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【Research Article】

Evaluation of Impacts of Environmental Factors and Operation Conditions on Catch of the Coastal Squid Jigging Fishery—Does the Amount of Light Really Matter?

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ABSTRACT

Factors that influence squid catch of the coastal squid jigging fishery were analyzed using data sets recorded by 9 boats in Tsushima Strait in January and February 2010 including daily catch amount, lighting pattern of fishing lamps, presence of dolphins during operations, and the number of other jigging boats operating within 2 nautical miles from the boat. Generalized linear modeling analysis indicated that catch is explained by the fishing ability of the captain and crew of each boat, illuminated fraction of the moon (lunar phase) and presence of dolphin, with assuming monthly differences in squid abundance. Influences on lighting patterns of fishing lamps and number of operating boats around the boat that fishermen always have keen interests are not detected in the analysis. The factor of fishing ability of the captain and crew of the boat may be interrupted as the ability to search the promising fishing locations in the fishing ground. Furthermore, presence of dolphin showed a negative impact on catch.

1. Introduction

Overinvestment in lighting apparatus has been made in the coastal squid jigging fishery in Japan because fishermen have believed that stronger lights attract more squids[1]. Application of light emitting diodes (LEDs) as highly energy-efficient fishing lamps has been promoted in the squid jigging fishery for reducing fuel consumption while maintaining the squid catch[2)～4)].

Fishing light is however not the only factor influencing squid catch. Squid catch of coastal jigging boats equipped with LEDs and metal halide lamps (MHs) was found to be influenced by : fishing ability of the captain and crew and change in monthly squid abundance in addition to the number of MHs[3], and illuminated fraction of the moon explaining direct and indirect influences of the lunar phase[5]. In addition, the experimental operation of a stepwise lighting method termed stage reduced lighting method (SRL), which lit all lamps for several hours at the beginning of lighting and then progressively reduced the number of lamps until the end of fishing, enabled the maintenance of commercial catch levels[5].

Factors influencing squid catch other than those demonstrated in the above studies may exist in the squid jigging fishery. For example, catch decrease was reported in hook and line and large scale trap-net fisheries in the Tsushima Strait when dolphins were observed[6]. Negative impacts of marine mammals on commercial catch are reported in gillnet fisheries[7)～11)], longline fisheries[10), 12)], hook and net fisheries[11), 18)]. Presence of dolphins around jigging boats may also impact squid catch because in other squid fisheries entanglement of southern sea lion *Otaria flavescens* in fishing lines[12] and depredation of hooked squid (*O. flavescens*[12], striped dolphin *Stenella coeruleoalba*[19]) are reported.

Another potential factor is the interaction of lighting of squid jigging boats. Many jigging boats come from all over Japan to capture Japanese common squid *Todarodes pacificus* in the Tsushima Strait, western Japan in the winter season. Under such crowded operational conditions, overlap of the illuminated areas by

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jigging boats as reported in the Tsugaru Strait, northern Japan in summer[20] may influence the catch performance.

In this study, we investigate influences of factors mentioned above on squid catch in the Tsushima Strait in winter through analysis of catch and related data collected in January and February 2010.

2. Material and methods

1) Operations and collected data

Nine coastal squid jigging boats of 19 gross tons equipped with blue LEDs (9kW output in total, Takagi Cooperation, Kagawa, Japan) and MHs (3kW output each, 50 bulbs in maximum number) carried out experimental operations that SRL was mandatory and conventional operations that captains could choose their lighting patterns and fishing locations at will in the Tsushima Strait in January and February 2010 (256 operations in total, **Fig. 1**, **Table 1**). Captains recorded daily catch amount of squid in number of cases, fishing location, lighting pattern (with or without SRL and number of MHs used with LEDs), and time sequence of operational processes and number of dolphins observed from the wheelhouse during the operation in distributed logbooks. Also captains photographed the radar display using digital cameras when they started lighting (around 18 O'clock). Photographs of the radar display were however not successful in 92 operations and consequently data sets having all items were obtained from remaining 164 operations (**Table 1**).

2) Factors influencing squid catch

We assumed that squid catch C is expressed as a product of the catchability coefficient q, fishing effort E, and abundance of squid in the fishing ground N.

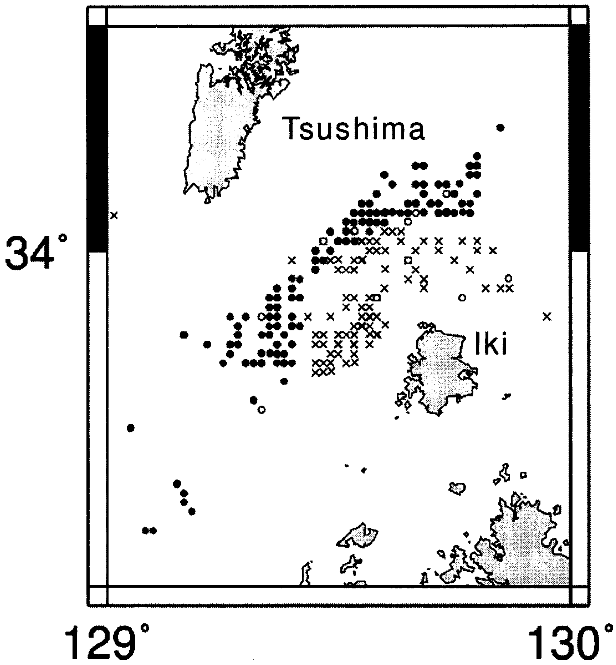

Fig. 1 Fishing ground.
● ; experimental operations with the stage reduced lighting, ● ; free operations outside 12 nautical mile boundary, × ; free operations inside 12 nautical mile boundary, ○ ; operations where dolphins were observed.

$$C = qEN \quad \cdots\cdots(1)$$

In equation (1), we used catch data of *T. pacificus* (33,255 cases, 99.4 % of total catch amount) as C for the analysis. One operation (from evening to next morning) was used for the unit of fishing effort E. Operated month as a two-level categorical variable (*month* : January or February) was used for squid abundance in the fishing ground N, assuming abundance was different by month.

Table 1 Types of operation and their numbers.

Boat ID	Experimental operations[a]			Outside of the boundary			Inside of the boundary			Total number of operations	Catch amount (cases)
	Number of operations	all items[b]	dolphins[c]	Number of operations	all items[b]	dolphins[c]	Number of operations	all items[b]	dolphins[c]		
A	4	2	1	2	1	1	16	14	2	22	1584
B	18	17	2	2	1	0	6	4	2	26	4010
C	15	13	0	2	2	0	10	6	0	27	3032
D	13	12	1	9	5	0	13	5	0	35	3583
E	18	16	0	5	1	0	10	4	0	33	3662
F	7	5	0	3	3	0	22	14	1	32	3382
G	16	15	0	2	1	0	13	9	0	31	4701
H	18	9	0	1	1	0	4	4	0	23	4950
I	5	0	0	8	0	0	14	0	1	27	4351
Total	114	89	4	34	15	1	108	60	6	256	33255

a : Stage Reduced Lighting method was tested outside of the boundary, b : Number of operations that contain all data items, c : number of operations that dolphins were observed.

We considered that the catchability coefficient q in equation (1) can be extracted as a product of factors ; we set the lighting pattern including number of MHs used[3] with or without SRL[5], fishing ability that explains the difference of the fishermen's skill[3], and illuminated fraction of the moon[5] for explaining direct and indirect influences of the lunar phase[21), 22)].

Nine boats took various lighting patterns in conventional operations while 2 lighting patterns were taken in the SRL experiment. We set a nine-level categorical variable for summarizing the lighting pattern (**Table 2**, *light* : L1-L9). L6 and L7 were patterns taken for the experiment and the other patterns were done by fishermen's decision. Squid jigging fishery council of Nagasaki Prefecture has placed a boundary at 12 nautical miles from the coastlines of Iki and Tsushima Islands to avoid conflict between large (>10 GRT) and small (<10 GRT) boats, so all squid jigging boats operating inside the boundary can use a maximum 60 kW electric output for fishing lights (LEDs and 17 MHs for experimental boats). Accordingly, the factor of the lighting pattern may contain this influence of fishing location, since selection of fishing location inside/outside of the boundary consequently limits the available electric output. Besides, we assume that fishing skill of the captain and crew of each boat may be different, so that a nine-level categorical variable corresponding to each boat (**Table 2**, *boat* : A-I) was set for describing fishing ability of the captain and crew of each boat. This factor may also contain the influence of fishing location because experimental boats had to operate outside of the boundary in the experimental operations with SRL (114 operations, *light* : L6 and L7), but captains chose their fishing locations at will in the remaining 142 operations. Illuminated fraction of the moon was also set as a continuous variable (**Table 2**, *lunar* : 0-1.00) .

When presence of dolphin was recorded, the catch seemed extremely small although number of records was also small (**Table 1**, 11 operations in total). We therefore considered presence of dolphin as a factor influencing catchability coefficient q. We set a simple two-level categorical variable for a factor of dolphin presence (*dolphin* : absence or presence) because the observation skill/range may differ among boats/time.

Jigging boats fishing close to each other may not catch a sufficient amount of squid as they compete for attraction. According to the interviews to some captains, they attempt to keep a distance of at least 1.5 nautical miles to the next boat during fishing to avoid the interaction of lighting in this area and season. We therefore set this factor as a discrete variable (*congestion* : 0～24) by counting the number of drifting boats within a 2 nautical miles radar range.

Details on factors and their settings for squid abundance N and the catchability coefficient q are presented in **Table 2**.

3) Catch models

Daily catch was analyzed as a function of factors mentioned above by the generalized linear modeling

Table 2 Explanatory variables considered for GLM analysis in the study.

Explanatory variable	Factor	Range
month[a]	Abundance index of Japanese common squid	January or February
light[b]	Lighting pattern	L1 ; 12 MHs + LED
		L2 ; 17 MHs + LED
		L3 ; 30 MHs + LED
		L4 ; 36 MHs + LED
		L5 ; All MHs[d] + LED
		L6 ; SRL[e] with 30 MHs + LED
		L7 ; SRL with 36 MHs + LED
		L8 ; SRL with 12 MHs + LED
		L9 ; SRL with 17 MHs + LED
boat[b]	Fishing ability of skipper	A to I for each boat
lunar[c]	Lunar phase	0 − 1.00
dolphin[b]	Impact of dolphin	Presence or Absence
congestion[a]	Number of squid jigging boats within 2 n. m. of each experimental boat	0 − 24

a, b and c indicates levels of measurement of factors (a ; ordinal scale, b ; nominal scale, c ; ratio scale), d ; 47-50 MHs depending on the boat, e ; Stage Reduced Lighting method.

(GLM) method using the statistical computing software R (with *glm.nb* function in the MASS package ver. 2.13.0, R Development Core Team). We assume the catch C_i (i.e., the number of cases of squid caught in the i th operation) is a random variable having a negative binomial distribution because squid catch showed a wide range of variations.

$$C_i \sim \text{Negative Binomial}\,(\mu_i, \theta) \quad \cdots\cdots(2)$$

μ_i and θ are an expected value of C in the i th operation and a potential dispersion parameter to be estimated respectively.

GLM analysis was performed by a cascade of process to utilize obtained data sets. Following full-model consisting of all explanatory variables in **Table 2** and interactions *month : dolphin, light : dolphin*, and *congestion : dolphin* were assumed in the first-stage of the analysis by using data sets which all explanatory variables were recorded (164 operations).

$$\begin{aligned}\log(\mu_i)=&\beta_0+\beta_1\, month + \beta_2\, light+\beta_3\, boat\\ &+\beta_4\, lunar+\beta_5\, dolphin+\beta_6\, congestion\\ &+\beta_7\, month : dolphin+\beta_8\, light : dolphin\\ &+\beta_9\, congestion : dolphin \quad \cdots\cdots(3)\end{aligned}$$

where β_0 is the intercept (constant) and β_1 to β_9 are coefficients for explanatory variables. Interactions *month : dolphin*, and *light : dolphin*, were chosen based on related studies ; seasonal difference in dolphin occurrence[6), 23)] and attraction of dolphins to squid fishing boats[19)]. For *congestion : dolphin*, we considered dolphin may move to other boats when many jigging boats are operating around the experimental boat.

At the first-stage of the GLM analysis, we applied data sets containing all data items (**Table 2**, 164 operations) for equation (3) and identified significant variables. Significant variables estimated in the first-stage of the analysis were used as a new full-model in the second-stage of the GLM analysis which uses all data sets (256 operations). The stepwise forward entry method was taken to verify all combinations of variables for parameter estimation and the model with the lowest AIC (Akaike's Information Criteria) was chosen.

3. Results

Daily catches of the 9 boats during the experimental period varied between 0-659 cases (mean 129.9±125.1SD). Catches were greater in operations in January (0-659 cases, mean 166.2±132.7SD) than operations in February (0-624 cases, mean 89.4±102.3SD, **Fig. 2**). Catch also increased in operations with SRL when compared only with lighting patterns (**Fig. 3**).

Daily catch amount was modeled as the following equation (4) for data sets in which all data items were recorded (164 operations, **Table 3**).

$$\begin{aligned}C \sim &Intercept + month + light + boat\\ &+ lunar + dolphin + month : dolphin\\ &+ light : dolphin \quad \cdots\cdots(4)\end{aligned}$$

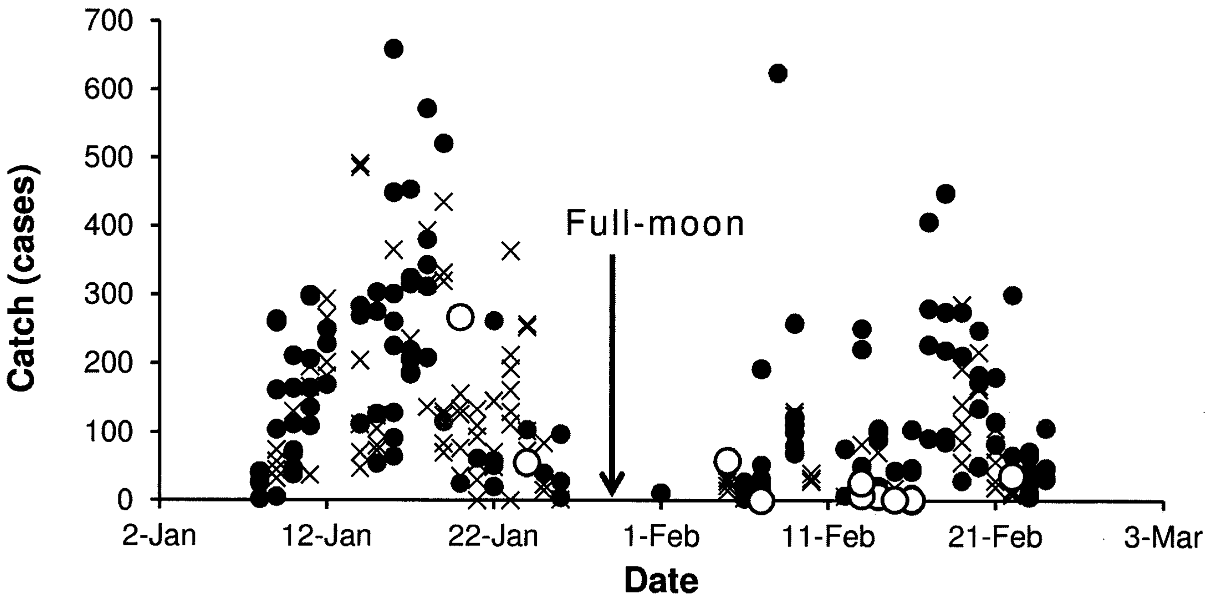

Fig. 2 Catch of Japanese common squid ***Todarodes pacificus.***
● ; catch in experimental operations with the stage reduced lighting, ● ; free operations outside 12 nautical mile boundary, × ; free operations inside 12 nautical mile boundary, ○ ; operations that dolphins were observed.

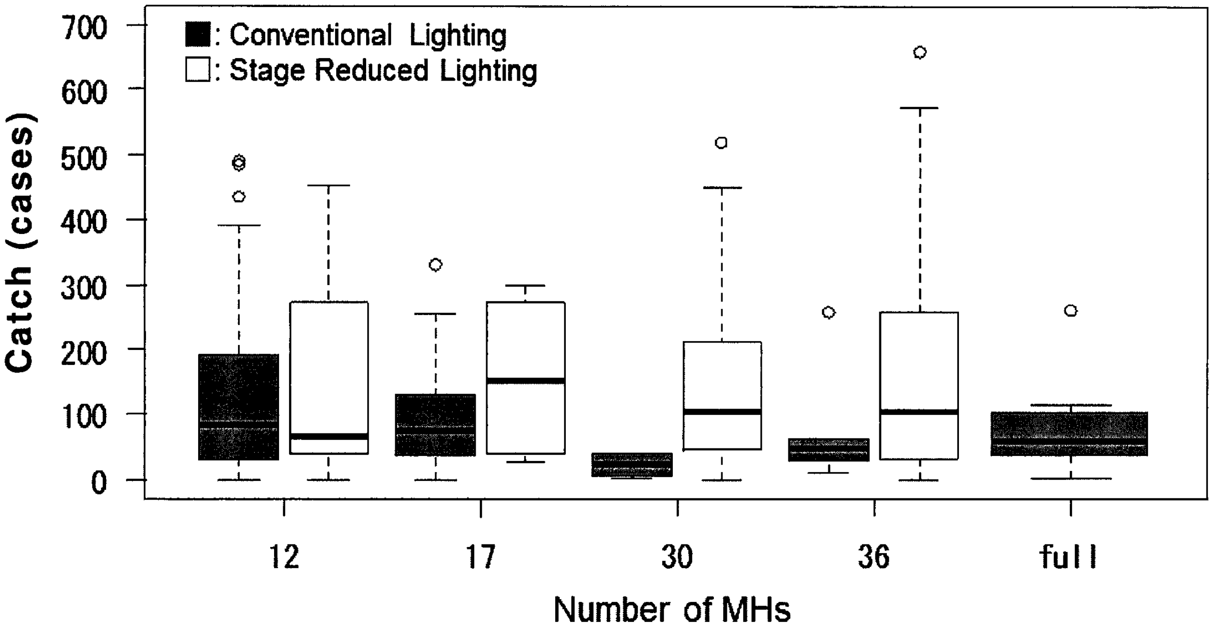

Fig. 3 Catch summary of *Todarodes pacificus* by lighting patterns.
Number of MHs means number of metal halide lamps used with LEDs in the operations. In the case of the stage reduced lighting, all MHs and LED were turned on for approximately 3.8 h at the beginning of operations, and then the number of MHs was reduced to the numbers shown on the horizontal axis.

Table 3 Parameter estimates, standard errors (s.e.), Wald's statistics (*W*), and their *p*-value in the GLM analysis using data set of operations that contain all data items (164 operations).

	Estimate	(s. e.)	*W*	*p*-value
Intercept	4.34	(0.28)	15.48	<0.001
month				
January	0.60	(0.15)	4.10	<0.001
light				
L3	−1.82	(0.67)	−2.72	<0.01
L9	1.36	(0.49)	2.76	<0.01
boat				
Boat B	0.56	(0.30)	1.85	0.06
Boat G	0.60	(0.28)	2.11	<0.05
lunar	−1.56	(0.41)	−3.83	<0.001
dolphin				
presence	−1.48	(0.77)	−1.92	0.05
month : dolphin	1.92	(1.11)	1.73	0.08
January:presense				
light : dolphin	−3.49	(1.49)	−2.34	<0.05
L6 : presense				

Estimate of intercept includes effects of the basis of incorporated factors (*month* : February, *light* : L1, *boat* : Boat A, *dolphin* : absence)

Influences of *congestion* and *congestion : dolphin* were not significant in this analysis ($P>0.1$). We removed *congestion* and *congestion : dolphin* from equation (3) and used equation (4) as the new full-model. Parameter estimation was performed using all data sets (256 operations) and the following equation (5), which did not include *light* as a significant factor, was obtained from this analysis.

$$C \sim Intercept + month + boat + lunar + dolphin + month:dolphin \quad \cdots\cdots(5) \quad (\mathrm{AIC}: 2949.2)$$

Since the fishing ability of 5 boats (A, C, D, E and F) was not significantly different (**Table 4**, $P>0.05$), we reduced the level of the categorical variable *boat* from nine to five by setting the fishing ability of the 5 boats (A, C, D, E and F) as the same and conducted the

Table 4 Parameter estimates, standard errors (s.e.), Wald's statistics (*W*), and their *p*-value in the GLM analysis using all data set (256 operations).

	Estimate	(s. e.)	*W*	*p*-value
Intercept	4.64	(0.13)	36.18	<0.001
month				
January	0.45	(0.12)	3.77	<0.001
boat				
Boat B	0.50	(0.20)	2.56	0.01
Boat G	0.40	(0.18)	2.25	0.024
Boat H	0.62	(0.21)	3.05	<0.01
Boat I	0.54	(0.19)	2.81	<0.01
lunar	−1.19	(0.26)	−4.69	<0.001
dolphin				
presence	−1.93	(0.33)	−5.84	<0.001
month : dolphin	1.94	(0.73)	2.66	<0.01
January : presense				

Estimate of intercept includes effects of the basis of incorporated factors (*month* : February, *light* : L1, *boat* : Boats A, C, D, E and F as the same level, *dolphin* : absence)

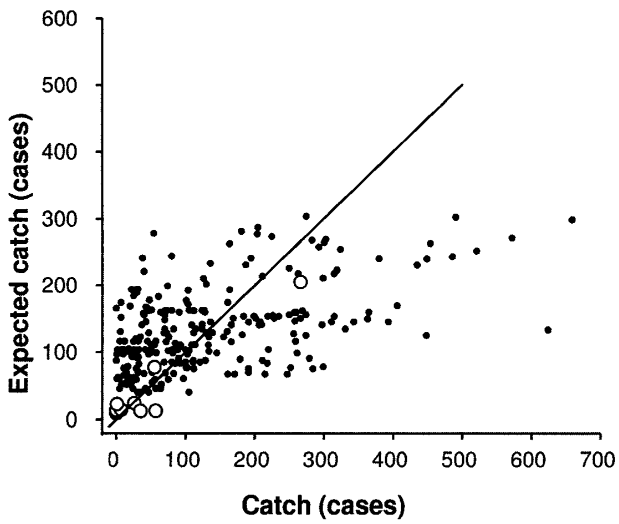

Fig. 4 Expected catch (cases) of *Todarodes pacificus* plotted against observed catch (cases) for the adopted model (eq. (6), Table 4).
○ designate plots when dolphins were present.

parameter estimation again. The following equation (6) with lower AIC value was obtained from this analysis (**Table 4, Fig. 4**) .

$$C \sim Intercept + month + boat + lunar + dolphin + month : dolphin \quad \cdots\cdots(6) \quad (\mathrm{AIC}: 2943.8)$$

Through all analyses conducted above, using partial and all data sets, the explanatory variables *month, boat, lunar*, and *dolphin* always influenced the squid catch. Equation (6) indicated that the fishing ability of the boats, illuminated fraction of the moon and presence of dolphins strongly influence the squid catch in operations (**Fig. 5**). Four boats (B, G, H, and I) are likely to capture more squid than the remaining 5 boats (A, C, D, E and F), but catches of all boats decrease when the illuminated fraction of the moon approaches to 1 (full moon) and/or dolphins occur around the boats. In addition, presence of dolphins showed an interaction with month (*month : dolphin*).

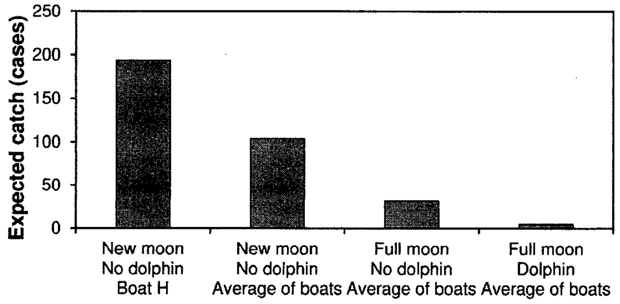

Fig. 5 Expected catch of *Todarodes pacificus* in in February by difference of fishing ability, lunar phase and presence of dolphins.
Average of boats designates boats A, C, D, E and F.

4. Discussion

Lighting pattern showed a significant influence on squid catch in the limited numbers of operations (164 operations, **Table 3**). More than half of these operations however consisted of experimental operations that showed a significant influence of SRL on squid catch[5]. In the experimental operations, captains had to maintain the lighting patterns (designated number of MHs), lighting schedule (SRL) and the boat position (outside of the boundary). On the other hand, the influence of lighting patterns conducted in this study was not significant in the whole operations (256 operations) containing more conventional operations (**Table 3**) of which captains could flexibly change their lighting pattern and fishing location inside/outside of the boundary, even in the crowded fishing ground in this season. We consider that the fishing ability, that explains the skill for choosing lighting patterns and fishing locations in conventional operations, is the primary factor for squid jigging fishery. It is likely that this factor strongly influencing the squid catch may be attributed to the selection of fishing location, because the rejected variable *light* limited available fishing ground (i.e. inside/outside of the boundary). Experimental boats may be able to catch more squid if the lighting pattern and fishing location were not designated, as observed in squid fishing in summer[3]. It is therefore important to consider not only fishing equipment (e.g. LEDs), but also developing fishermens skill that is accumulated from conventional fishing practices, for improving productivity of squid jigging fishery and reducing fuel consumption.

Our study showed that the presence of dolphin(s) reduced squid catch to be 0.14 times (coefficient of *dolphin*, -1.93) in February, and the negative impact, was compensated to be 1.01 times in January, due to the effect of interaction of *dolphin* : *month* (coefficient 1.94). Thus presence of dolphin (s) did not always produce a negative impact on the squid catch, although the dolphin information was quite limited; different observation skills, dark condition and consequent unreliable information on numbers observed and appearance time. According to interviews with captains, frequently observed dolphins were Pacific white-sided dolphin *Lagenorhynchus obliquidens* and bottlenose dolphin *Tursiops truncatus*. Occurrences of these two species and their interactions with hook and line and trap-net fisheries have been reported since the 1950s in the Tsushima Strait[25].

The difference in geographical distribution of dolphins between January and February may be a potential reason of the effect of interaction of *dolphin : month* although this was not proven in a previous study[23]. Squid are a primary prey for *L. obliquidens* and *T. truncatus*[26]. It is known that the distribution of L. *obliquidens* and congeneric *species L. acutus* is restricted by the distribution of prey items[27)~29]. Estimated high squid abundance in January (**Table 4**, *month* : 0.45 for January, i.e. 1.6 times higher than February) might reduce the interaction between dolphins and squid jigging boats because dolphins were able to have more opportunities to prey off the boats.

Nishida[30] categorized mitigation measures against depredation by small cetaceans and sharks in tuna longline fishery as : 1) improvements of vessel maneuvering, operation procedures and selection of fishing ground, 2) use of passive acoustic instruments to detect presence of predators, 3) use of emitting acoustic instruments to warn predators. In the squid jigging fishery in the Tsushima Strait, boats belonging to Katsumoto Fisheries Cooperative, Nagasaki have been using the acoustic alarms (DDD, Dolphin Dissuasive Device, STM Products, Verona, Italy) since 2007 to warn dolphins and all experimental boats are equipped with this device. Captains of those boats have indicated the validity of the acoustic alarms according to interviews, but we consider the validity of this device may be limited because the distance between the fishing boat and dolphins was not significantly different when DDD was used in the squid fishing in the Mediterranean Sea[19]. In addition, we think that frequent use of the acoustic alarm may act as an attraction signal for predation.

Selection of fishing location based on information sharing is important for further reduction of interactions between squid jigging fishery and dolphins. In the squid jigging fishery, a small number of boats (generally less than 10 boats) form a group for sharing information relating to catch in coded messages. Under such conditions, information of dolphin presence is communicated only within a limited number of boats and information for making decision of fishing location for less interaction would not spread to all squid boats. We consider that fishing ability, explained as fishermens skill, could be improved if squid fishermen establish an information network based on dolphin presence and share information on a real-time basis in the Tsushima Strait in winter. Besides, introduction of passive acoustic instruments that detect presence of dolphins[31,32] to squid jigging boats will help operations to locate fishing away from dolphins. Fishermen will be able to enhance value of fishery as the dolphin-free fishery in the limited spatio-temporal scale (i.e. Tsushima Strait in winter) through practices and improvements presented above.

Acknowledgements

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【研究論文】

環境条件および操業状況がイカ釣り漁獲量に及ぼす影響の評価—光量の多寡は本当に問題か

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和 文 要 旨

2010年１～２月に対馬海峡で操業を行ったイカ釣り漁船９隻が記録したスルメイカの日々の漁獲箱数，集魚灯の点灯数，イルカの出現状況，自船２海里以内で操業する漁船数の資料を用いて，一般化線型モデル解析を行った。漁獲箱数は月輝面比とイルカの有無および月ごとのスルメイカの現存量で船別に表現され，漁業者が意識する集魚灯数と周囲の漁船数の影響は有意ではなかった。日々の漁獲が船ごとに表現されたことは，イカ釣り漁船の漁獲能力が集魚灯などの装備だけでなく，操業位置の決定など乗員の技能の影響を受けたことを示唆している。

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