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Assessing the Relationship between Sea Turtle Strandings and Anthropogenic Impacts in Taiwan

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Abstract: Data acquired from stranded sea turtles can provide awareness of human activities that adversely affect sea turtle populations. We assessed strandings of five sea turtle species between 2017 and 2021. This study utilizes principal component analysis (PCA) and structural equation modeling (SEM) to reveal potential causes of sea turtle strandings linked to anthropogenic effects in Taiwan. Although our study did not observe a statistically significant impact of offshore wind turbines on sea turtle strandings, it did find evidence of a significant direct effect of coral colony density, heavy metals, and fishing disturbance on such strandings. For the conservation of endangered sea turtles, we recommend the incorporation of PCA and SEM in further contexts for validating anthropogenic impact assessments.

Keywords: *Chelonia mydas*; anthropogenic influences; principal component analysis; structural equation modeling; latent variables

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1. Introduction

Sea turtles can serve as sentinel indicators of the health of marine ecosystems [1,2]. Five of the seven internationally recognized marine turtle species are present in the coastal areas of Taiwan: the green turtle (*Chelonia mydas*; Endangered), hawksbill turtle (*Eretmochelys imbricata*; Critically endangered), olive ridley turtle (*Lepidochelys olivacea*; Vulnerable), leatherback turtle (*Dermochelys coriacea*; Vulnerable), and loggerhead turtle (*Caretta caretta*; Vulnerable) [2,3]. These species of sea turtles are all included in the Red List of Threatened Species maintained by the World Conservation Union (IUCN Red List), and are also listed under the Schedule of Protected Marine Species (Ocean Affairs council, Executive Yuan) in Taiwan. Of these, the green turtle is the most prevalent in Taiwan [2,3]. Furthermore, coastal areas in Taiwan contain important feeding and nesting sites for green turtles. However, as green turtles face numerous threats that are unrelated to wind farms (e.g., human activity, including fishery bycatch, illegal egg poaching, coastal development, marine debris, global environmental change, marine pollution, and anthropogenic-exacerbated disease including fibropapillomatosis (FP), etc.) [2–12], it can be difficult to distinguish between the effects of these threats and the impact of wind farms on the marine turtles.

The offshore wind energy industry has been growing since the 1990s, when the first offshore wind farms began operating [13]. Enthusiasm for offshore wind farms and other sources of sustainable energy is currently surging as the widespread development and adoption of sustainable energy are critical to mitigating climate change and its effects [13–17]. However, the precautionary principle dictates that offshore wind farms should not be deployed in close proximity to biodiversity hotspots, significant fish spawning areas, important migration routes, or sensitive habitats (including deep-sea corals, maerl beds, and crinoid assemblages), especially when these habitats occur within Marine Protected Areas [13].

Offshore wind turbines can have potential impacts on sea turtles in several ways. These include (1) vessel collisions with turtles, such as collisions involving the working boats of wind turbines [18]; (2) underwater sounds resulting from wind turbine operation, including pile driving [19,20]; and (3) local magnetic disturbances caused by cables, which can interfere with sea turtle migration [21,22]. Therefore, determining which effects result from offshore wind turbines, other human activities, and/or environmental factors can be difficult. Furthermore, collecting sufficient high-quality data on sea turtles over expansive ocean areas is also extremely challenging. For example, sea turtles generally spend more than 90% of their time submerged under the surface of the water [23–28]. This has limited our ability to decipher what problems sea turtles face underwater. Therefore, sea turtle stranding events could provide us with an opportunity to understand the potential negative impacts of anthropogenic activities (e.g., entanglement in fishing nets/lines/marine debris, ingestion of fish hooks, boat strikes, etc.) [4,8,10,22,26,29–34] and this could serve as a reference for sea turtle conservation management. In addition, recent advances in computer processing power and statistical methods, as well as the growing availability of large amounts of high-quality environmental data have greatly improved the ability to analyze the structure of ecological systems using mathematical methods. In recent years, the growing availability of publicly available environmental and species data has created opportunities for large-scale data analyses to investigate the impacts of specific anthropogenic disturbances on numerous species of conservation concern.

As a consequence of the aforementioned circumstances, data obtained from stranded sea turtles can provide insight into human activities that negatively impact sea turtle populations [2,8,9,26,27,29]. Such activities include vessel collisions or oil spills that damage feeding or swimming abilities [18,28,29]. This study quantitatively analyzed the impacts that numerous human disturbances and natural effects have on sea turtles, including the potential effects of offshore wind turbines. This study will contribute to our understanding of the potential causes for stranded marine turtles, thereby providing important information for application in sea turtle conservation efforts.

2. Materials and Methods

2.1. Data Collection

Sea turtle stranding records: This study collated stranded sea turtle data (data years: from 1 January 2017 to 30 September 2021) from the Marine Animal Rescue Network (MARN) of the Ocean Conservation Administration in Taiwan. Our dataset included data from each county and city where MARN operates. MARN records data from both dead and living sea turtles that were found (1) washed ashore, (2) floating in coastal waters, or (3) as fishery bycatch.

Marine environmental data: Marine environmental data (including salinity, water temperature, dissolved oxygen, and dissolved oxygen saturation as well as concentrations of chlorophyll a, ammonium, nitrate-nitrogen, phosphate, nitrite-nitrogen, silicate, copper, lead, and zinc) were obtained from the Ocean Conservation Administration website (https://iocean.oca.gov.tw/OCA_OceanConservation/PUBLIC/Marine_WaterQuality.aspx) (accessed on 10 March 2022).

The number of fishermen: We determined the number of people employed in the fishery industry using data from the Fishery Yearbook 2020, published by the Fisheries Agency of Taiwan (https://www.fa.gov.tw/view.php?theme=FS_AR&subtheme=&id=20) (accessed on 10 March 2022).

Coral coverage area: We determined the coral coverage area, using data obtained from the Report on the Results of the 2019 Coral Reef Ecosystem Survey Project [35] (https://www.oca.gov.tw/ch/home.jsp?id=394&parentpath=0,299&mcustomize=research_list.jsp) (accessed on 10 March 2022).

Additionally, we determined the number of offshore wind turbines under construction and operation in coastal areas of Taiwan (i.e., monthly turbine count) with which to estimate the impact of wind turbines on marine turtles in each county and city.

2.2. Study Area

Investigation areas were delineated around monitoring stations. These areas were typically large scale and included both coastal cities and counties in Taiwan. Specifically, these areas included New Taipei City (including Keelung City; A1), Taoyuan City (A2), Hsinchu County (A3), Miaoli County (A4), Taichung City (A5), Changhua County (A6), Yunlin County (A7), Chiayi County (A8), Tainan City (A9), Kaohsiung City (A10), Pingtung County [including North Pingtung (A11), Hengchun Peninsula (A12) and Liuchiu Island (A13)], Taitung County (A14), Hualien County (A15), and Yilan County (A16) (Figure 1). Therefore, datasets included data that fell within 16 different investigation areas. Data on stranded sea turtles were aggregated separately for the 16 investigation areas according to season [spring (S1): March to May, summer (S2): June to August, autumn (S3): September to November, winter (S4): December to February] and then matched with water quality, coral, and fisheries data. In total, there were 134 data (including salinity, water temperature, dissolved oxygen, and dissolved oxygen saturation as well as concentrations of chlorophyll a, ammonium, nitrate-nitrogen, phosphate, nitrite-nitrogen, silicate, copper, lead, and zinc) entries available for analysis.

Figure 1. Study area located in Taiwan.

2.3. Data Analysis

We first employed principal component analysis (PCA) to conduct exploratory research on water quality data. Principal component axes identified by this analysis were considered latent variables [36,37] that influenced oceanic environmental changes. The meaning of each principal component (PC) axis was determined by examination of the factor loadings of the variables as well as the temporal and spatial changes of each PC score [38], which were assessed using two-way ANOVA and multiple comparisons (using Duncan's Method). Once the primary environmental factors (latent variables) were recognized, we incorporated the data pertaining to the number of stranded sea turtles, the number of fishery employees, coral coverage, and offshore wind turbines to construct SEM for the conceptual model of ecological system changes in coastal area waters. In so doing, we used SEM, which employs both factor analysis and path analysis and can analyze complex relationships between organisms and their environment [36,39]. In other words, SEM can analyze the intricate networks of causal relationships in ecosystems [40–42]. In building our models, we used data on stranded sea turtles from the Marine Animal Rescue Network (MARN) of the Ocean Conservation Administration in Taiwan (Figure 1). Lastly, the LISREL8 program was used to perform structural equation modeling (SEM) and thereby verify conceptual models [36]. The detailed assumptions and the concept of SEM are elaborated by [36,42].

3. Results

During the study period, we recorded 810 sea turtle strandings: 692 green turtles (*C. mydas*) (85.4%) (juvenile = 567; sub-adult = 70; adult = 55), 48 hawksbill turtles (*E. imbricata*) (5.9%), 37 olive ridley turtles (*L. olivacea*) (4.5%), 30 loggerhead turtles (*C. caretta*) (3.7%), and 3 leatherback turtles (*D. coriacea*) (0.3%) (Table 1). For green turtles, juveniles (Curved carapace length; CCL < 67 cm) [2,9] were the most abundant size class (Table 2). The most prevalent oceanic-stage juveniles (CCL < 30 cm) [32,43] identified in our study were hawksbill turtles (12.5%; *n* = 6), followed by loggerhead turtles (6.6%; *n* = 2), olive ridley turtles (2.7%; *n* = 1), and green turtles (0.7%; *n* = 5) (Table 1). We found 90 turtles alive and 720 dead. The results of marine environmental data were shown in Table 3.

Table 1. Sea turtle strandings recorded from 1 January 2017 to 30 September 2021 in Taiwan.

Species	***n***	**%**	**Curved Carapace Length (cm)**			**Oceanic Juvenile (%)**
			Range	**Mean**	**SD**	
Green turtle	692	85.4	6.50–130.00	53.95	17.21	5 (0.7%)
Hawksbill turtle	48	5.9	12.00–90.00	43.50	15.47	6 (12.5%)
Olive ridley turtle	37	4.5	22.00–124.50	58.59	18.17	1 (2.7%)
Loggerhead turtle	30	3.7	11.50–120.00	78.86	21.62	2 (6.6%)
Leatherback turtle	3	0.3	140.00–150.00	144.50	5.07	-
Total	810	100				14 (1.7%)

Table 2. The life stage of green turtles in this study.

Life Stage	***n***	**%**
Juvenile (CCL < 67 cm)	567	81.9
Sub-adult (CCL 67–84 cm)	70	10.1
Adult (CCL > 84 cm)	55	7.9
Total	692	100

Table 3. Ranges and mean values (±SD) of the hydrological and metal variables included in the study (N = 134).

Variable	Range	Mean	SD
Temperature (°C)	15.8 (16.8–32.6)	26.193	3.9008
Salinity (psu)	11.6 (23.4–35.0)	32.956	1.9412
Dissolved oxygen (mg/L)	4.4 (4.5–8.9)	6.631	0.7615
Dissolved oxygen saturation (%)	87.2 (54.2–141.4)	95.927	12.2051
A chlorophyll-a (µg/L)	22.4 (0.1–22.4)	1.389	2.4330
Ammonium (mg/L)	0.46 (0.01–0.46)	0.0642	0.08872
Nitrate-nitrogen (mg/L)	0.415 (0.005–0.420)	0.07183	0.079210
Phosphate (mg/L)	0.17 (0.00–0.18)	0.0318	0.03600
Nitrite-nitrogen (mg/L)	0.130 (0.001–0.130)	0.01262	0.021747
Silicate (mg/L)	4.0010 (0.0090–4.0100)	0.425836	0.6160038
Copper (mg/L)	0.0349 (0.0001–0.0350)	0.001175	0.0035777
Zinc (mg/L)	0.0429 (0.0001–0.0430)	0.005887	0.0054381
Lead (mg/L)	0.00195 (0.00005–0.00200)	0.0001832	0.00031616

Table 4 presents the results of a two-factor analysis of variance conducted using data from 401 stranded sea turtles across 16 county districts (paired with water quality data). Results indicated that the number of stranded sea turtles in spring (March to May) was significantly higher than in autumn (September to November), winter (December to February), and summer (June to August). Furthermore, New Taipei City, the Hengchun Peninsula, Yilan-Hualien, and Liuchiu Island had significantly more stranded turtle events than did Taichung-Changhua, and Yunlin-Chiayi.

Table 4. Results of two-way ANOVA for the influence of station and seasons and the interaction between these two factors upon the number of stranded sea turtles.

Variables	Two-Way ANOVA		Multiple Comparison *
	F	p-Value	
Station	42.65	<0.001	$\mathrm{A1_{a}A12_{b}A14_{b}A15_{b}A16_{b}A13_{bc}A2_{cd}A3_{cd}A4_{cd}A9_{cd}A10_{cd}A11_{cd}A5_{d}A6_{d}A7_{d}A8_{d}}$
Season	16.37	<0.001	$\mathrm{S1_{a}S2_{b}S3_{b}S4_{b}}$
Station × Season **	5.712	<0.001	S1 $\mathrm{A1_{a}A12_{b}A14_{b}A15_{b}A16_{b}A2_{c}A3_{c}A4_{c}A5_{c}A6_{c}A7_{c}A8_{c}A9_{c}\ A10_{c}A11_{c}A13_{c}}$
			S2 $\mathrm{A1_{a}A14_{a}A15_{a}A16_{a}A2_{ab}A3_{ab}A4_{ab}A7_{ab}A8_{ab}A9_{ab}A10_{ab}A11_{ab}\ A12_{ab}A13_{ab}A5_{b}A6_{b}}$
			S3 $\mathrm{A1_{a}A12_{b}A2_{bc}A3_{bc}A4_{bc}A5_{bc}A6_{bc}A9_{bc}A10_{bc}A11_{bc}A13_{bc}A14_{bc}A15_{bc}A16_{bc}A7_{c}A8_{c}}$
			S4 $\mathrm{A1_{a}A14_{b}A15_{b}A16_{b}A9_{bc}A10_{bc}A11_{bc}A12_{bc}A13_{bc}A2_{c}A3_{c}A4_{c}A5_{c}A6_{c}A7_{c}A8_{c}}$

* = Compared using Duncan's Method. Different small letters indicate statistically significant differences ($p < 0.05$). ** = Interaction of Station and Season. A1 = New Taipei City, A2 = Taoyuan City, A3 = Hsinchu County, A4 = Miaoli County, A5 = Taichung City, A6 = Changhua County, A7 = Yunlin County, A8 = Chiayi County, A9 = Tainan City, A10 = Kaohsiung City, A11 = North Pingtung, A12 = Hengchun Peninsula, A13 = Liuchiu Island, A14 = Taitung County, A15 = Hualien County, A16 = Yilan County. S1 = Spring, S2 = Summer, S3 = Autumn, S4 = Winter.

Regarding the geographical distribution of the number of fishermen (Table 5), Kaohsiung City (48,540) and New Taipei City (including Keelung City) (41,909) had the highest "total number of professional fishermen", while Hsinchu County (1902) and Taoyuan City (623) had the lowest total number of professional fishermen. North Pingtung (5112) and Kaohsiung City (15,221) had the highest "number of coastal professional fishermen", while Changhua County (453) and Taichung City (0) had the lowest numbers of coastal professional fishermen.

Table 5. The geographical distribution of the number of fishermen included in this study.

Area	The Number of Professional Fishermen	The Number of Coastal Professional Fishermen
A1	41,909	1225
A16	16,135	3254
A15	3020	1216
A14	3555	914
A12	4597	2045
A13	7355	1789
A11	18,693	4686
A10	48,540	15,221
A9	17,646	1991
A8	7442	684
A7	18,889	2162
A6	6989	453
A5	4304	0
A4	8926	3613
A3	1902	1535
A2	623	623

A1 = New Taipei City, A2 = Taoyuan City, A3 = Hsinchu County, A4 = Miaoli County, A5 = Taichung City, A6 = Changhua County, A7 = Yunlin County, A8 = Chiayi County, A9 = Tainan City, A10 = Kaohsiung City, A11 = North Pingtung, A12 = Hengchun Peninsula, A13 = Liuchiu Island, A14 = Taitung County, A15 = Hualien County, A16 = Yilan County.

The largest extent of coral coverage was found in the Hengchun Peninsula (44.69%), followed by Taitung (38.21%), New Taipei City (30.55%), Hualien (26.88%), Yilan (23.02%), and Liuchiu Island (15.70%) (Table 6).

Table 6. The geographical distribution of the coral cover used in this study.

Area	%
A1	27.56
A16	23.02
A15	26.88
A14	38.21
A12	44.69
A13	15.70
A11	0
A10	0
A9	0
A8	0
A7	0
A6	0
A5	0
A4	0
A3	0
A2	0

A1 = New Taipei City, A2 = Taoyuan City, A3 = Hsinchu County, A4 = Miaoli County, A5 = Taichung City, A6 = Changhua County, A7 = Yunlin County, A8 = Chiayi County, A9 = Tainan City, A10 = Kaohsiung City, A11 = North Pingtung, A12 = Hengchun Peninsula, A13 = Liuchiu Island, A14 = Taitung County, A15 = Hualien County, A16 = Yilan County.

Results of principal component analysis (PCA) on water quality data from 16 coastal districts in Taiwan between 2017 and 2021 revealed that the first (PC1) to fourth (PC4) principal components explained 68.42% of the overall water quality variation (Table 7).

Among these components, the loadings of salinity, ammonium, nitrate-nitrogen, nitrite-nitrogen, phosphate, and silicate on the first component axis (PC1) were relatively high, with salinity having a negative value and the other nutrients having positive values. These results were indicative of the effects of nutrient input from freshwater rivers into the sea. Therefore, we named this component axis "river-derived nutrients". Variance analysis of the component scores through this axis showed that river-derived nutrients were significantly higher in northern Pingtung and significantly lower in the Hengchun Peninsula, Yilan, Hualien, and Taitung (Table 8).

Table 7. The loadings of the principal components (PC) 1–4 for abiotic variables assessed in this study area (*N* = 134).

Variables	PC1	PC2	PC3	PC4
Temperature	−0.10	−0.12	0.00	−0.87
Salinity	−0.71	0.03	0.02	0.51
Dissolved oxygen	−0.04	0.83	0.02	0.39
Dissolved oxygen saturation	−0.20	0.89	0.03	−0.00
A chlorophyll-a	0.13	0.71	−0.07	−0.07
Ammonium	0.51	0.05	−0.06	0.04
Nitrate-nitrogen	0.89	−0.08	0.02	0.19
Phosphate	0.58	−0.01	−0.06	0.52
Nitrite-nitrogen	0.69	0.08	0.06	−0.02
Silicate	0.87	−0.21	0.00	0.07
Copper	−0.08	−0.04	0.89	0.03
Zinc	−0.04	−0.05	0.77	−0.23
Lead	0.10	0.05	0.80	0.16
Eigenvalues	3.22	2.06	2.04	1.57
Total variance (%)	20.73	40.60	56.32	68.42

The second component axis (PC2) (Table 8) had larger loadings for dissolved oxygen, saturated dissolved oxygen, and chlorophyll a. All of these values were positive, and we posited that this was indicative of vigorous photosynthesis by phytoplankton, which is an oxygen-releasing process. We, therefore, named this axis "phytoplankton photosynthesis". Results of variance analysis revealed that phytoplankton photosynthesis was significantly higher in northern Pingtung and significantly lower in Yilan, Hualien, Keelung, and the Hengchun Peninsula.

The third component axis (PC3) (Table 8) had larger loadings of copper, zinc, and lead, indicating that these three heavy metals were found together. Therefore, this component axis was named "heavy metals".

The fourth component axis (PC4) (Table 8) had larger loadings of water temperature and salinity, with the former being negative and the latter being positive overall. In Taiwan, the low winter water temperature coincides with the dry season, which is characterized by reduced river flow and freshwater input to the sea. Therefore, this component axis was named "seasonal variation".

In SEM, squares represent observed variables while circles represent latent variables estimated and identified by observed variables [38,42]. Path coefficients between environmental and biological latent variables range from −1 to 1, with the absolute value indicating the degree of influence of a given latent variable. Solid lines indicate significant effects while dotted lines indicate insignificant effects, with arrowheads indicating the direction of influence. Figure 2 presents the ecological model constructed in this study. Specifically, our model was constructed by combining environmental data, fishery statistics, water quality data, coral data, and sea turtle data. The latent variables used in this model, including "nutrients (−) from rivers", "phytoplankton photosynthesis", and "heavy metals", were derived from the principal component analysis of water quality in the model. The latent variable "fishing disturbance" was estimated using two measured parameters: "the total number of all professional fishery personnel" and "the number of coastal fishery personnel". The latent variables "coral colony density", "stranded sea turtle quantity", and "offshore wind turbine effects" were estimated using a single measured variable: "coral coverage area", "the number of stranded turtles", and "offshore wind turbine (unit) operating quantity", respectively.

Table 8. Results from two-way analysis of variance (ANOVA) tests and all pairwise multiple comparisons (using Duncan's Method) on principal components 1 (PC1) to 4 (PC4).

(A) PC1			
Variables	**Two-Way ANOVA**		**Multiple Comparison***
	F	***p*-Value**	
Station	6.562	<0.001	$A11_a$ $A7_{ab}$ $A8_{ab}$ $A5_{bc}$ $A6_{bc}$ $A13_{bc}$ $A2_c$ $A3_c$ $A4_c$ $A1_{cd}$ $A9_{cd}$ $A10_{cd}$ $A12_{cd}$ $A14_d$ $A15_d$ $A16_d$
Season	2.491	0.065	
Station × Season **	1.383	0.136	
(B) PC2			
Variables	Two-way ANOVA		Multiple Comparison *
	F	*p*-value	
Station	2.208	0.033	$A11_a$ $A13_{ab}$ $A2_{abc}$ $A3_{abc}$ $A4_{abc}$ $A5_{abc}$ $A6_{abc}$ $A7_{abc}$ $A8_{abc}$ $A9_{abc}$ $A10_{abc}$ $A14_{bc}$ $A15_{bc}$ $A16_{bc}$ $A12_c$
Season	2.352	0.077	
Station × Season **	0.9	0.601	
(C) PC3			
Variables	Two-way ANOVA		Multiple Comparison
	F	*p*-value	
Station	0.631	0.75	
Season	0.773	0.512	
Station × Season **	0.451	0.986	
(D) PC4			
Variables	Two-way ANOVA		Multiple Comparison *
	F	*p*-value	
Station	7.062	<0.001	$S4_aS1_bS3_bS2_c$
Season	65.28	<0.001	$A1_aA5_aA6_aA2_{ab}A3_{ab}A4_{ab}A14_{bc}A15_{bc}A16_{bc}A12_{bcd}$ $A9_{cd}A10_{cd}A13_{cd}A7_dA8_dA11_d$
Station × Season **	1.917	0.014	

* = Compared using Duncan's Method. Statistically significant differences ($p < 0.05$) are indicated by different small letters. ** =Interaction of Station and Season. A1 = New Taipei City, A2 = Taoyuan City, A3 = Hsinchu County, A4 = Miaoli County, A5 = Taichung City, A6 = Changhua County, A7 = Yunlin County, A8 = Chiayi County, A9 = Tainan City, A10 = Kaohsiung City, A11 = North Pingtung, A12 = Hengchun Peninsula, A13 = Liuchiu Island, A14 = Taitung County, A15 = Hualien County, A16 = Yilan County. S1 = Spring, S2 = Summer, S3 = Autumn, S4 = Winter.

In our model, "nutrients (−) from rivers" and "phytoplankton photosynthesis" had significant effects on "coral density", with coefficients of 0.22 and −0.40, respectively. The former indicates that environments characterized by excessive nutrient input from rivers are not suitable for coral growth, while the latter indicates that areas characterized by vigorous phytoplankton photosynthesis are also unsuitable (because they are likewise nutrient-rich, eutrophic environments). With regard to the impact of "nutrients originating from rivers" and "photosynthesis of phytoplankton" on the "stranded sea turtle quantity", the values of 0.08 and −0.02, respectively, indicate that the nutrients brought by rivers and the strength of photosynthesis in the water were not related to the stranding of sea turtles. Conversely, "heavy metals" and "fishing disturbance" had significant and positive effects (0.24 and 0.26, respectively) on the stranded sea turtle quantity. The impact of "offshore wind turbine effect" on stranded sea turtles (a key focus of this study) was not significant at 0.06. This strongly suggests that, to date, the installation of wind turbines in Miaoli and Changhua has not directly increased the number of sea turtle strandings.

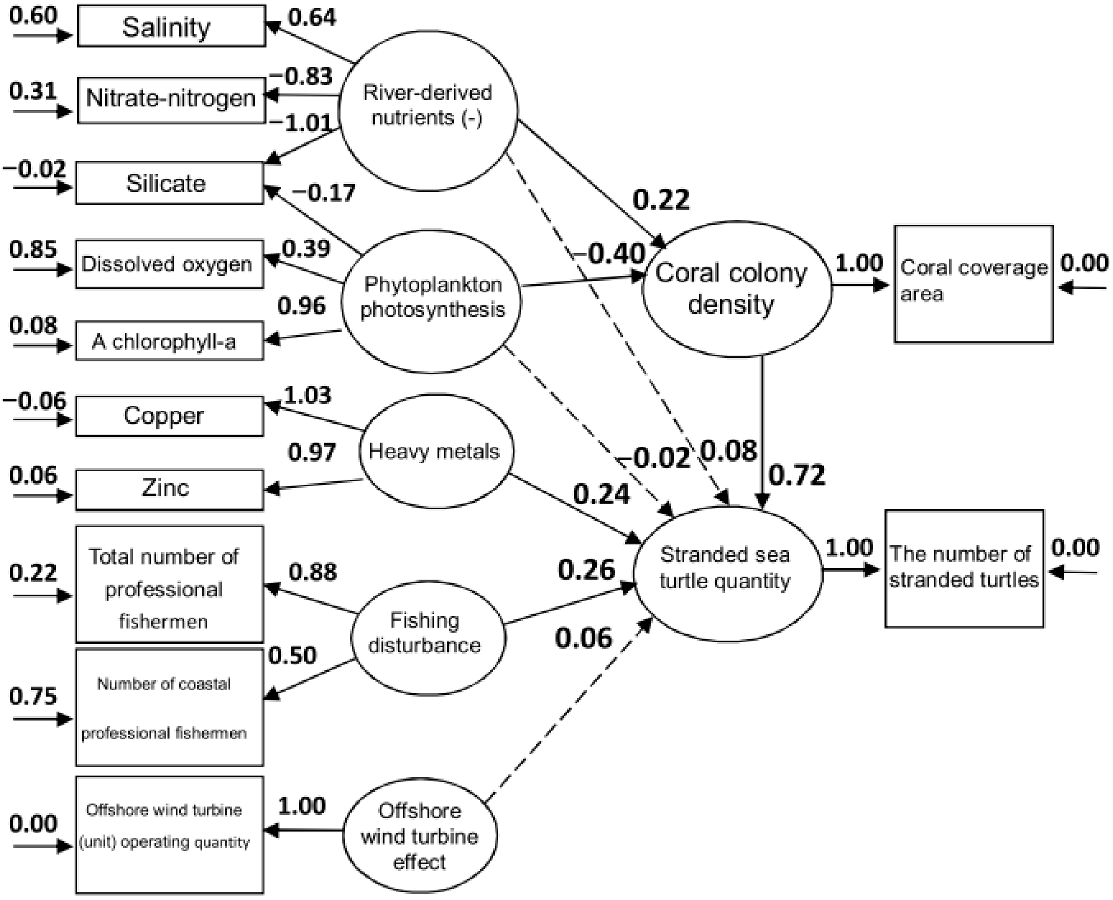

Figure 2. Final structural equation modeling (SEM) with standardized coefficients. Solid arrows: significant impact; dashed arrows: insignificant impact.

4. Discussion

Knowledge of the interactions between offshore wind farms and sea turtles in foraging areas/migratory corridors in Taiwan remains very limited. This is the first study to employ SEM and data from multiple databases to conduct quantitative analysis and establish a model to elucidate the potential causes of sea turtle strandings in Taiwan. This study analyzed the coastal areas of major counties and cities in Taiwan using publicly available water quality data.

In the present study, the *C. mydas* was the most frequent species involved in stranding. As has been found in previous studies, the green turtle is the most common species of sea turtle in Taiwan [3,10,44,45]. Furthermore, green turtle strandings have been recorded more frequently than other species in all regions of Taiwan [34,45,46]. We also found that coastal areas of densely populated western regions were characterized by greater eutrophication and land-based pollution than coastal areas in the eastern, northern, and southern regions. The water quality monitoring station of Pingtung is adjacent to Donggang Creek, where the livestock industry is highly developed and eutrophication is most severe, while areas with fewer river-derived nutrients were associated with sparsely populated eastern counties and better river water quality (in most cases). Lower nutrient concentrations can also be explained by the dilution effect of the Pacific Ocean and the lack of large rivers in the Hengchun Peninsula. The high level of photosynthesis in northern Pingtung can be primarily explained by the severe eutrophication of Donggang Creek, while lower photosynthesis levels are found in marine areas that are strongly diluted by the eastern ocean and do not feature large rivers that input high amounts of land-based pollutants. The study conducted by Liu et al. (2015) [47] suggested that southwestern Taiwan is also a highly problematic region for coastal eutrophication. With regard to the possible effects of the increased eutrophication in these areas on the populations of sea turtles, previous studies also found that fibropapillomatosis (FP) is more prevalent in areas exposed to greater eutrophication [48–50]. FP is a tumor-forming disease that affects all sea turtle species and is most common in green turtles [5]. Reports on FP in green turtles in Asia are still very limited. However, the disease has recently been described in endangered green turtles in Taiwan [6,44,51].

SEM is a powerful multivariate statistical technique increasingly used in scientific research to evaluate and test multivariate causal relationships [42]. In addition, over the past 20 years ecologists have applied SEM to test multi-variable hypotheses. The complex networks of causal relationships in ecosystems can be analyzed using SEM [40–42]. In terms of the SEM results (Figure 2), the SEM indicated that coral colony density had a positive effect on the number of turtle strandings. The green turtle is the most common species of sea turtle in Taiwan [3]. Because green turtles mainly feed on seagrass, seaweed, and in coral reef terrains [43,52,53], the highly significant positive correlation between “coral density” and “stranded sea turtle quantity” of 0.72 (Figure 2) revealed that suitable coral reef habitats attracted a large number of sea turtles, which may naturally result in larger numbers of stranded sea turtles (e.g., anthropogenic interactions). In other words, the majority of green turtles in this study were identified to be juveniles (CCL < 67 cm) to sub-adults (CCL 67–84 cm) (Table 2) and were more likely to be resident animals (neritic-stage) [32]. As such, they are more likely to be affected by anthropogenic activities due to their high dependence on coastal feeding grounds and frequent use of nearshore habitats [2,32].

Regarding fishing disturbance and stranding, the SEM (Figure 2) showed a significant effect of fishing disturbance on the number of stranded sea turtles (0.26). Previous literature has reported that bycatch, net entanglement, and collisions with ocean vessels can cause significant harm to sea turtles [28]. In addition, sea turtle strandings in the Mediterranean are also strongly linked to bycatch: according to a 14-year annual study [30], more than half of loggerhead sea turtle (*C. caretta*) strandings were the result of human activities such as fishing. In Turkey, strandings were primarily caused by bycatch and marine pollution [31]. Another study reported that the mortality of loggerhead, olive ridley, and leatherback sea turtles in southern Brazil was also associated with fishing activities in feeding habitats or in migratory corridors between breeding and feeding areas [32]. In a study conducted in Hawaii and the insular Pacific, the main reasons for sea turtle strandings were bycatch and collision (excluding FP) [33]. Bycatch was identified as a significant concern for sea turtles in Spain and Taiwan [30,34]. In Taiwan, a report titled “Twenty-three Years of Sea Turtle Stranding/Bycatch Research in Taiwan” indicated that eighty percent of the sea turtles that were stranded or caught had already perished [34]. One report by Chen et al. (2012) [46] indicates that fishery bycatch is likely the cause of stranded sea turtle mortality in Taiwan. In addition to coral colony density, ocean currents and wind may also influence the detection of sea turtle strandings. The lack of data on ocean currents and wind in our study is a limitation of this study.

With regard to heavy metals, we also observed higher concentrations of heavy metals in waters where there were more sea turtle strandings. Although this study cannot confirm whether high levels of heavy metals are harmful to the health of wild sea turtles, other researchers have raised concerns about heavy metal pollution in sea turtle habitats [2,9,54–56]. In fact, it has been suggested that sea turtles’ immune systems may be more susceptible to the harmful effects of heavy metals than those of other vertebrates [54,56]. As a consequence of the aforementioned circumstances, the current study focused on threats from environmental contaminants, a priority area of research for marine sea turtle conservation [4,57]. Fibropapillomatosis (FP), for example, is a tumor-forming disease that affects all species of sea turtles and is most commonly found in green turtles [5,6,11,12]. A higher prevalence of FP in sea turtles has been documented in highly contaminated marine environments or environments with poor water quality [48,49,58,59]. Reports of FP in sea turtles in Asia are still very limited. However, cases of FP have been discovered in Taiwanese waters in recent years [6,44,51]. Another issue related to environmental contaminants in marine ecology research is that the green turtles in Taiwan may have encountered coastal pollution containing antimicrobial agents or heavy metals when they migrated to nearshore feeding areas after recruitment. [2]. As a consequence of the aforementioned circumstances, in order to benefit sea turtle conservation, future research should focus on how to prevent pollution in the main sea turtle activity areas in Taiwan.

Our findings suggest that offshore wind turbines do not have a significant impact on sea turtle strandings. Although our results cannot determine whether offshore wind turbines lead to physiological disturbances in sea turtles that cause them to leave an area, our results can serve as an important reference in future evaluations of wind turbine installations. Note that in this study, the offshore wind turbines located in Miaoli and Changhua, Taiwan are not situated in sea turtle foraging hotspots or significant migratory corridors for sea turtles. Satellite tracking studies to date do not provide conclusive evidence that the Miaoli and Changhua Sea are hot spots for sea turtle foraging, or that they are significant sea turtle migration corridors [3,10,27,45]. However, the impact of offshore wind turbines on sea turtles may include collisions with these reptiles caused by the working boats of wind turbines [18], undersea sounds created by wind turbines such as pile driving [19,20], and local magnetic disturbances generated by cables may have negative impacts on sea turtles [21,22,60,61]. Therefore, the potential impact of offshore wind turbines on sea turtles needs to be further investigated in the future. It is essential for sea turtle conservation management to document important foraging sites and the composition and numerical importance of foraging aggregations [62]. Further study of sea turtle movements (e.g., satellite tracking) in these areas should be pursued to characterize their main foraging areas and ultimately to assess their interactions with human activities in these habitats. Furthermore, as new molecular and genetic technologies (e.g., environmental DNA, eDNA) are developed, it is possible to adapt and optimize them for sea turtle conservation. For example, eDNA detection has complemented traditional in-water monitoring of sea turtles by allowing detection even when turtles have not been visually observed [63]. Therefore, eDNA techniques could be a viable and efficient alternative to traditional sea turtle monitoring methods.

5. Conclusions

In conclusion, to the best of our knowledge, this is the first study to unravel the complex relationships between environmental factors, anthropogenic interactions, and sea turtle strandings in Taiwan. The results of the SEM indicated that coral colony density, heavy metals, and fishing disturbance had a significant influence on sea turtle stranding events. As a result of the aforementioned circumstances, future analyses examining the impact of offshore wind turbines in significant sea turtle habitats ought to be conducted. Additionally, to conserve endangered sea turtles, we recommend applying PCA and SEM techniques to determine potential causes of sea turtle strandings and verify their direct and indirect effects in other areas of concern to establish upcoming environmental impact assessments.

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