increase susceptibility to diseases.
AMaxT	Annual extreme maximum temperature	Indicates the highest temperature recorded in a year. Extreme heat can lead to oxygen depletion and stress aquatic organisms, potentially leading to higher mortality rates and altered metabolic rates.

Table 1. (*Continued*).

Variable	Description	Meaning and potential impact in aquaculture
AMinT	Annual extreme minimum temperature	Signifies the lowest temperature recorded in a year. Extreme cold can affect the survival and growth of species, particularly those not adapted to low temperatures. It might also slow down metabolism and growth, affecting annual yields.
AAH	Annual average relative humidity	Reflects the average moisture content in the air over a year. High humidity can influence evaporation rates and water quality, whereas low humidity might affect the water balance in aquaculture systems.
ASH	Annual sunshine hours	The total hours of sunshine per year impacts photosynthesis in aquatic plants and algae, which is critical for maintaining the ecological balance in aquaculture environments. It also influences water temperature.
AP	Annual precipitation	Measures yearly rainfall, crucial for water supply in aquaculture. Variations in precipitation can lead to changes in water levels, quality, and flow, all of which significantly impact aquaculture operations and the health of aquatic species.
PA	Pond aquaculture area	The area dedicated to pond farming reflects the prevalence of this traditional aquaculture method. Ponds' susceptibility to climate changes like flooding or drying can significantly impact overall production and sustainability.
GNA	General net cage aquaculture area	Represents the area used for net cage farming. This method's exposure to open water bodies makes it susceptible to changes in water quality and temperature, thus impacted by climate variability.
DNA	Deep water net cage aquaculture area	The area for deep-water cage farming indicates advanced aquaculture practices. These systems might face challenges such as varying water temperatures and oxygen levels at different depths, influenced by climate conditions.
RA	Raft aquaculture area	The extent of raft aquaculture, often used for shellfish and seaweed, highlights its importance in specific regions. These systems are directly exposed to climatic elements like sea surface temperature changes and storm surges.
CA	Cage aquaculture area	The area for cage aquaculture suggests intensive farming practices. These systems, while efficient, may face heightened risks from water pollution and temperature changes, potentially exacerbating disease outbreaks and environmental impact.
UA	Bottom seeding aquaculture area	Indicates areas practicing bottom seeding, essential for species like shellfish. These practices are directly impacted by seabed conditions and water quality, which can be significantly altered by climate change, affecting growth and survival of species.
FA	Factory aquaculture area	The area dedicated to factory or industrial aquaculture points to technologically advanced methods. These systems, while controlled, can face challenges like maintaining optimal conditions amidst external climatic changes and managing resource efficiency.

2.3. Analysis of data

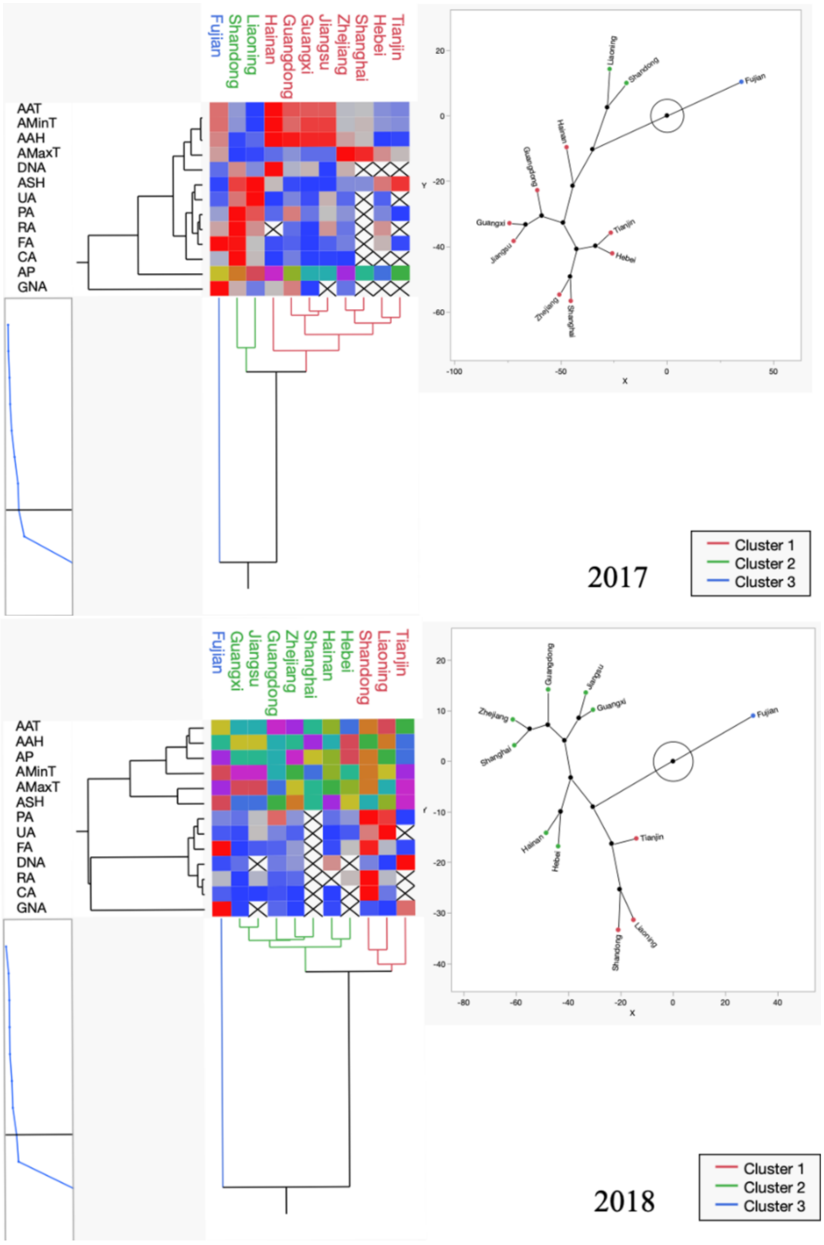
Prior to analysis, data preprocessing was meticulously conducted. We addressed missing values using Singular Value Decomposition (SVD), a method preferred for its ability to preserve the underlying data structure and intricate relationships more effectively than simpler imputation methods (Audigier et al., 2014).

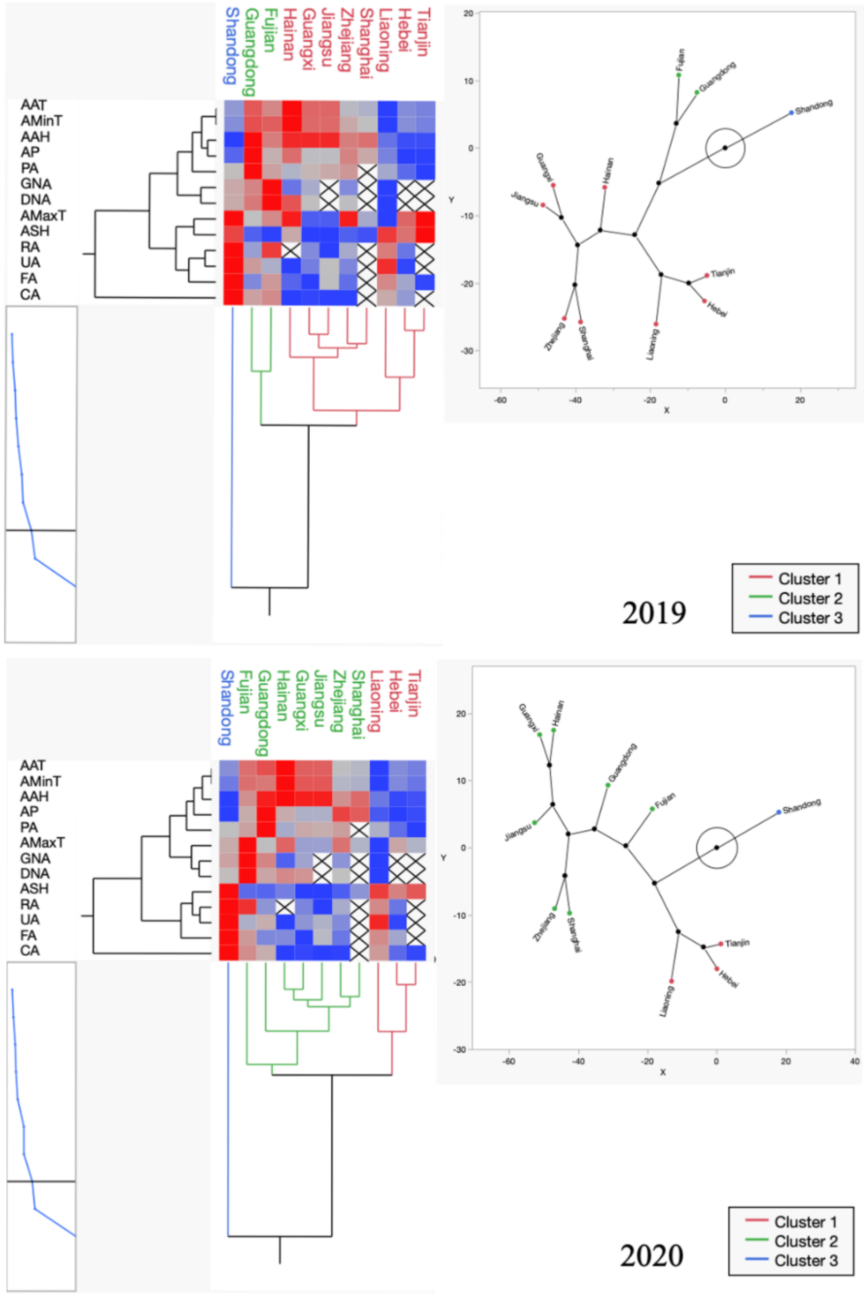
In our research, we apply cluster analysis as a methodological tool to discern and understand the adaptability and resilience of various regions in China to the impacts of climate change on aquaculture. This statistical technique organizes the regions into clusters based on similarities in their climate data, which includes metrics such as annual average temperature, extreme temperature variations, precipitation, and relative humidity, among others, collected between 2017 and 2021 (China Fishery Statistical Yearbook, 2018, 2019, 2020, 2021, 2022).

3. Results

Initially, we start by observe constellation plots (top row) (**Figure 2**): These plots visualize the 'distance' between regions—closer points indicate more similar climate and aquaculture characteristics. These help us see how closely related different regions are in terms of their response to climate change and aquaculture practices. For example, regions clustered close together in 2021 suggest similar conditions or adaptation strategies.

Dendrograms with heatmaps (bottom row) (**Figure 2**): The dendrograms, shown as inverted 'trees,' map out the structure of how regions are related, starting from individual 'branches' (regions) and joining together at 'nodes' (the points where lines intersect), indicating a grouping. The heatmaps below each dendrogram use colors to represent different clusters—each color corresponds to a group of regions with similar attributes, with red, blue, and green representing different clusters.




Shandong
Guangdong
Fujian
Hainan
Guangxi
Jiangsu
Zhejiang
Shanghai
Liaoning
Hebei
Tianjin
AAT
AMinT
AAH
AP
PA
GNA
DNA
AMaxT
ASH
RA
UA
FA
CA
Cluster 1
Cluster 2
Cluster 3
2019
Shandong
Fujian
Guangdong
Hainan
Guangxi
Jiangsu
Zhejiang
Shanghai
Liaoning
Hebei
Tianjin
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Cluster 1
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Cluster 3
2020

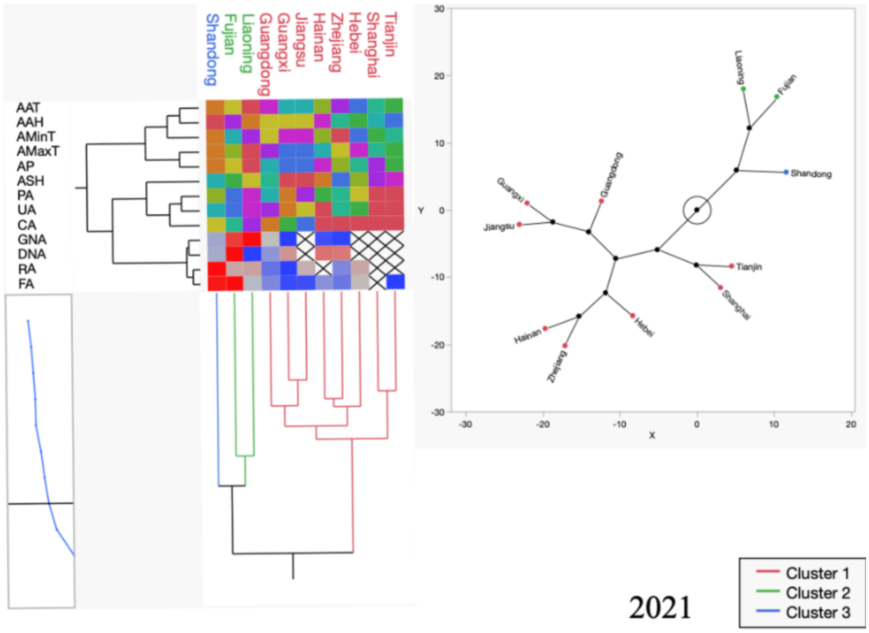

Figure 2. Hierarchical clustering dendrogram and constellation plot.

These visuals allow us to track how regions have shifted in terms of their grouping over time, which can reflect changes in the climate or in how aquaculture is managed. For instance, if a region shifts from a red cluster in one year to a blue cluster in another, it might indicate that the region experienced changes such as warmer temperatures or different rainfall patterns, affecting aquaculture. By observing the color shifts in the heatmaps, we can infer which regions have undergone significant changes and might need to adapt their aquaculture practices to cope with climate change. The consistent color grouping over the years can indicate stability, suggesting that these regions' aquaculture industries might not have needed to make significant changes in response to climate conditions during that time. Through this visual analysis, we are able to identify trends and shifts in regional groupings related to climate and aquaculture practices over the five-year period. This information is invaluable for developing region-specific strategies to enhance resilience to climate change within China's aquaculture sector.

Therefore **Figure 2** proves that regions in Tianjin, Hebei, Hainan, and Guangxi consistently group together in the same cluster across multiple years, it indicates a shared pattern of climate conditions and, potentially, similar strategies in dealing with climate variability. This repeated grouping suggests that these regions have certain stable climatic and aquacultural characteristics, which may reflect successful adaptation strategies that have allowed them to maintain consistent conditions despite the broader trends of climate change.

On the other hand, the shifting cluster membership of regions like Liaoning, Fujian, and Shandong highlights a different aspect of adaptability. The movement between clusters for these regions indicates a more dynamic interaction with climate change. Such shifts could suggest that these regions are experiencing more pronounced climatic variations or are undergoing significant changes in their aquaculture practices as a response to these variations. For instance, if Liaoning moves from a cluster characterized by warmer and more humid conditions to one with cooler and drier conditions, it might indicate a significant climatic shift in the region, necessitating adaptive responses in aquacultural practices.

Next, we focus on the study of cluster means (**Table 2**), we found that regions in Cluster 1 exhibited higher annual average temperatures and annual precipitation in most of the years, especially in 2017, 2019, and 2021. This suggests that these regions possess warm and moist climate conditions, potentially more suitable for certain types of aquacultures. However, the data from 2020 and 2018 indicated lower annual average temperatures and higher annual sunshine duration in these regions, suggesting a tendency towards colder climate conditions in these years, necessitating a reassessment of adaptability for aquaculture.

For regions in Cluster 2, they consistently showed lower annual average temperatures and annual precipitation in most years, particularly in 2021 and 2020, indicating that these areas experienced colder and drier climate conditions. This might require local aquaculture to adapt to more stringent environmental conditions. Meanwhile, the data from 2019 revealed relatively higher annual extreme minimum temperatures in these regions, implying potentially milder climate conditions.

The data for Cluster 3 were relatively limited across the years, mainly represented by Shandong Province and Fujian Province. Shandong Province demonstrated lower annual average relative humidity and higher annual sunshine duration over several years, while Fujian Province exhibited higher annual average temperatures and annual precipitation. These data suggest that these regions may possess unique climatic characteristics.

Through analyzing the climate data and clustering results of different regions over several consecutive years, we can better understand the climatic adaptability and resilience of each region. This not only aids in guiding local aquaculture practices but also provides important references for adaptation strategies in the face of future climate changes.

Next, our analysis focused on the comprehensive assessment of cluster characteristics and regional adaptability, aiming to reveal how each region adjusts its aquaculture strategies to cope with the challenges posed by climate change.

Analysis of clusters with high temperatures and humidity (Clusters 1 and 2) showed that regions like Guangdong, Zhejiang, and Jiangsu frequently appeared in these clusters due to their higher annual average temperatures and precipitation. These areas may have adopted aquaculture methods suited to warm and humid conditions, such as choosing tropical and subtropical fish and aquatic plant species or using deep water culture and warm water recirculation systems to maintain suitable breeding environments.

In colder clusters (Cluster 3), regions like Liaoning and Shandong were categorized in colder clusters in certain years, indicating lower annual average temperatures and harsher winters. Thus, these areas might have adopted insulation measures, like warm water pond systems, or chosen cold-tolerant aquatic species to cope with low-temperature conditions.

Finally, our analysis synthesizes the prominent regional disparities in aquaculture practices from 2017 to 2021, and their corresponding capabilities to adapt to climate change. The consistent stability in the southern regions, namely Fujian, Guangdong, Guangxi, Hainan, Jiangsu, and Zhejiang, reflects their advantageous subtropical and tropical climates that inherently support aquaculture with higher annual temperatures and abundant rainfall. This climatic advantage, coupled with advanced aquaculture technologies and robust management practices, has significantly mitigated the impact of climatic fluctuations, fostering a stable environment conducive to aquaculture.

Conversely, the northern regions, such as Hebei and Tianjin, maintained within Cluster 2, have adopted specialized technological adaptations to contend with cooler climates and harsh winter conditions. These adaptations, supported by local government initiatives, highlight the critical role of policy and technological support in enhancing regional aquaculture resilience.

Shandong and Liaoning, with their varied positioning in Clusters 2 and 3, and frequent shifts in the case of Liaoning, illustrate the necessity for diverse and innovative aquaculture strategies tailored to local climatic realities and ecological capacities. The adaptation strategies in these regions underscore the dynamic nature of aquaculture management, necessitating ongoing adjustments and technological innovations to sustain productivity and stability.

Lastly, Shanghai's experience, oscillating primarily within Cluster 1 with occasional deviations, points to the challenges posed by urbanization. These include significant alterations in water quality and ecological conditions, which demand flexible and advanced aquacultural practices to maintain the sustainability of the industry.

In **Table 2**, all values are represented in scientific notation with two decimal places to enhance the readability and uniformity of the data.

This research conducted a comprehensive annual cluster analysis of climatic data and aquaculture operations from 2017 to 2021 across 11 coastal regions in China, to deeply explore regional adaptability and resilience in response to climate change. The analysis reveals that different regions demonstrate varied levels of adaptability and resilience, influenced by their distinct climatic conditions and aquaculture practices. In the southern regions, including Fujian, Guangdong, Guangxi, Hainan, Jiangsu, and Zhejiang, a high degree of stability was observed in cluster outcomes over the five years, supported by the regions' relatively warm and humid climates favorable for aquaculture. These areas have developed highly adaptive aquaculture technologies and management strategies, such as efficient water quality management and disease control systems, suited to their local climates.

Conversely, northern regions like Tianjin and Hebei, despite facing colder climatic conditions, have maintained stability and productivity in aquaculture through technological adaptations such as greenhouse cultivation and water temperature control, which mitigate the adverse effects of colder temperatures. Shandong and Liaoning, with their unique geographical and climatic characteristics, exhibited certain cluster variations. Shandong's long winters and Liaoning's climatic fluctuations necessitate diversified and flexible adaptation strategies, such as adopting species suited for cold-water environments and improving farming structures.

Table 2. Cluster means.

	Cluster	Count	AAT	AMaxT	AMinT	AAH	ASH	AP	PA	GNA	DNA	RA	CA	UA	FA
	1	8	2.01×10^{4}	3.82×10^{4}	-3.80	7.22×10	2.02×10^{3}	1.35×10^{3}	2.39×10^{4}	2.30×10^{6}	4.58×10^{6}	2.46×10^{4}	5.99×10^{3}	2.16×10^{4}	2.76×10^{6}
2021	2	2	9.20×10^{3}	3.48×10^{4}	-2.60×10	6.50×10	2.13×10^{3}	7.92×10^{2}	8.72×10^{4}	1.64×10^{7}	3.33×10^{5}	5.20×10^{4}	7.23×10^{3}	4.64×10^{5}	3.53×10^{6}
	3	1	1.55×10^{4}	3.76×10^{4}	-1.83×10	5.60×10	2.41×10^{3}	1.04×10^{3}	1.23×10^{5}	2.85×10^{6}	3.44×10^{6}	1.40×10^{5}	1.21×10^{5}	2.14×10^{5}	1.27×10^{7}
	1	3	1.26×10^{4}	3.68×10^{4}	-1.61×10	6.00×10	2.54×10^{3}	7.05×10^{2}	9.32×10^{4}	2.00×10^{4}	9.12×10^{3}	4.45×10^{5}	4.44×10^{4}	5.27×10^{5}	2.24×10^{4}
2020	2	7	2.14×10^{4}	3.83×10^{4}	1.90	7.69×10	1.64×10^{3}	1.38×10^{3}	2.96×10^{5}	6.50×10^{4}	3.59×10^{4}	4.94×10^{5}	3.18×10^{4}	3.00×10^{5}	1.39×10^{4}
	3	1	1.50×10^{4}	3.82×10^{4}	-1.40×10	5.70×10	2.97×10^{3}	6.62×10^{2}	2.20×10^{5}	8.28×10^{4}	2.75×10^{4}	1.89×10^{6}	1.06×10^{6}	1.71×10^{6}	1.58×10^{5}
	1	8	1.80×10^{4}	3.78×10^{4}	-3.80	6.95×10	1.96×10^{3}	1.14×10^{3}	1.61×10^{5}	9.14×10^{3}	1.12×10^{4}	2.94×10^{5}	1.54×10^{4}	3.03×10^{5}	1.14×10^{4}
2019	2	2	2.18×10^{4}	3.82×10^{4}	5.50	7.80×10	1.62×10^{3}	1.90×10^{3}	4.99×10^{5}	2.01×10^{5}	4.78×10^{4}	9.85×10^{5}	1.13×10^{5}	5.54×10^{5}	2.39×10^{4}
	3	1	1.57×10^{4}	3.90×10^{4}	-1.06×10	5.20×10	2.39×10^{3}	7.03×10^{2}	2.20×10^{5}	7.20×10^{4}	2.41×10^{4}	1.88×10^{6}	9.76×10^{5}	1.61×10^{6}	1.37×10^{5}
	1	3	1.32×10^{4}	3.94×10^{4}	-1.68×10	5.53×10	2.33×10^{3}	5.85×10^{2}	5.46×10^{4}	1.37×10^{7}	6.01×10^{6}	8.61×10^{4}	6.91×10^{4}	2.31×10^{5}	4.38×10^{6}
2018	2	7	2.10×10^{4}	3.69×10^{4}	4.67×10^{-1}	7.82×10	1.74×10^{3}	1.61×10^{7}	2.69×10^{7}	1.01×10^{6}	2.14×10^{6}	2.46×10^{4}	7.93×10^{2}	2.85×10^{4}	6.54×10^{5}
	3	1	2.09×10^{4}	3.81×10^{4}	-2.00×10^{-1}	7.30×10	1.49×10^{3}	1.40×10^{3}	2.07×10^{4}	6.43×10^{8}	5.18×10^{5}	4.59×10^{4}	6.24×10^{3}	1.77×10^{4}	1.23×10^{7}
	1	8	1.95×10^{4}	3.91×10^{4}	1.08	7.13×10	1.83×10^{3}	2.20×10	2.25×10^{4}	7.31×10^{5}	1.31×10^{6}	2.09×10^{4}	4.57×10^{3}	2.22×10^{3}	8.48×10^{5}
2017	2	2	1.24×10^{4}	3.75×10^{4}	-1.56×10	5.60×10	2.36×10^{3}	9.42	9.62×10^{4}	1.23×10^{6}	1.25×10^{6}	8.10×10^{4}	5.36×10^{4}	3.44×10^{5}	6.71×10^{6}
	3	1	2.11×10^{4}	3.93×10^{4}	4.00	7.30×10	1.59×10^{3}	2.40×10	2.75×10^{4}	4.09×10^{7}	3.24×10^{5}	4.48×10^{4}	6.96×10^{3}	1.68×10^{4}	1.08×10^{7}

Moreover, the highly urbanized area of Shanghai showed cluster variability potentially influenced by urbanization processes, such as fluctuations in water quality and ecological pressures, requiring continuous adjustments in management measures and technological adaptations to cope with these changes.

Hypotheses were formulated to validate these observations:

1) Hypothesis H1 posited that significant regional differences in adaptability and resilience within aquaculture practices can be identified through cluster analysis based on annual mean temperature, extreme temperatures, relative humidity, sunlight duration, annual precipitation, and diverse aquaculture practices. The distinct cluster distributions observed, such as the stability in southern regions and variability in the north, confirmed these differences, validating Hypothesis H1.

2) Hypothesis H2 suggested that specific regional aquaculture environments might exhibit adverse characteristics in response to climate change, leading to inefficiency and limited productivity, potentially related to unique combinations of regional climatic factors and aquaculture methods. The cluster shifts observed in Liaoning between 2018 and 2019 and the variability in Shanghai under urban pressures further substantiated this hypothesis.

According to the China Fisheries Statistical Yearbook 2018 and 2022 (China Fishery Statistical Yearbook, 2018, 2019, 2020, 2021, 2022) we found that Guangdong Province mainly farms tropical fish and shrimp due to its subtropical climate. In 2021, the province's total fish production reached 8.845 million tons, an increase of 5.717% from 2017. This growth reflects the region's effective adaptation to the challenges posed by climate change through the adoption of advanced water quality management techniques and disease control strategies. Shandong Province mainly farms cold-water fish, such as grass carp, due to its colder climatic conditions. Despite facing a warming trend, grass carp production in Shandong Province remained stable at about 205,000 tons in 2021, with little change from 2017 (231,000 tons) through improved farming facilities and enhanced disease prevention measures. In addition, we observed that Jiangsu and Zhejiang showed significant regional differences in adapting to climate change. Both provinces adopted a multi-trophic level aquaculture system (IMTA), which effectively utilizes the ecological relationships between different aquatic organisms and enhances overall ecosystem stability and production. Algae (Spirulina) production in Jiangsu Province has increased by about 13.75% over the past five years, demonstrating a high degree of adaptability to environmental changes. Through the demonstration of these concrete examples, we can not only see how different regions choose appropriate species for aquaculture according to their respective climatic conditions, but also learn how they respond to climate change through technological and management innovations to maintain or improve aquaculture production and efficiency.

In conclusion, the validation of these hypotheses illuminates the diversity and complexity of regional responses to climate change within the aquaculture sector, as well as the challenges some regions face due to inadequate environmental factors and management strategies. This underscores the importance of developing region-specific strategies and enhancing research into climate adaptability to optimize the climate resilience and sustainability of aquaculture practices.

4. Discussion

This study focused on evaluating the adaptability and resilience of different regions to climate change within aquaculture practices. By employing cluster analysis, we have identified significant regional differences, affirming our first hypothesis (H1) that such disparities can be discerned based on climatic factors like annual mean temperature, extreme temperatures, relative humidity, sunlight duration, annual precipitation, and diverse aquaculture practices. Our analysis revealed pronounced stability in southern regions like Fujian, Guangdong, and Jiangsu, contrasting with the variability observed in northern areas like Liaoning and Shandong. This aligns with findings from a study on urban expansion in China’s coastal zone from 2000 to 2020 (Du et al., 2022), which highlights differential growth patterns between the northern and southern regions. Specifically, southern provinces like Guangdong exhibited significant urban land increases compared to northern areas such as Shandong. Additionally, another study on the environmental factors affecting aquaculture production and fisherfolk incomes in China (Wang and Mendes, 2022) provides insights into regional environmental variability, further underscoring the contrasting stability between the southern regions and the more variable northern areas. These observations are crucial for understanding the regional differences noted in our analysis.

Hypothesis H2 suggested that specific regional environments might exhibit adverse characteristics in response to climate change, leading to inefficiency and limited productivity. The observed cluster shifts in Liaoning and the variability in Shanghai, particularly under urban pressures, substantiate this hypothesis. Studies such as those by the General Fisheries Commission for the Mediterranean Scientific Advisory Committee (2009) have documented similar trends where urban aquaculture systems faced heightened stress due to climatic and anthropogenic pressures, mirroring our findings.

The differences noted between the northern and southern regions in our study reflect broader global patterns documented in comparative research. For instance, the variability in climate adaptability observed in northern China parallels findings from studies in northeastern America where variable climatic conditions have prompted shifts in aquaculture practices (Swanston et al., 2017). Theoretical frameworks in ecological resilience, such as those proposed by Cretney (2014), provide a basis for understanding how these regions adapt to and recover from climatic stressors, thereby supporting our analytical approach using cluster analysis. The findings from this study suggest specific regional strategies to enhance aquaculture resilience. In regions with stable climates, maintaining and possibly enhancing current adaptive practices is advisable, while in more variable climates, developing flexible, responsive aquaculture systems is critical. Policymakers should consider these differences when designing support mechanisms, such as subsidies for technology that can enhance adaptability in variable climates.

While our study provides valuable insights, it is limited by the scope of data regarding the long-term impact of climatic changes on aquaculture. Future research could expand on this by incorporating longer temporal datasets and more granular regional analyses. Additionally, exploring the impact of other environmental factors, such as water salinity and ecosystem health, could further refine our understanding of aquaculture adaptability.

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