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Research on the Relationship between Marine Environment with Seafood Exploitation Productivity and Catch per Unit Effort in the Upwelling Area of the South Central Coast of Vietnam

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Abstract: The analysis of the relationship between oceanographic and environmental factors and fish production and productivity reveals that during the Southwest monsoon season, fish production and productivity are typically higher and more variable compared to the Northeast monsoon season. These metrics exhibit a relatively strong relationship with oceanographic structural variables, with a multiple correlation coefficient of R_0 = 0.56 during the Southwest monsoon season, which decreases to R_0 = 0.4 in the Northeast monsoon season. Specifically, fish production and productivity show a positive correlation with seawater temperature during the Northeast monsoon season, a negative correlation during the Southwest monsoon season, and a negative correlation with salinity in both seasons. Multivariate regression analysis further highlights a significant relationship between marine resource productivity and various oceanographic and environmental factors. Notably, factors such as Tday (Bottom Water Temperature), H0, PHY (Phytoplankton), and ZOO (Zooplankton) demonstrate high pairwise correlation coefficients with fish production and are positively correlated with each other. Additionally, fishing productivity peaks in areas with low flow speeds (20-40 cm/s) and regions characterized by alternating cyclonic and anticyclonic circulations.

Key words: Seafood productivity, marine environment, upwelling zone, the South-Central Vietnam.

1. Introduction

Upwelling is a key dynamic process occurring in both oceans and seas, playing a crucial role in marine ecosystems. Depending on their geographical location, upwelling can be categorized into two types: offshore upwelling and coastal upwelling. When considering the formation of coastal upwelling centers, it becomes evident that the nutrient sources in these areas exhibit distinct local and regional characteristics. Due to the nature of coastal upwelling currents and the varying biological response times, the areas with the highest concentrations of phytoplankton, zooplankton, and fish resources can differ significantly across regions. Notably, regions with high fish concentrations are often found far from the areas with the highest nutrient availability. The positions of these zones depend on factors such as the velocity of the upwelling currents and the integrated biological response time, including the rate at which phytoplankton cells double.

Upwelling zones are critical for marine productivity, serving as hotspots that attract a diverse range of species across various trophic levels. These areas typically support large populations of species at lower trophic levels, such as plankton, as well as significant numbers of predators, including fish, seabirds, and marine mammals, which feed at higher trophic levels.

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However, in many highly productive ecosystems, especially those influenced by upwelling, there is often a notable intermediate trophic level. This level is typically occupied by small, plankton-eating pelagic fish and may be dominated by one or a few species [1].

For example, in the marine fauna of South Africa, which is particularly rich and well-documented, three groups—mollusks, crustaceans, and vertebrates—are represented by 3,062, 2,333 and 2,492 species, respectively [2]. Of the 2,000 marine fish species recorded, approximately 70% are bottom-dwelling species, including benthic organisms and those found in coral reefs. In contrast, only 6.1% are large pelagic fish species, and 3.7% are small pelagic fish species. Species diversity is relatively high at the end of the food chain (e.g., 429 species of decapods, 2,262 species of amphipods) and at the top, with 92 species of seabirds and 41 species of marine mammals.

The food webs of current upwelling systems at the eastern boundary share several structural characteristics, such as the dominance of pelagic fish over benthic consumers, cell/body size, and the population structure at coarse taxonomic levels in both plankton and fish. The microbial loop, which includes heterotrophic bacteria, very small photosynthetic autotrophs, and unicellular planktonic microbes, is present in plankton across all regions, yet it is often overshadowed by the planktonic food web, which is dominated by medium to large photosynthetic autotrophs [3-5].

In upwelling areas, in addition to the high primary productivity driven by diatom algae of medium to large cell sizes, which are typically localized over time and space, productivity and consumption patterns also exhibit spatial and temporal variability. The biomass of plankton is often dominated by a few medium to large arthropod species, one or two species of crustaceans, and one or more invertebrates [4]. Predatory species commonly found in these areas include migratory fish (such as mackerel and tuna) that enter upwelling systems to forage but spend part of their lives offshore. Larger predators, such as larger fish, squid, seabirds, and whales, target specific prey groups [6]. The diversity of benthic species can be high, although it may be reduced in regions with low oxygen levels. Nearshore benthic species, along with their larval plankton, typically rely on the combination of coastal currents and expansion to return to their settlement locations [4].

The interplay within the temporal scope also affects the behavior of zooplankton and larval fish. For instance, in the Benguela Current, many species of zooplankton and larval fish exhibit vertical migration—ascending to the surface at night and descending to deeper, darker regions during the day to evade daytime predators. However, it has been demonstrated that this behavior interacts with the seasonal flow patterns, helping to retain these organisms at specific latitudes and distances offshore [7].

In Vietnam, during the southwest monsoon season from June to August, the continental shelf waters of the South-Central region, particularly around Ninh Thuan and Binh Thuan, experience the strongest upwelling phenomenon. This effect becomes evident from May to October, peaking between June and September. In the deeper waters off Khanh Hoa province, upwelling originates from the intermediate layer at depths of 100-125 m, while in the shallower waters near Phan Thiet and southeast of Con Dao Island, it rises from the seabed. The summer upwelling in this region occurs due to the Ekman effect caused by southwest winds, which push surface waters offshore, allowing cold, nutrient-rich deep water to rise along the sloping seabed to upper layers. This results in cooler surface temperatures in the upwelling zone compared to surrounding areas. Upwelling plays a crucial role in marine resources, as it creates high primary biological productivity in and around the upwelling zone due to favorable conditions of nutrients, temperature, and light. This, in turn, supports the concentration of zooplankton, other marine organisms, and economically important species like shrimp and fish [8-14].

This study focuses on clarifying the relationship between certain oceanographic and environmental factors and the productivity of specific marine resource groups in the South-Central upwelling zone, aiming to develop models and forecasts for marine resources under the influence of this phenomenon.

2. Material and Methods

2.1 Oceanographic Data

Meteorological and oceanographic factors, including wind, air pressure, sea surface temperature, sea level, and ocean currents, are collected daily. Ocean color (phytoplankton concentration) data are collected four times a week. These data are analyzed and interpreted using high-resolution satellite imagery with spatial resolutions of 2 km or 4 km (NOAA 17-18, TERRA, AQUA satellites) and low-resolution imagery of 25 km (TRMM, AQUA satellites). The data are sampled within a 0.25° × 0.25° latitude-longitude grid.

The dataset used for analyzing the relationship with marine biological resources spans from 2014 to 2019, a period during which a substantial amount of fishery resource data was collected. These data were continuously updated through various projects and programs, with a particular focus on commercial fishery data and logbooks from coastal provinces. Data collection was conducted on a monthly and continuous basis from 2016 to 2019.

2.2 Fishery Data

Fishery data are sourced from the fisheries database maintained by the Research Institute for Marine Fisheries. This dataset is compiled and updated through various projects and studies conducted by the institute over the years. For this analysis, data from fishing logbooks are utilized to explore the relationship between environmental factors and upwelling events. The logbook data, collected continuously for each fishing operation, include records from key fishing methods such as oceanic tuna longlining, drifting gillnets, purse seining, and squid jigging. Additionally, fishery data are supplemented with observations from onboard monitoring of fishing activities. The collected data include fishing grounds, catch volumes, species composition of commercial groups for each fishing operation, and other relevant information. Detailed data are provided in Table 1 and Fig. 1.

2.3 Method for Analyzing the Fish-Environment Relationship

2.3.1 Selection of Oceanographic Factors for Correlation Analysis

In ecology in general, and marine ecology in particular, environmental temperature is not only a dominant and crucial ecological factor for any ecosystem, but its spatial and temporal distribution and

Table 1 Statistics of fishery data within the upwelling area of the South-Central coast from 2014 to 2019.

Month	*Demersal Fish*		*Large Pelagic Fish*		*Small Pelagic Fish*		*Reef Fish*		*Others*		*Total*
	Data count	Percentage (%)	Data count	Percentage (%)	Data count	Percentage (%)	Data count	Percentage (%)	Data count	Percentage (%)	
1	722	9.8	2,528	34.4	2,609	35.5	823	11.2	672	9.1	7,354
2	726	10.5	2,209	31.9	2,467	35.7	790	11.4	725	10.5	6,917
3	200	1.8	2,649	23.8	4,024	36.1	1,723	15.5	2,547	22.9	11,143
4	100	1.6	2,268	36.3	2,160	34.5	521	8.3	1,204	19.3	6,253
5	66	1.0	2,656	39.0	2,455	36.0	429	6.3	1,211	17.8	6,817
6	80	1.0	3,057	37.2	2,992	36.4	635	7.7	1,458	17.7	8,222
7	69	1.2	2,441	43.7	1,750	31.3	498	8.9	833	14.9	5,591
8	114	1.6	2,925	42.1	1,772	25.5	772	11.1	1,368	19.7	6,951
9	208	2.7	3,677	47.2	1,919	24.6	695	8.9	1,286	16.5	7,785
10	845	7.3	4,523	39.2	2,883	25.0	1,357	11.7	1,941	16.8	11,549
11	491	5.5	4,138	46.0	2,060	22.9	1,011	11.2	1,300	14.4	9,000
12	54	0.8	2326	35.2	1797	27.2	1038	15.7	1386	21.0	6601

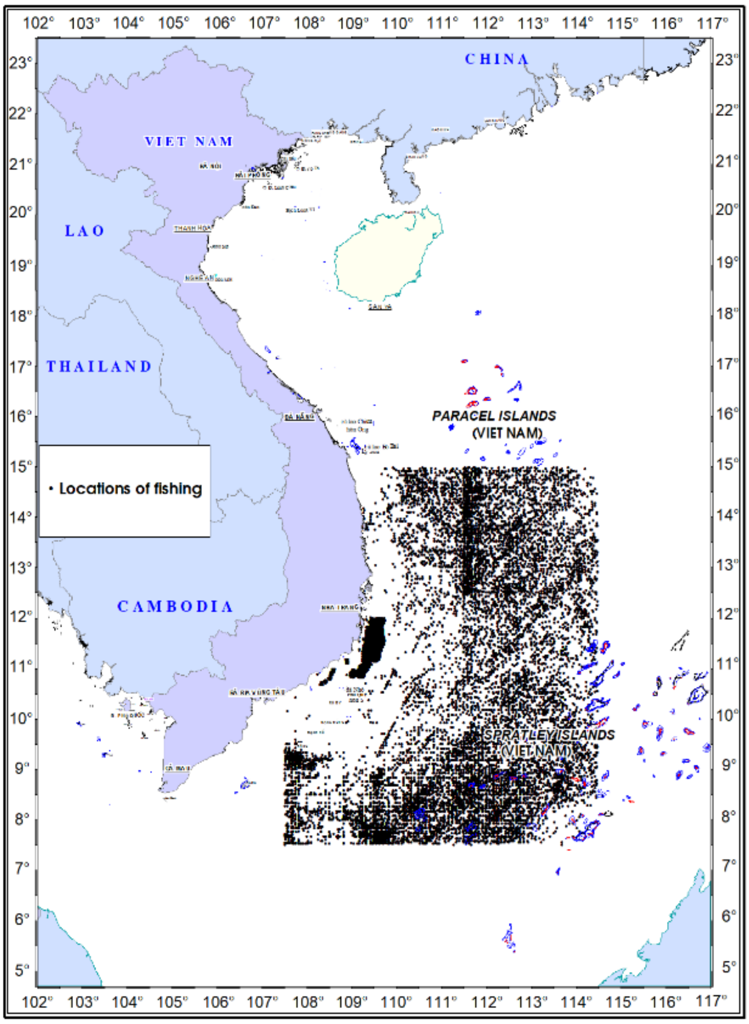

Fig. 1 Distribution of fishery data in the study area.

variation (as indicated by characteristics such as vertical and horizontal thermal structure, homogeneous layers, upwelling zones, frontal zones, thermal anomalies, etc.) are also considered biological indicators [15, 16]. In addition, many other environmental factors such as food availability (represented by primary organic matter sources—chlorophyll-a, zooplankton, phytoplankton), salinity, turbidity, dissolved oxygen, and current patterns, as well as fluctuations in these factors, also have direct or indirect effects on the distribution and behavior of fish [1, 2, 4, 17, 18].

Moreover, numerous studies have examined fish distribution and movement with depth. Therefore, to investigate the relationship between catch yield and fishing productivity with oceanographic and environmental factors in the upwelling regions of Vietnam, this study selected 14 primary environmental factors, mainly within the range from the surface layer to a depth of 150 m (Table 2).

2.3.2 Multiple Linear Regression Analysis Method

Using the synchronized fish-environment dataset mentioned above, a multiple linear regression analysis is applied between the dependent variable Catch Per Unit Effort (CPUE) and the independent variables (environmental factors). This method aims to derive a linear regression equation that reflects the fish-environment relationship, in the following general form [7, 19].

$$y = a_0 + a_1 \times 1 + a_2 \times 2 + ... + a_m \times m$$

where:

Table 2 Selected oceanographic and environmental factors for studying the fish-environment correlation in the upwelling area.

No.	*Factor*	*Notation*	*Unit of measurement*
1	Sea surface temperature	T0	℃
2	Bottom water temperature	Tday	℃
2	Sea surface temperature anomaly	AnoT	℃
3	Thickness of the upper mixed layer	H0	m
4	Depth	Dosau	m
5	Photosynthetic rate	DQU.m.	m
6	Phytoplankton	PHY	
7	Zooplankton	ZOO	
8	Sea surface temperature horizontal gradient	GraT0xy	℃/10km
9	Sea surface salinity	S0	‰
10	Bottom water salinity	Sday	‰
11	Chlorophyll-a concentration	Chlo	mg/m^3
13	Solar radiation intensity	EKE	cm^2/s^2
14	Current velocity	Cur	cm/s

y is the dependent variable, representing the overall catch productivity (CPUE) as well as the productivity for each specific fish group, including large pelagic fish, small pelagic fish, demersal fish, other fish, and the bycatch group.

x_j (j = 1, ..., m) are the independent variables, representing the m oceanographic and environmental factors.

a_0 and a_j (j = 1, ..., m) are the regression coefficients, determined using the least squares method based on the synchronized fish-environment dataset, which has m columns and n rows as previously outlined.

The multiple correlation coefficient R is calculated using the formula:

$$R = \frac{\sum_{i=1,j=1}^{n,m} x_{ij}y_{ij} - n\bar{x}.\bar{y}}{\sqrt{\left(\sum_{i=1,j=1}^{n,m} x_{ij}^2 - \bar{x}^2\right)\left(\sum_{i=1,j=1}^{n,m} y_{ij}^2 - \bar{y}^2\right)}}$$

The absolute value of R ranges from 0 to 1, where:

$|R| < 0.1$ indicates a very weak correlation;

0.2-0.3 indicates a weak correlation;

0.4-0.5 indicates a moderate correlation;

0.6-0.7 indicates a strong correlation;

$|R| > 0.8$ indicates a very high correlation [14].

Thus, the correlation and multiple linear regression analysis employs several independent variables. In some cases, certain “independent variables” may have a strong correlation with each other, meaning they are “not independent”. In such cases, one representative variable can be selected from the correlated variables. Removing “non-independent variables” ensures that the remaining variables are the most significant and have the greatest impact on fishing productivity. This approach not only explains which environmental factors primarily drive resource fluctuations but also reduces computation time in predictive models while maintaining necessary reliability.

3. Results and Discussion

3.1 Relationship between Upwelling and Productivity and Distribution of Marine Resources during Upwelling Events

Fish catch productivity shows a positive correlation with sea surface temperature during the Northeast monsoon and a negative correlation during the Southwest monsoon, while both monsoons exhibit a negative correlation with salinity. This can be explained as follows: During the Northeast monsoon, from January to March, cold, nutrient-poor waters from the north move towards the study area, lowering the sea surface temperature (which can drop below 25.0 ℃) and increasing salinity due to the dry season. As a result, small pelagic fish migrate southwards and to deeper, warmer waters, particularly near the boundary of the cold coastal water and the warmer offshore water, such as the area near Phu Quy Island. From October to December, sea surface temperatures range from 26.0-28.5 ℃, and during the peak of the rainy season, salinity decreases in coastal areas, where freshwater forms near-shore low-salinity water masses, while saline offshore water masses also occur. Nutrient-rich waters are brought to the surface, attracting fish to these areas.

During the Southwest monsoon, from April to June, sea surface temperatures are high and relatively stable across the region, with high salinity. Consequently, fish move to areas with shallower depths and lower temperatures, especially nearshore for spawning. From July to September, temperatures and salinity decrease, particularly with the onset of upwelling, prompting fish to migrate offshore to areas with upwelling activity. The study results also show that fishing areas with high productivity are located in regions where sea surface temperatures range from 28.5-30 ℃ and salinity ranges from 33.0‰-34‰ (Fig. 2).

Chlorophyll-a concentration, zooplankton, and phytoplankton serve as primary nutritional sources, while turbulent kinetic energy (degree of water mass mixing) shows a positive relationship with catch productivity during both monsoons. In other words, areas with abundant nutrients and good water mixing have higher small pelagic fish catch productivity, and vice versa. This relationship is more pronounced during the Southwest monsoon (the period of upwelling) (Fig. 3).

It is evident that both horizontal and vertical oceanographic structures in the sea are influenced by the circulation patterns of water masses. The results of the ecological adaptation index analysis indicate that the highest fish catch productivity is concentrated in areas with moderate current speeds (from 20-40 cm/s), particularly where alternating cyclones and anticyclones form (Figs. 4 and 5).

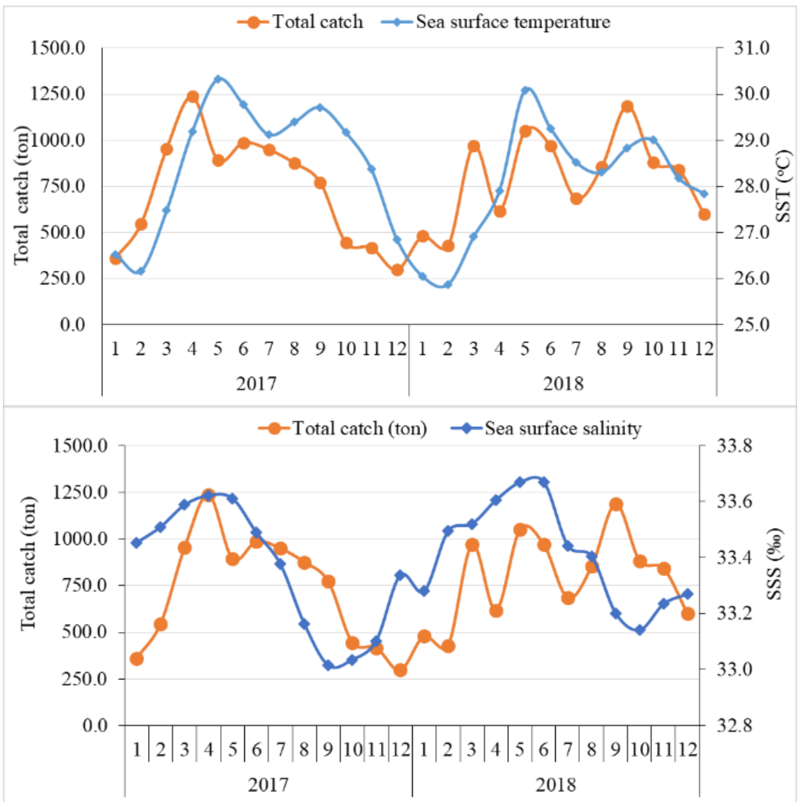

Fig. 2 Monthly variations in average sea surface temperature, salinity, and total catch in 2017-2018 in the South-Central Vietnam upwelling area.

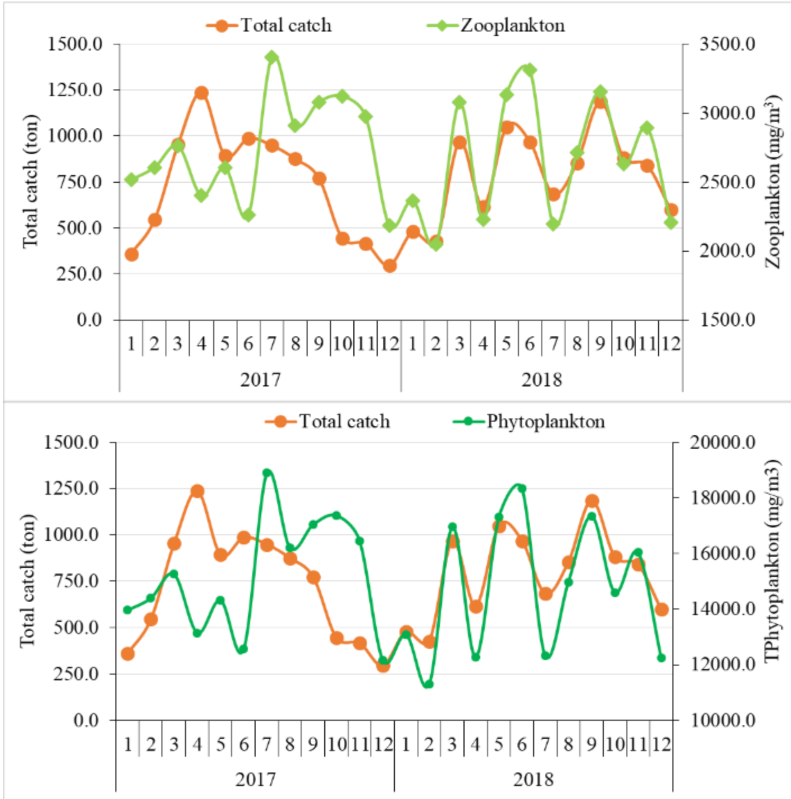

Fig. 3 Monthly variations in average phytoplankton, zooplankton, and total catch in 2017-2018 in the South-Central Vietnam upwelling area.

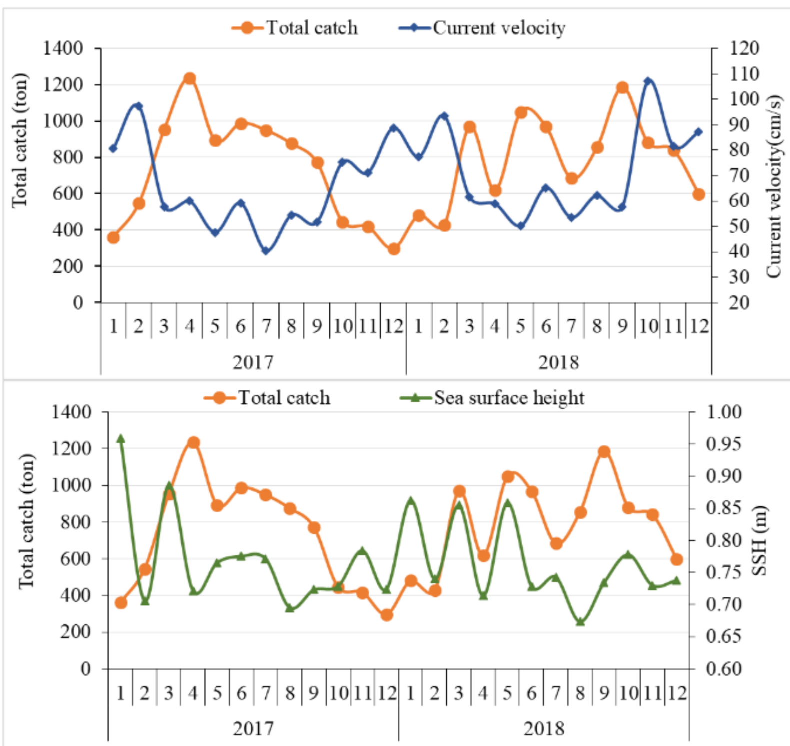

Fig. 4 Monthly variations in average current velocity, sea surface height, and total catch in 2017-2018 in the South-Central Vietnam upwelling area.

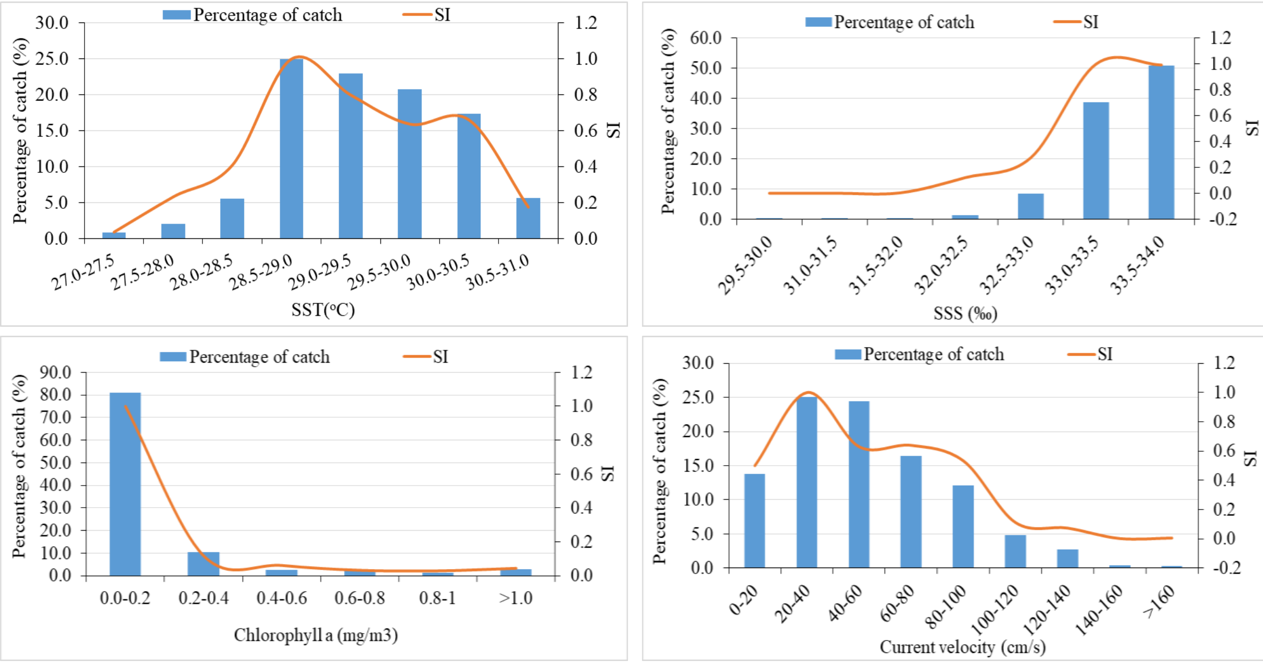

Fig. 5 Ecological SI (Suitability Index) of some environmental factors for marine resources in the South-Central Vietnam upwelling area.

The results of multivariate regression correlation analysis between overall and individual marine resource productivity and oceanographic and environmental factors show a relatively strong relationship between them (Tables 4-5). Among these factors, Tday, H0, PHY, and ZOO exhibit high pairwise correlation coefficients with fish catch productivity, and they are positively correlated with each other. This explains that in areas near the center of upwelling, sea bottom temperatures tend to be lower than in surrounding areas, similarly with the depth of the mixed layer. This implies that fish catch productivity is lower near the center of upwelling, while productivity increases in areas with higher zooplankton and phytoplankton concentrations. On the other hand, salinity and depth exhibit a negative correlation with catch productivity.

The fishing season in the upwelling area is divided into two seasons: the northern fish season (Northeast monsoon, when upwelling does not occur) and the southern fish season (Southwest monsoon, during upwelling periods). For each season, there are significant differences in both the productivity and species composition of the catch [19, 20]. Furthermore, as analyzed in Section 3.1, oceanographic and environmental factors differ notably between the two monsoon seasons. Therefore, analyzing the relationship between fish and environmental factors in the study area must be done separately for each season to accurately reflect the nature of their relationship. The results of this analysis for the Northeast and Southwest monsoon seasons show that fish productivity during the Southwest monsoon is generally higher and more variable than during the Northeast monsoon, with a relatively close relationship to oceanographic structural variables (multiple correlation coefficient $R_0 = 0.56$). In contrast, the correlation coefficient during the Northeast monsoon is smaller ($R_0 = 0.40$) (Table 3).

It can be observed that, in the analysis results above, both for the Northeast and Southwest monsoon seasons, the concentrations of chlorophyll-a, phytoplankton, and zooplankton (considered as the primary food source for fish) exhibit a negative correlation with fish catch productivity. However, this does not mean that lower values of chlorophyll-a or zooplankton will necessarily lead to higher fish catch productivity, or vice versa. Instead, it suggests that there is a threshold beyond which further decreases in chlorophyll-a or zooplankton concentrations will result in maximum fish catch

Table 3 Correlation analysis results between the catch productivity of resource groups and oceanographic and marine environmental factors in the South-Central Vietnam upwelling area.

Resource group	*Time Period*	*N (Number of data)*	*Correlation coefficient R*
General resources	Upwelling occurred	344	0.56
	No upwelling	346	0.4
Small fish	Upwelling occurred	135	0.53
	No upwelling	175	0.42
Large fish	Upwelling occurred	241	0.60
	No upwelling	346	0.54
Squid	Upwelling occurred	39	0.86
	No upwelling	96	0.6
Other fish	Upwelling occurred	68	0.68
	No upwelling	114	0.55
Crustaceans	Upwelling occurred	66	0.71
	No upwelling	119	0.68

Table 4 Results of correlation matrix analysis between marine resource catch productivity and oceanographic and marine environmental factors during the upwelling period (from May to October).

	CPUE	*T0*	*Tday*	*AnoT*	*H0*	*S0*	*GraT0xy*	*Sday*	*Cur*	*Chlo*	*PHY*	*ZOO*	*DQU.m.*	*Dosau*	*EKE*
CPUE	1.00														
T0	0.12	1.00													
Tday	0.38	0.09	1.00												
AnoT	-0.06	0.73	0.08	1.00											
H0	0.26	-0.27	0.21	-0.55	1.00										
S0	-0.17	0.11	-0.53	0.13	-0.09	1.00									
GraT0xy	-0.19	-0.27	0.00	0.33	-0.38	0.03	1.00								
Sday	-0.30	0.04	-0.92	0.01	-0.10	0.71	-0.02	1.00							
Cur	-0.07	0.24	-0.04	0.30	-0.33	-0.20	0.11	0.03	1.00						
Chlo	0.14	-0.16	0.46	-0.05	-0.08	-0.74	0.11	-0.69	-0.05	1.00					
PHY	0.35	0.08	0.96	0.19	0.10	-0.46	0.16	-0.85	0.00	0.41	1.00				
ZOO	0.31	0.05	0.93	0.23	0.00	-0.43	0.23	-0.85	0.01	0.42	0.99	1.00			
DQU.m.	-0.09	0.26	-0.72	0.01	0.11	0.62	-0.31	0.81	-0.08	-0.60	-0.71	-0.74	1.00		
Dosau	-0.28	-0.03	-0.92	-0.21	0.08	0.49	-0.22	0.89	0.00	-0.51	-0.96	-0.98	0.82	1.00	
EKE	0.07	-0.06	0.09	0.08	-0.21	-0.15	0.15	-0.14	0.61	0.14	0.14	0.16	-0.21	-0.15	1.00

Table 5 Results of correlation matrix analysis between marine resource catch productivity and oceanographic and marine environmental factors during the non-upwelling period (from January to April and November, December).

	CPUE	*T0*	*Tday*	*AnoT*	*H0*	*S0*	*GraT0xy*	*Sday*	*Cur*	*Chlo*	*PHY*	*ZOO*	*DQU.m.*	*Dosau*	*EKE*
CPUE	1.00														
T0	0.18	1.00													
Tday	0.10	-0.14	1.00												
AnoT	0.15	0.87	-0.03	1.00											
H0	-0.09	-0.26	0.08	-0.31	1.00										
S0	-0.17	-0.44	-0.21	-0.31	0.01	1.00									
GraT0xy	-0.13	-0.51	0.19	-0.26	-0.21	0.27	1.00								
Sday	-0.12	0.21	-0.96	0.11	-0.06	0.26	-0.18	1.00							

Table 5 to be continued

Cur	*0.05*	*-0.08*	*-0.08*	*0.07*	*-0.23*	*0.00*	*0.28*	*0.06*	*1.00*						
Chlo	-0.12	-0.26	0.46	-0.25	-0.16	0.09	0.49	-0.44	-0.10	1.00					
PHY	0.10	-0.14	0.98	-0.02	0.07	-0.21	0.17	-0.97	-0.07	0.47	1.00				
ZOO	0.11	-0.16	0.98	-0.03	0.03	-0.19	0.19	-0.98	-0.06	0.47	1.00	1.00			
DQU.m.	-0.03	0.43	-0.79	0.35	0.07	0.15	-0.34	0.85	0.02	-0.70	-0.80	-0.82	1.00		
Dosau	-0.07	0.27	-0.94	0.16	-0.01	0.19	-0.25	0.97	0.07	-0.59	-0.96	-0.97	0.91	1.00	
EKE	-0.04	-0.26	0.12	-0.08	-0.10	0.18	0.39	-0.10	0.83	0.07	0.12	0.12	-0.13	-0.12	1.00

productivity. The analysis results show that when the chlorophyll-a concentration is within the range of 0.1-0.2 mg/m^3, fish catch productivity reaches its maximum (Fig. 5).

This might seem counterintuitive because, in biological terms, areas with more food tend to attract more organisms. However, when considering the "negative correlation" in the context of the predator-prey relationship, it becomes reasonable. The abundance of prey fluctuates based on the predation intensity of predators, while the growth of predator populations is determined by the quantity and state of the prey, thus forming a dynamic balance between them. Therefore, the population changes between them may sometimes show a positive correlation and at other times a negative correlation. Additionally, there are other intermediary links between them, such as zooplankton and small pelagic fish species... [4].

4. Conclusions

The results of the multivariate regression correlation analysis between overall and specific fishery productivity and oceanographic and environmental factors indicate a relatively strong relationship between them. Among these, the factors Tday, H0, PHY, and ZOO exhibit high pairwise correlation coefficients with fish catch productivity, and they are positively correlated with each other. In contrast, these factors show a negative correlation with salinity and depth in both monsoon seasons.

Fish catch productivity during the Southwest monsoon season (when upwelling occurs) is generally higher and more variable than during the Northeast monsoon season (when large-scale upwelling is absent). Moreover, it is more closely related to the oceanographic structural variables during the Southwest monsoon season than in the Northeast monsoon season.

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