Catch performance of coastal squid jigging boats using LED panels in combination with metal halide lamps

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Abstract

Squid attracting light systems consisting of low power light emitting diode panels (LEDs) and conventional metal halide lamps (MHs) were tested to describe the influence of combinations of LEDs and MHs on squid catch. Fishing trials using LEDs (9 kW) and different numbers of MHs were carried out in August and September 2009 targeting two squid species: (1) Japanese common squid *Todarodes pacificus* in northern waters of the Sea of Japan (off Hokkaido) by 4 coastal squid jigging boats (19 gross tonnage) and (2) swordtip squid *Photololigo edulis* in western waters (off Iki) by 5 boats of the same class. Catches of both species tended to increase with the number of MHs. Generalized Linear Model analysis revealed that in addition to the number of MHs, the catch amount was influenced by fishing power (ability) of boat and by the monthly variation of squid abundance (only for *P. edulis* off Iki). The expected catch (number of boxes) was not proportional to the number of MHs. The largest catch was expected for *P. edulis* off Iki by using LEDs with 24 MHs. The optimal combination of LEDs and MHs for *T. pacificus* off Hokkaido was less clear because the combination with 36 MHs had the largest positive effect on the catch; this was the maximum number MHs used.

Keywords: squid jigging, LED, metal halide lamp, catch performance, GLM

1. Introduction

Squid fishing has attracted interest world-wide over the last two decades due to its commercial potential under the present condition of targeting species lower down the food web (FAO, 2005). Among the various harvesting methods for squid, jigging with artificial lights is considered as a highly selective fishing method (Rathjen, 1991; Tubino et al., 2007). This fishing method is mainly conducted by Japan, China (Chen et al., 2008), South Korea (Choi et al., 2003) and Taiwan (Zhou, 2003) in east Asia. The Japanese squid jigging fisheries target cephalopods, such as Japanese common squid *Todarodes pacificus* and swordtip squid *Photololigo edulis*.

The squid jigging fishery operating around Japan consists of two size classes: large boats (more than 20 gross tonnage (GT)) in offshore and coastal waters licensed by the national government, and small boats (less than 20 GT) in coastal waters licensed by local governments. In 2007, these coastal boats of less than 20 GT landed 103,000 tons of cephalopod (approximately 32% of the annual landing of cephalopods in Japan).

Squid jigging fishery typically uses two specialized fishing machines that make operations efficient: one is fishing lights to attract squid and the other is automated squid jigging machines to catch them with less labor. Fishermen generally think that the catch of squid increases with the increase of light power. High power metal halide lamps (MHs) are therefore extensively used in most jigging boats in Japan.

To avoid competition of over-capitalization and consequent excessive fishing capacity of high power fishing lamps among fishermen, efforts have been made to promote the use of the optimum number of fishing lamps and restrictions to limit the output power for fishing lights have been suggested (Arimoto et al., 2003). However, the scientific basis for selecting the type of light source and its power as fishing lights still remains unverified. There are many factors that affect squid attraction such as the quality of light (e.g. wave length), quantity of light (e.g. power), and arrangement of fishing lights. In addition, underwater irradiance level and distribution created by these factors are influenced by the optical characteristics of seawater and influence squid behavior (Arakawa et al. 1998; Shikata et al. 2011). Information about the relationship between fishing lights and squid behavior is still limited and consequently fishermen determine the type, number and power of fishing lights based on their personal experience.

The squid jigging fishery now has set up voluntary regulations for each class of boat and for each fishing ground (e.g. 19 GT boats operating further than 12 miles from the coastline can use a maximum of 160 kW electric power for lighting). Power for fishing lights with such high energy consumption accounts for about half of the operating costs (Demura, 2008).

Low power light emitting diode panels (LEDs) have recently been focused on as a new light source for use as a fish attracting light. LEDs have different characteristics over conventional light sources (e.g. MHs) including emitting light of a specific band of wavelength, narrow beam spread, longer lifetime, and lower energy consumption. In squid jigging fishing trials with only LEDs, catches were less than conventional operations with MHs however fuel consumption was greatly reduced (Fishing Boat and System Engineering Association of Japan, 2009). Consequently, the use of LEDs with a lower number of MHs has been tested so far in the squid jigging fishery in Japan.

In order to confirm catch performance of coastal squid jigging boats using a combination of LEDs and MHs, we carried out fishing trials targeting *T. pacificus* and *P. edulis* by using LEDs with different numbers of MHs. We analyzed the catch results in relation to the number of MHs and other relevant factors, through model analysis using generalized linear models (GLMs).

2. Materials and methods

2.1. Fishing trials

Fishing trials were conducted with 9 boats (19 GT) belonging to the Katsumoto Fisheries Cooperative in Nagasaki Prefecture. Five boats targeted *P. edulis* in the southwestern waters of the Sea of Japan around Iki and Tsushima islands and off Shimane Prefecture (hereafter referred to as “Iki”), and 4 boats targeted *T. pacificus* in the northwestern waters off Hokkaido Prefecture (hereafter referred to as "Hokkaido") during 1 August - 30 September 2009 (Fig. 1).

All boats were equipped with 50 blue LEDs (Takagi Kogyo Corporation, Kagawa, Japan) consisting of 180 devices (1 W for each, 0.18 kW for a panel and 9 kW in total). The number of LEDs for a boat was determined based on the availability of deck space and panels were installed as two rows on the starboard and port sides from the bow to stern. Boats were also equipped with 37 to 50 MHs (Hokuto Lighting Company Limited, Fukuoka, Japan; 3 kW each, total of 111 to 150 kW).

During the fishing trials, each boat used a fixed number of MHs and all LEDs (50 LEDs) according to the experimental plan: 0, 4, 24, and 30 MHs were employed by 5 boats on the same day off Iki, and 8, 12, 24 and 36 MHs by 4 boats on the same day off Hokkaido (Table 1). The number of MHs used by each boat was changed day by day. For fishing trials off Hokkaido, more MHs than in Iki were used because fishermen suggested that greater power for fishing lights is necessary for *T. pacificus* compared to *P. edulis*.

Captains of the boats were requested to record the catch and times of fishing events (e.g., lights-on and lights-off) every day. The catch was recorded as the number of boxes each containing 20 to 30 squids according to sorted size of the squid. Compositions of boxes by number of contained squid were almost constant during fishing trials. One box weighs approximately 5 kg for *P. edulis* and 6 kg for *T. pacificus*. In addition, we obtained the daily landing data by conventional squid fishing boats equipped with 53 MHs (159 kW; hereafter referred to as "conventional boats"; twenty boats off Iki and 6 boats off Hokkaido) to compare the catch data.

2.2. Statistical analysis

It is assumed that at small spatial scales the catch C is proportional to the fishing effort, abundance of squid and the fraction of the abundance that is captured by one unit of effort (often referred to as the catchability) according to the equation:

$$C = qEN \tag{1}$$

where E is the fishing effort (in this study, one day), N is the abundance of squid, and q is the catchability. In the squid jigging fishery, the catchability is not constant; it is influenced by the fishing lights, fishing power attributed to fishing skill of the captain and the crew, fishing equipments (excluding fishing light) and the lunar phase. Catchability is represented according to the equation:

$$q = q_M \cdot q_B \cdot q_L \tag{2}$$

where q_M is the fraction of the catchability via lighting attributed to the number of MHs used (*MH*), q_B, for fishing power that is different by boat (*Boat*) and q_L, for phase of the moon appearing as the illuminated portion (*Lunar*). In this study, these variables are called catch factors.

Catch factors (*MH*, *Boat*, and *Lunar*) and the abundance of squid (*Month*) as explanatory variables were chosen for the following reasons.

i. *MH*: We set the number of MHs as four-level categorical variables. Electrical power required for fishing lights increases linearly with the number of MHs used. However, underwater optical characteristics for MHs and LEDs are different and we do not know which characteristics are important for catching squid (e.g. electrical power, spectral irradiance, etc). We therefore consider that is not appropriate to use the power or number of fishing lamps as a continuous variable.

ii. *Boat*: To consider the fishing power that is different by boats, we set a nine-level categorical variable from A to I: A to E for Iki and F to I for Hokkaido, respectively. All boats were equipped with 12 automated squid jigging machines on the starboard and port sides. The number of jigs on each line, distances between jigs and a sinker, the maximum depth of the jigging line and jigging interval, were set by the captain and these were different among boats. The choice of fishing location in the fishing ground and the operational processes, such as departure and arrival time of port or fishing ground, fishing time and lighting time were also different. These operational procedures except the number of MHs used were adjusted by fishermen to obtain the best results. We therefore set a categorical variable "*Boat*" that may explain the catches.

iii. *Lunar*: The ratio of the illuminating area of the moon was taken into the model as a continuous variable. This ratio varies between zero (new moon) and one (full moon) corresponding to the lunar phase at midnight on each date of the trial. These data were obtained from the U.S. Naval Observatory website as used by Ortega-Garcia et al. (2008). We considered this catch factor expressed the influences of lunar rhythm and natural light on the squid catch.

iv. *Month*: A two-level categorical variable was used as an indicator of the abundance of squid. From monitoring catches, we assumed that the abundance shifted between August and September.

Catch results of fishing trials were analyzed as a function of catch factors and abundance index of squid by using generalized linear models (GLMs; Nelder and Wedderburn, 1972; McCullagh and Nelder, 1989; Dobson, 2002). Let the catch C (i.e., the number of squid boxes caught) be a random variable having a negative binomial distribution such that

$$E(C) = \mu,$$

$$\mathrm{var}(C) = \mu + \mu^2/\theta, \tag{3}$$

where $E(C)$ is the expected value of C, var(C) is the variance of C, μ (>0) is the mean value, and θ (>0) is a potential dispersion parameter to be estimated (Venables and Dichmont, 2004; Punt et al., 2000). Here, overdispersion (the amount in excess of μ) is expressed as the multiplicative factor $1+\mu/\theta$, which depends on μ. Because our data set for each area showed very large dispersion (i.e., the variance 2318.08 against the mean 45.2 for Iki and 3975.74 against the mean 81.6 for Hokkaido).

For the negative binomial regression, we assumed $C_i \sim NB(\mu_i, \theta)$, where we let the mean μ_i for the ith operation vary as a function of the covariates for that operation. Since the mean μ_i is always positive, we modeled it for generalization by p variables according to the equation:

$$\mu_i = \exp(\beta_0 + \beta_1 x_{1,i} + \cdots + \beta_p x_{p,i}). \tag{4}$$

We can express equation (4) as the vector of mean parameters $\boldsymbol{\mu} = \mathrm{g}^{-1}(\mathbf{X}\boldsymbol{\beta})$, where g^{-1} is the exponential function and g is called the link function, $\mathbf{X}$ is a design matrix of both continuous and categorical covariates, and $\boldsymbol{\beta}$ is a vector of parameters. The ith row $\mathbf{x}_i'$ of $\mathbf{X}$ contains the covariates for the ith operation. By all variables considered in this study, the log-transformed catch LnC_i is described as a linear combination of the explanatory variables and its error according to the equation:

$$\mathrm{Ln}C_i = \beta_0 + \beta_m MH_i + \beta_b Boat_i + \beta_l Lunar_i + \beta_a Month_i + \varepsilon_i, \qquad (5)$$

where β_0 is the intercept (constant), β_m the coefficients of the *MH*, β_b of the *Boat*, β_l of the *Lunar*, β_a of the *Month* and ε the error.

Model-fits through parameter estimation were performed by the maximum likelihood method (*glm.nb* function in the MASS package (Venables and Ripley, 2002) in R ver. 2.12.1, R Development Core Team). First, we incorporated *MH* which is the most important factor in this study, into the null model (only intercept). Selection of other variables was then proceeded by a stepwise forward entry. At each stage of the forward entry, the AIC (Akaike's Information Criteria) was computed for every candidate model and the model with the lowest AIC was chosen.

3. Results

3.1. Catches of *P. edulis* off Iki

A total of 139 operations were conducted on 30 days by 5 boats during 1 August - 30 September. There were no operations around the full moon (6 August and 5 September) and most operations were done in waters shallower than 200 m (Fig. 1A). Daily catch of each experimental boat ranged from 0 to 232 boxes (mean 46.2 ± 48.15 SD). During the same period, catches by 20 conventional boats (equipped with only MHs) ranged from 0 to 320 boxes (mean 51.9 ± 45.47 SD). The daily catches by both experimental and conventional boats were higher in September (mean 76.0 boxes) than August (mean 28.8 boxes; Fig. 2A).

The catches for 0, 4, 24, and 30 MHs were 21.1 ± 15.88 SD, 40.1 ± 37.66 SD, 64.9 ± 57.63 SD and 59.0 ± 57.46 SD, respectively. There were good catches (more than 100 boxes) when MHs were used (Fig. 2B). The catch tended to increase with the number of MHs, but varied among boats. The catches with 0 and 4 MHs were statistically less than the mean amount of landings by conventional boats on the corresponding day, but landings with 24 and 30 MHs were not significantly different from conventional boats (Wilcoxon test, α=0.05).

3.2. Fitted models for *P. edulis* off Iki

The most appropriate model expressing *P. edulis* catch was a combination of catch factors including *MH*, *Month* and *Boat* (hereafter referred to as “Model Iki”) by using GLMs (Table 2; lowest AIC value). The predicted value of the most appropriate model for *P. edulis* catch off Iki indicated a good fit against the observed values less than 100 boxes (Fig. 3). A plot of the deviance residual versus the linear predictor of the model distributed uniformly and there was no evidence of heteroscedacity.

The estimate of intercept had the largest value because this parameter includes effects of the basis of incorporated factors (*MH*: 0 MH; *Month*: August; *Boat*: boat A), and is statistically significant (Table 3; W = 13.374, p < 0.001). All the estimates for *MH* of Model Iki indicated positive effects on *P. edulis* catch and the estimate of 24 MHs was the highest among the numbers of MHs used. A marked change in abundance of *P. edulis* was also estimated from Model Iki, that is, the estimate of *Month* indicated that the abundance of *P. edulis* in September was about 3 times larger than August. Besides the effect of fishing power was significantly different for boats B and C. On the other hand, estimates were not significant for boats D and E, suggesting that fishing power of boats D and E are at the same level of boat A.

We summarized the results of Model Iki in Fig. 4. It is clear that the expected catch (boxes) of boat A in August was not proportional to the number of MHs, and seems to be saturated when 24 or more MHs are used (Fig. 4A). Concerning fishing power, the expected catches are different by boats and these values for boats B and C were 1.6 times larger than other boats (Fig. 4B). Therefore, when effects of *MH* and *Boat* are taken into account against the same abundance, the expected catches by boats B and C with 0 MH become similar to catches by other boats with 4 MHs.

3.3. Catches of *T. pacificus* off Hokkaido

A total of 105 operations on 27 days were conducted during from 1 August to 30 September off Hokkaido. Operations were also carried out during full moon (6 August and 5 September), unlike operations off Iki. Depths of fishing locations varied from shallower than 100 m to 3000 m; most boats concentrated their fishing effort in the slope regions (Fig. 1).

Daily catches of *T. pacificus* by 4 boats with different numbers of MHs ranged from 5 to 322 boxes (mean 81.6 ± 63.05 SD). During the same period catches by 6 conventional boats (equipped with only MHs) ranged from 14 to 440 boxes (mean 130.9 ± 91.82 SD). Small and large catches were often recorded throughout the whole period, regardless of whether conducted by experimental or conventional boats (Fig. 5A). Daily catch levels were similar between August (mean 127.2 boxes) and September (mean 138.7 boxes).

Average catch (boxes) by 4 boats with 8, 12, 24, and 36 MHs were 60.1 ± 37.10 SD, 65.4 ± 39.06 SD, 72.8 ± 49.10 SD and 128.6 ± 89.43 SD, respectively. The mean catch moderately increased with the number of MHs and markedly increased when using 36 MHs which was the maximum number of MHs in this experiment, although the catches varied among boats (Fig. 5B). The catches with 36 MHs were statistically equal to the mean landings by conventional boats on the corresponding day (Wilcoxon test, α=0.05).

3.4. Fitted models for *T. pacificus* off Hokkaido

From the GLMs analysis, a combination of two factors, *MH* and *Boat*, were chosen as the most appropriate model expressing *T. pacificus* catch (Table 4; lowest AIC value; hereafter referred as "Model Hokkaido"). *Month* did not contribute to the catch in the case of Hokkaido. The predicted value of Model Hokkaido indicated a good fit against the observed value around 150 boxes (Fig. 6). However, predicted values over 150 boxes did not fit well, whereas a plot of deviance residual versus linear predictor of the model showed an unbiased distribution and there was no evidence of heteroscedacity.

The estimate of the intercept included effects of incorporated factors (*MH*: 8 MHs and *Boat*: boat F), and was the largest and statistically significant (Table 5; W = 23.434, p < 0.001). In the factor *MHs*, the estimate of 36 MHs was only statistically significant, although every estimate of *MH* was positive. This indicates that fishing with 36 MHs was only able to catch more *T.*

pacificus against other lighting conditions. The estimate of fishing power was also only significant for boat I, suggesting that fishing power was similar except for boat I.

The expected catch (boxes) of boat F was compared by different numbers of MHs (Fig. 7A) and by different boats with 8 MHs (Fig. 7B) from Model Hokkaido. It showed that the catch with 36 MHs was about twice of other numbers of MHs. Also the expected catch by boat I was 1.5 times larger than by other boats. Therefore, the expected catch by boat I with 8 MHs could be calculated to be similar to catch by other boats with 36 MHs.

4. Discussion

In this study, we attempted to describe the influence of LEDs with different numbers of MHs on squid catch, to seek an optimum combination of these light sources for coastal squid jigging boats in Japan. Variances of squid catch by 9 boats with different numbers of MHs were analyzed through addressing significant catch factors (*MH*, *Boat*, and *Lunar*) and a relevant factor to squid abundance (*Month*) using GLMs. The Model Iki indicated that the catch of *P. edulis* was influenced not only by the lighting, but also by the difference in fishing power of boats and monthly change of squid abundance. On the other hand, *T. pacificus* catch in Hokkaido was strongly affected by the difference in fishing power of boats in addition to the lighting.

The fishing light using LEDs with MHs had a significant and strong positive effect on the catch amount of squid. Use of MHs especially showed a significantly positive effect against 0 MH (only LEDs) for *P. edulis.* The effect of lighting to expected catch was not proportional to the number of MHs, and the most positive effect was estimated at 24 MHs for targeting *P. edulis* off Iki and at 36 MHs for *T. pacificus* off Hokkaido. This result agrees with well-known knowledge among squid fishermen that catching *P. edulis* requires less light power than catching *T. pacificus* (personal communications with captains of the boats participating in the experiment).

A combination of LEDs and MHs achieved a conventional catch level with less electrical output, but the required number of MHs was different by target species. Catch amounts with MHs of the peak effects (24 MHs for Iki and 36 MHs for Hokkaido) were at the same level as conventional boats in both fishing grounds, indicating that 9 kW LEDs compensated for the reduction in number of MHs; 29 MHs (87 kW) off Iki and 17 MHs (51 kW) off Hokkaido. We however do not know if the use of 36 MHs is optimal for *T. pacificus* because 36 MHs was the maximum number in the experimental plan. National Federation of Fisheries Co-operative Associations of Japan (1996) concluded that a reasonable electrical power generation limit for MHs for class 19 GT was 180 kW (corresponding to 60 MHs) for targeting *T. pacificus*. Use of 36 MHs (108 kW + LEDs 9 kW = 117 kW) is 63 kW lower than the 180 kW limit recommendation. Nevertheless, we expect that the best capture performance for *T. pacificus* could be obtained with electrical power less than 160 kW (voluntary regulation), since LEDs seems to have a higher performance than MHs for the same electrical power as mentioned above. Furthermore, the relationship between electrical power generation and fuel consumption of squid jigging boats should be explored in detail with an aim of maximizing efficiency for a value-oriented fishery.

The fishing power *Boat* was chosen for expressing squid catch in addition to a lighting factor *MH* for both Iki and Hokkaido. Estimate for boat I (2.0 times greater than boat F) which was evaluated as the most positive effect of fishing power was comparable for the estimate of 36 MHs (2.2 times greater than other combinations of MHs and LEDs), the most positive effect of lighting off Hokkaido. Consequently, predicted catch for boat I with 8 MHs was similar to the catches for other boats with 36 MHs (Fig. 7). Thus, fishermen's experiences and skill may have a similar effectiveness to lighting for increasing squid catch. Furthermore, identifying the behavior and fishing technique (e.g., how to light) used by successful boats may inspire improvement of software of fishing technology, and will produce ideas for new research. Conversely, consideration of the fishermen's skill is necessary to evaluate the effect of lighting on catch when this type of experiment using multiple boats is conducted.

The fishing power involves techniques to respond to changes in behavior, habitat and abundance of squid in relation to environmental factors (e.g. temperature, current, region). Prior to fishing, most fishermen search for a school of squid to decide on the fishing locations based on their experiences in combination with the use of acoustic instruments. They also base their fishing practices on information; e.g., schools of *T. pacificus* form in relation to interactions of bottom topography, surface-layer water temperature, depth of the thermocline and upwellings (Tameishi, 2003). In fact, the lights of fishing boats were observed in the waters surrounding Japan using night-time satellite data (Elvidge et al., 2001), and their fishing locations were in accordance with the migration route of *T. pacificus* in the Sea of Japan (Kiyofuji and Saitoh, 2004). In addition, fishermen's activities are also affected by economic factors (e.g. the price of fuel). Therefore, we consider that effects of other factors mentioned above are all included in the fishing power.

Models Iki and Hokkaido did not include the variable of *Lunar*, although it was understood that the lunar phase influences the squid catch in other squid fisheries (e.g., Postuma and Gasalla, 2010; Schön et al., 2002) and among Japanese fishermen. This is probably due to the lack of data around full moon off Iki and new moon off Hokkaido that are periods exhibiting the strongest effect on squid catch. To examine the influence of lunar phase on *P. edulis* and *T. pacificus*, comprehensive data through the whole lunar phase will be required.

The model analysis showed different influences of squid abundance to the catch amount between Iki and Hokkaido. The results from the Iki data indicate the factor of abundance can appreciate by a two-level categorical variable in monthly level instead of the actual abundance. In contrast, we could not analyze the influence of squid abundance off Hokkaido as a variable. The actual abundance of *T. pacificus* may progressively shift on a daily basis at small spatial scales, since they are at the feeding stage of the annual round-trip migration. An index relating to the actual squid abundance such as daily landing amount of squid by conventional boats may be adequate for the variable of abundance.

In conclusion, we found variance of daily catch amount of squid was influenced by the number of MHs with LEDs, fishing power of boats and squid abundance. Among these factors, the number of MHs is the only humanly controllable factor that explains the squid catch and therefore important to maximize the efficiency to establish a value-oriented fishery. Because our research did not cover sufficient ranges of light power and lunar phase we need further studies to seek the optimal number of MHs for *T. pacificus* through further use of more than 36 MHs or other combinations with LEDs and MHs, which cover the whole period of the lunar phase.

Acknowledgements

We are deeply grateful to the late Masa-aki Yamakawa, a director of general affair division, Katsumoto Fishermen's Cooperative, Nagasaki, and captains and crews of experimental boats for their cooperation during fishing trials. We appreciate the helpful comments and suggestions by Professor Tadashi Tokai, Tokyo University of Marine Science and Technology on an earlier version of this manuscript. This study was supported by the energy saving project of Fisheries Agency, Government of Japan.

References

Arakawa, H., Choi, S., Arimoto, T., Nakamura, Y., 1998. Relationship between underwater irradiance and distribution of Japanese common squid under fishing lights of a squid jigging boat. Fish. Sci. 64, 553-557.

Arimoto, T., Choi, S.J., Arakawa, H., 2003. Syuugyotou gijutsu [The technology of fish attracting lights], In: Arimoto, T., Inada, H. (Eds.), Surumeika no sekai – shigen, gyogyou, riyou [The World of the Japanese Common Squid (*Todarodes pacificus*) – Resources, Fishery and Utilization]. Seizando Shoten Publishing Co., Tokyo, pp. 203-221 (in Japanese).

Chen, X., Bilin, L., Yong, C., 2008. A review of the development of Chinese distant-water squid jigging fisheries. Fish. Res. 89, 211-221.

Choi, S.J., Kim, D.A., Kim. D.S., 2003. Kankoku no ikatsurigyogyou [The squid jigging fishery of South Korea], In: Arimoto, T., Inada, H. (Eds.), Surumeika no sekai – shigen, gyogyou, riyou [The World of the Japanese Common Squid (*Todarodes pacificus*) – Resources, Fishery and Utilization]. Seizando Shoten Publishing Co., Tokyo, pp. 269-292 (in Japanese).

Demura, M., 2008. Nenyu kakaku kouto no gyogyo e no eikyo [Influence of a rise of fuel price on fisheries]. Accessed April 2011: <http://www.nochuri.co.jp/report/pdf/nri0809re2.pdf> (in Japanese).

Dobson, A.J., 2002. An Introduction to Generalized Linear Models, second ed. Chapman & Hall/CRC Press, Boca Raton.

Elvidge, C.D., Imhoff, M.L., Baugh, K.E., Hobson, V.R., Nelson, I., Safran, J., Dietz, J.B., Tuttle, B.T., 2001. Night-time lights of the world: 1994-1995. ISPRS J. Photogramm. Rem. Sens. 56, 81-99.

FAO, 2005. Review of the state of world marine fishery resources. FAO Fisheries Technical Paper 457, 235 pp.

Fishing Boat and System Engineering Association of Japan, 2009. Heisei 20 nendo syo energy gijutsu donyu sokushin jigyo houkokusyo [Project report on promotion of introduction of energy saving technologies into fisheries, 2008]. Fishing Boat and System Engineering Association of Japan, 289 pp. (in Japanese).

Kiyofuji, H., Saitoh, S., 2004. Use of nighttime visible images to detect Japanese common squid *Todarodes pacificus* fishing areas and potential migration routes in the Sea of Japan. Mar. Ecol. Prog. Ser. 276, 173-186.

McCullagh, P., Nelder, J.A., 1989. Generalized Linear Models, second ed. Chapman & Hall, London.

National Federation of Fisheries Co-operative Associations, 1996. Kogata ikatsuri kouryoku tekiseika kento jigyo jittai tyosa · jissyo tyosa houkokusyo (sosyuhen) [Compiled report on the present condition of small scale squid jigging fishery and the empirical research for standardizing a lighting power output]. Tokyo, 261 pp. (in Japanese).

Nelder, J.A., Wedderburn, R.W.M., 1972. Generalized linear models. J. Roy. Stat. Soc. Ser. A 135, 370-384.

Ortega-Garcia, S., Ponce-Diaz, G., O'Hara, R., Merila, J., 2008. The relative importance of lunar phase and environmental conditions on striped marlin (*Tetrapturus audax*) catches in sport fishing. Fish. Res. 93, 190-194.

Postuma, F.A., Gasalla, M.A., 2010. On the relationship between squid and the environment: artisanal jigging for *Loligo plei* at São Sebastião Island (24°S), southeastern Brazil. ICES J. Mar. Sci. 67, 1353-1362.

Punt, A.E., Walker, T.I., Taylor, B.L., Pribac, F., 2000. Standardization of catch and effort data in a spatially-structured shark fishery. Fish. Res. 45, 129-145.

Rathjen, W.F., 1991. Cephalopod capture methods: an overview. Bull. Mar. Sci. 49, 494-505.

Schön, P-J., Sauer, W.H.H., Roberts, M.J., 2002. Environmental influences on spawning aggregations and jig catches of chokka squid *Loligo vulgaris reynaudii*: a 'black box' approach. Bull. Mar. Sci. 71, 783-800.

Shikata, T., Shima, T., Inada, H., Miura. I., Daida, N., Sadayasu, K., Watanabe, T., 2011. Role of shaded area under squid jigging boat formed by shipboard fishing light in the processes of gathering and capturing Japanese common squid, *Todarodes pacificus*. Nippon Suisan Gakkaishi 77, 53-60 (in Japanese, with English abstract).

Tameishi, H., 2003. Surumeika no gyojoukeisei to kaiyuu [Fishing-ground formation and current for the Japanese common squid (*Todarodes pacificus*)], In: Arimoto, T., Inada, H. (Eds.), Surumeika no sekai – shigen, gyogyou, riyou [The World of the Japanese Common Squid (*Todarodes pacificus*) – Resources, Fishery and Utilization]. Seizando Shoten Publishing Co., Tokyo, pp. 149-188 (in Japanese).

Tubino, R.A., Monteiro-Neto, C., Moraes, L.E.S., Paes, E.T., 2007. Artisanal fisheries production in the coastal zone of Itaipu, Niterói, RJ, Brazil. Braz. J. Oceanogr. 55, 187-197.

U. S. Naval Observatory website, http://aa.usno.navy.mil/data/docs/MoonFraction.php (Accessed May 2011)

Venables, W.N., Dichmont, C.M., 2004. GLMs, GAMs and GLMMs: an overview of theory for applications in fisheries research. Fish. Res. 70, 319-337.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S. Springer-Verlag Press, New York.

Zhou, Y.J., 2003. Taiwan no ikatsuri gyogyou [The squid jigging fishery of Taiwan], In: Arimoto, T., Inada, H. (Eds.), Surumeika no sekai – shigen, gyogyou, riyou [The World of the Japanese Common Squid (*Todarodes pacificus*) – Resources, Fishery and Utilization]. Seizando Shoten Publishing Co., Tokyo, pp. 307-322 (in Japanese).

Figure captions

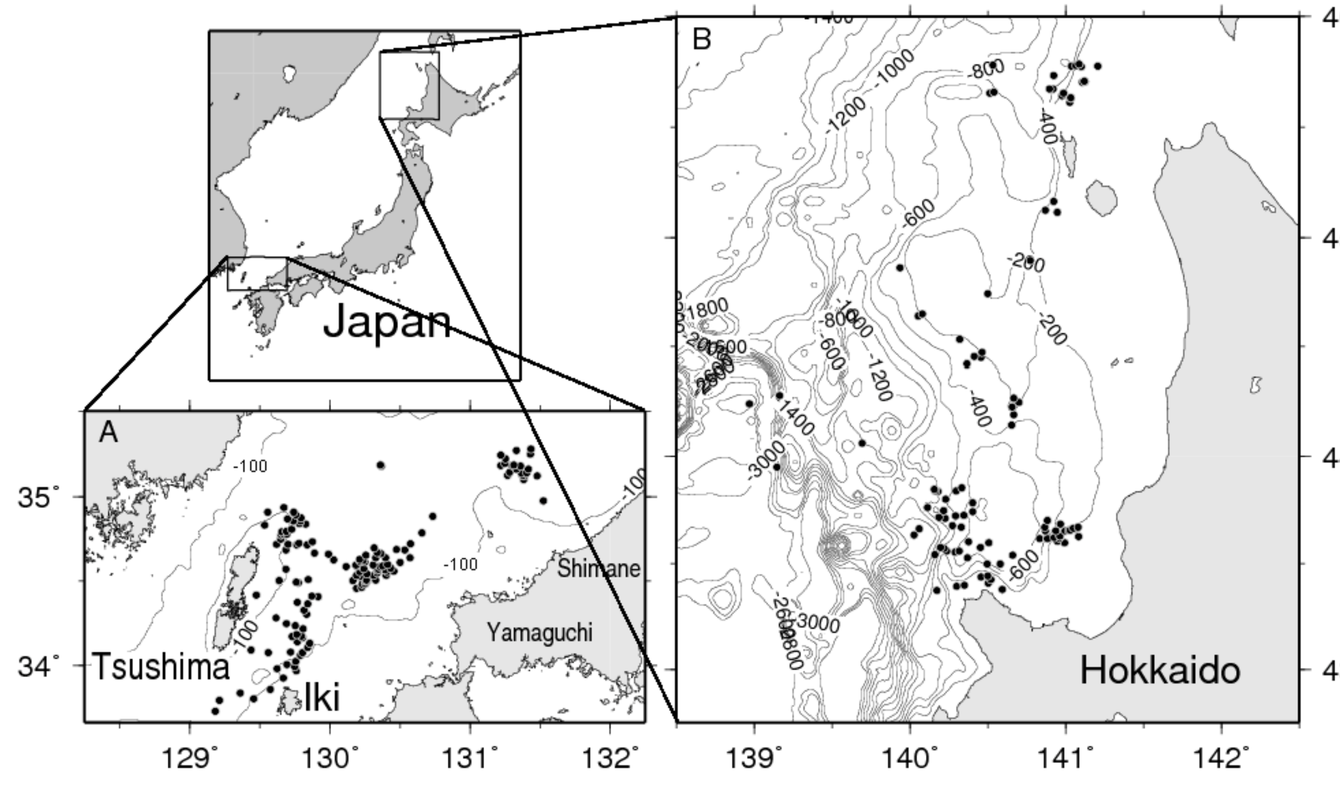

Fig. 1 Fishing grounds off Iki (A) and Hokkaido (B). Each point (●) represents the location where fishing was carried out.

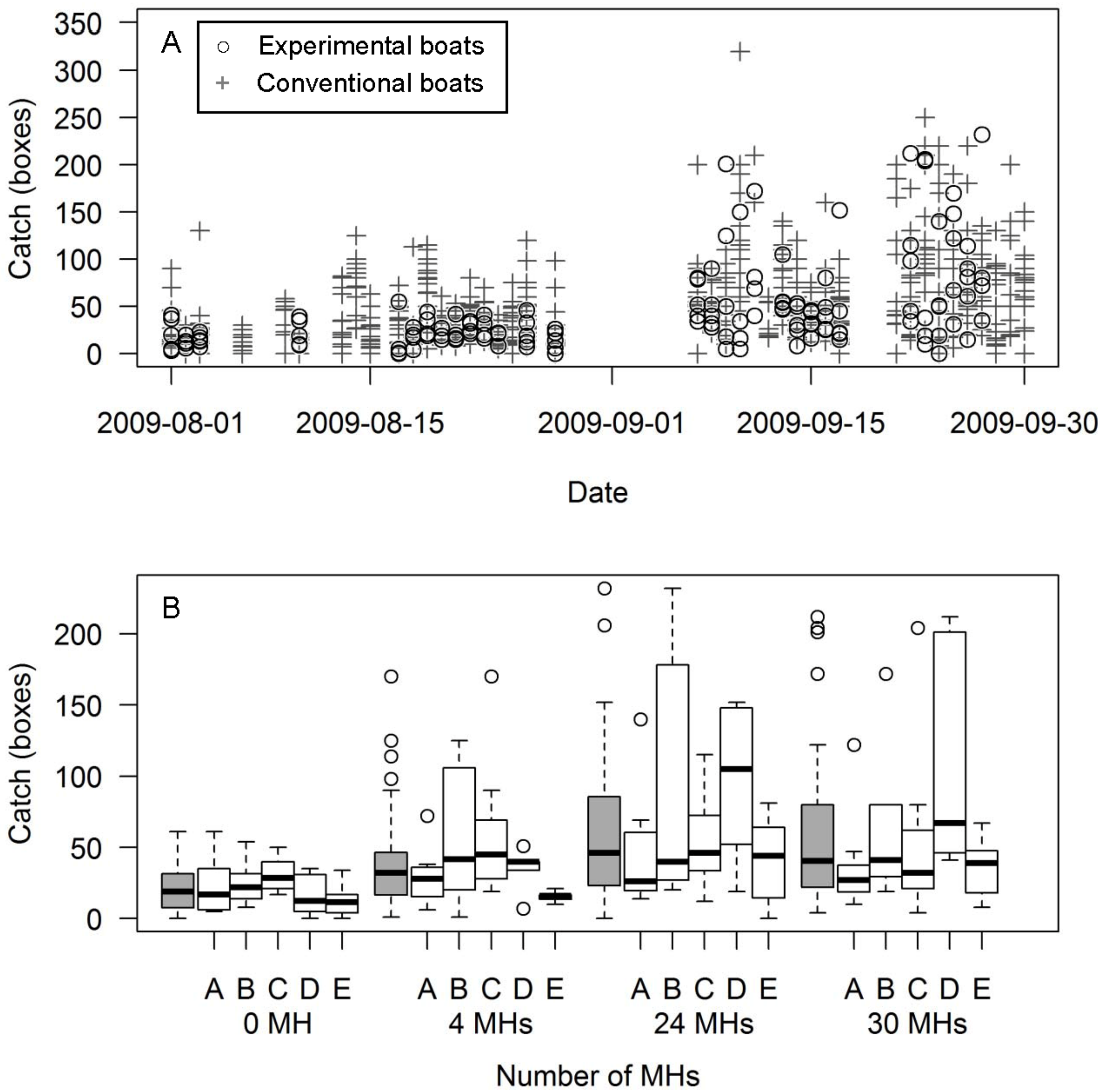

Fig. 2 Daily catch (boxes) of swordtip squid (*Photololigo edulis*) (A) and box-plots of *P. edulis* catches by number of metal halide lamps (MHs) and experimental boats during fishing trial off Iki (B). The shaded box-plots indicate statistics by number of metal halide lamps (MHs) for 5 boats.

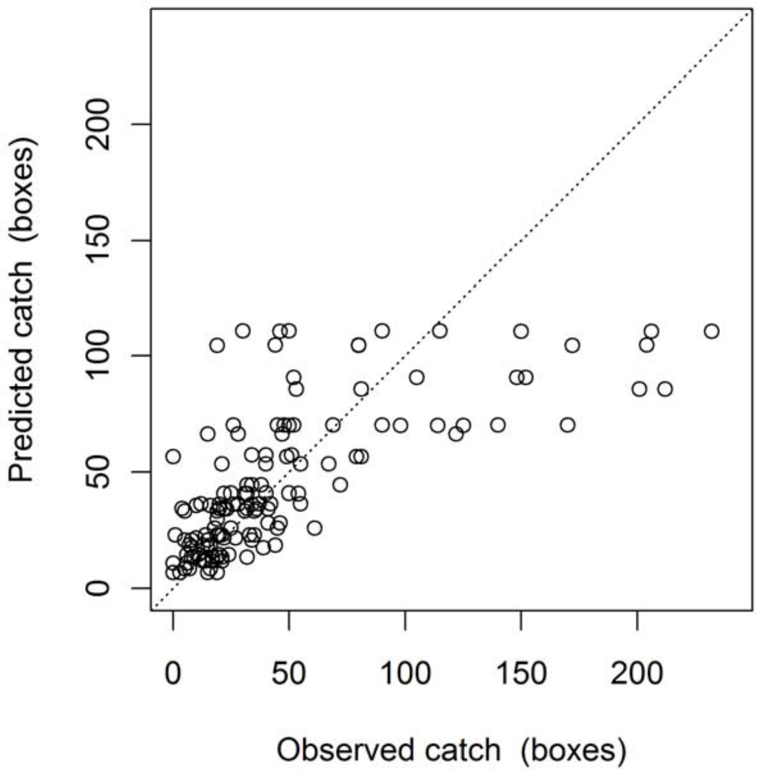

Fig. 3 Predicted catch (boxes) plotted against observed catch (boxes) for Model Iki.

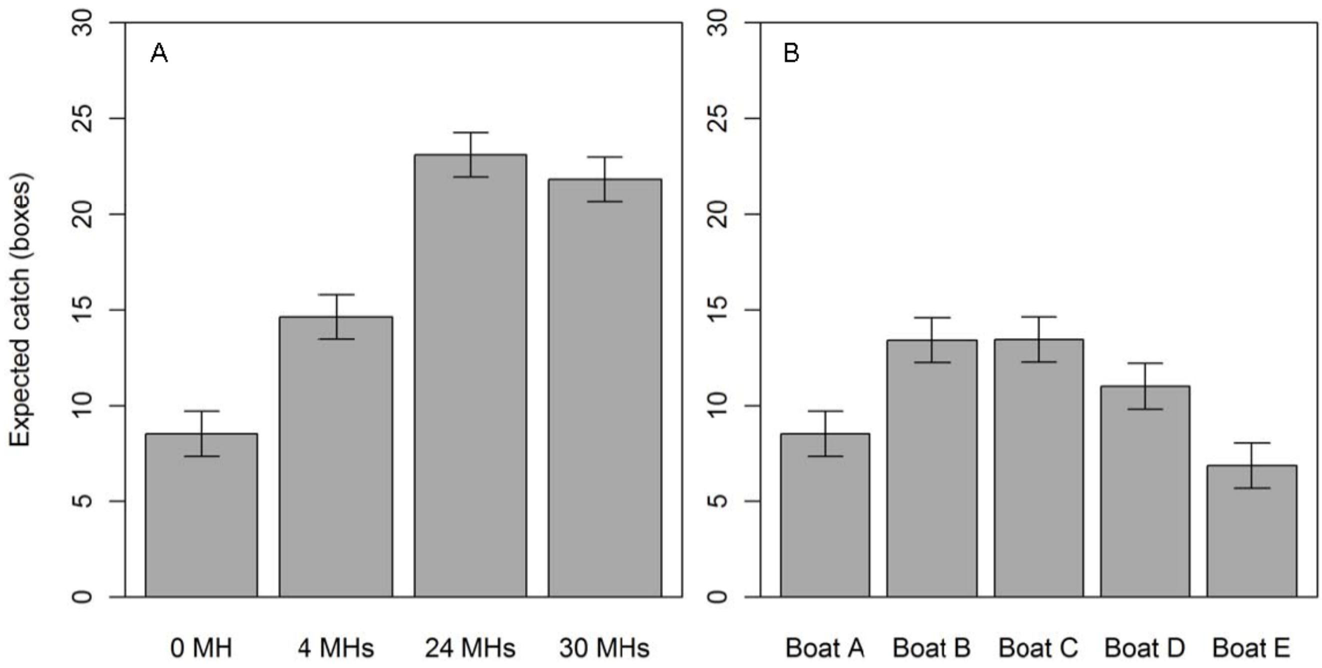

Fig. 4 Expected catch (boxes) of boat A in August by numbers of metal halide lamps (MHs) (A) and expected catch with 0 metal halide lamp (MH) in August by experimental boats (B) as calculated from Model Iki. Vertical lines denote standard errors.

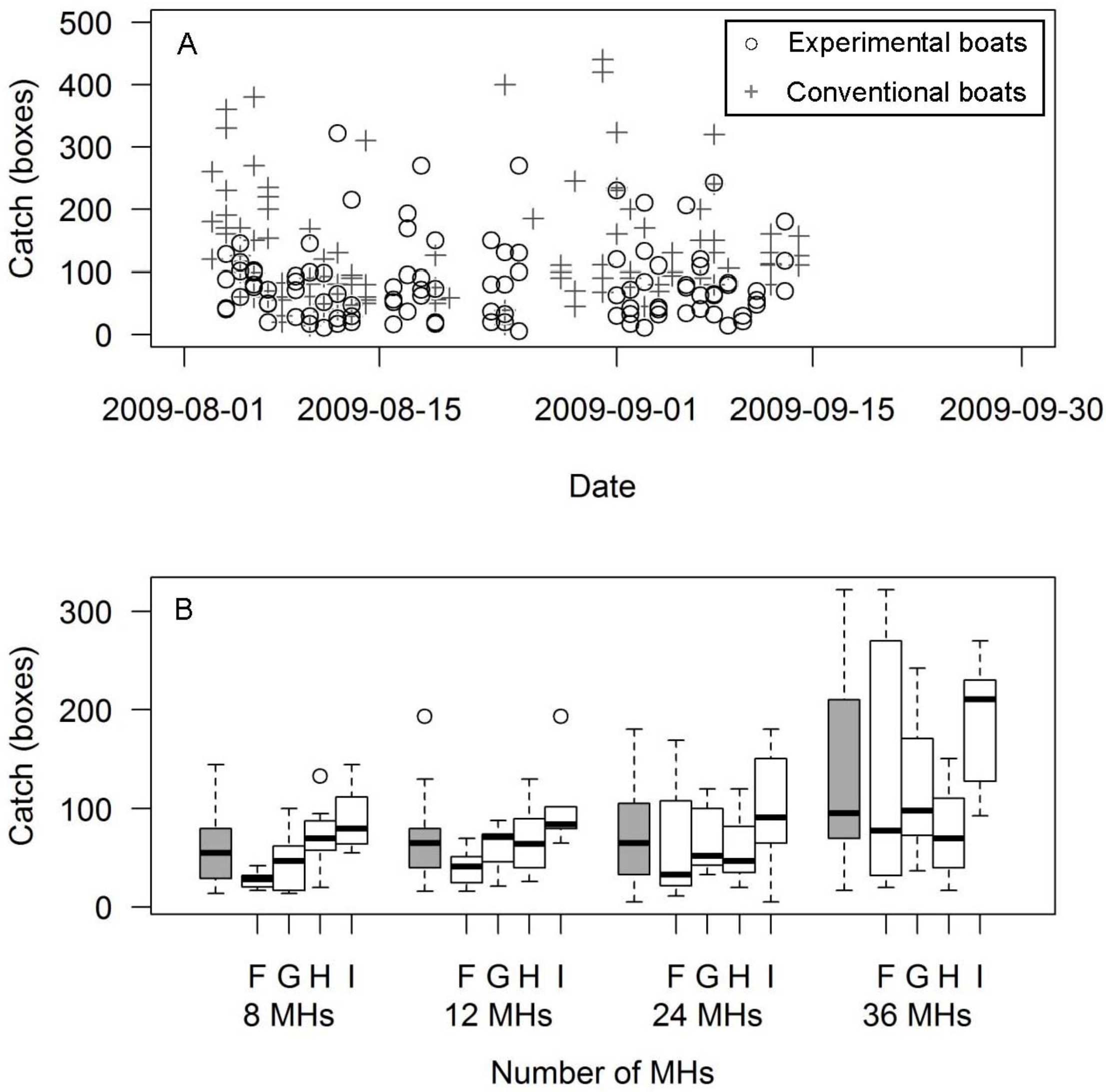

Fig. 5 Daily catch (boxes) of Japanese common squid (*Todarodes pacificus*) (A) and box-plots of *T. pacificus* catches by number of metal halide lamps (MHs) and experimental boats during fishing trial off Hokkaido (B). The shaded box-plots indicate statistics by number of metal halide lamps (MHs) for 4 boats.

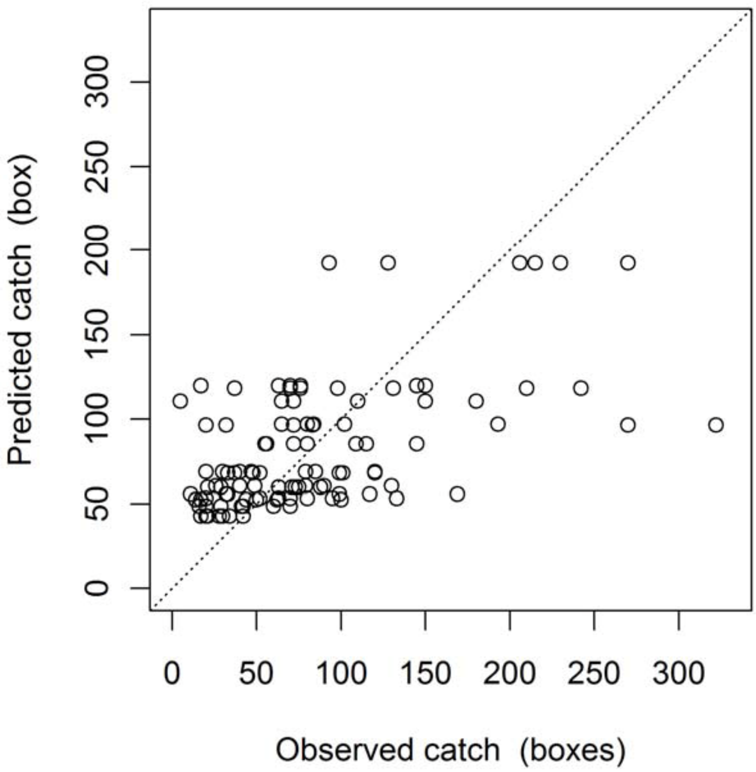

Fig. 6 Predicted catch (boxes) plotted against observed catch (boxes) for Model Hokkaido.

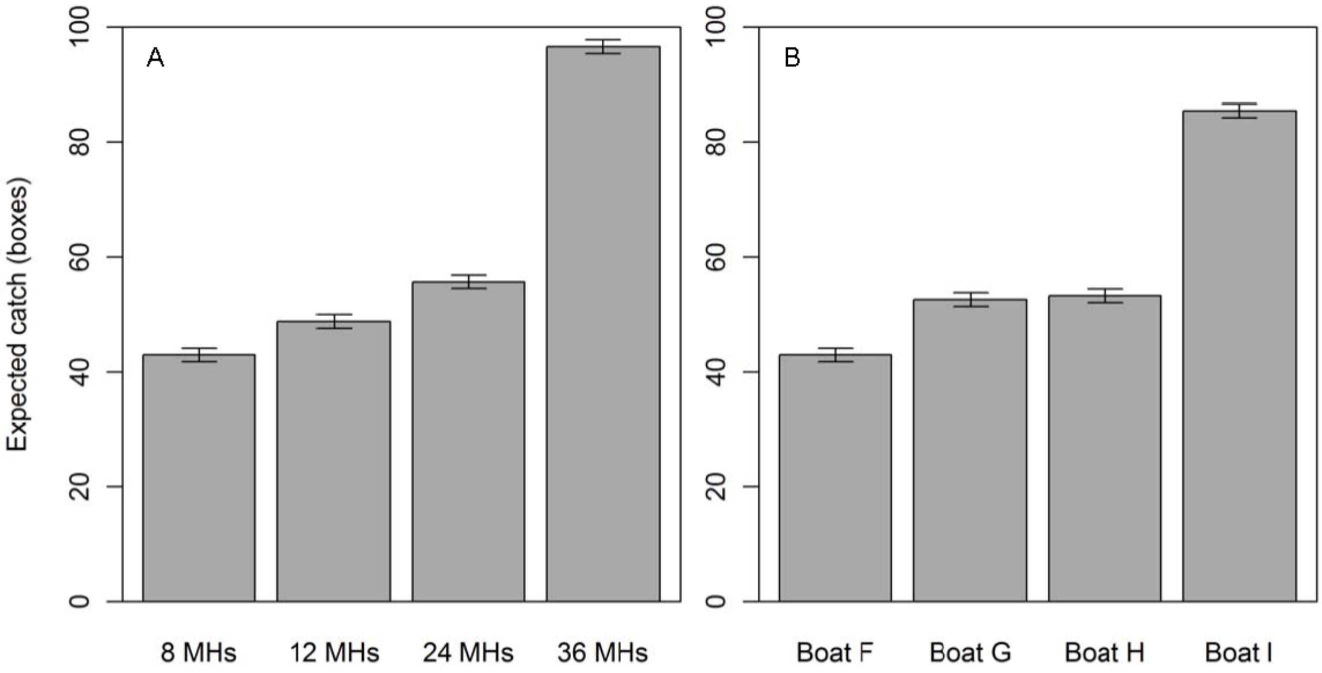

Fig. 7 Expected catch (boxes) of boat F by number of metal halide lamps (MHs) (A) and expected catch with 8 metal halide lamps (MHs) by experimental boats (B) as calculated from Model Hokkaido. Vertical lines denote standard errors.

Table 1 Summary of fishing trials off Iki and Hokkaido

	Iki	Hokkaido
Duration	1 August to 27 September	4 August to 13 September
Total number of fishing days	30	27
Total number of operations	139	105
Number of boats	5	4
Name of boats	A, B, C, D, and E	F, G, H, and I
Number of MHs used with LEDs	0, 4, 24, 30	8, 12, 24, 36

Table 2 The formulae and values of statistics from GLMs fitted to *Photololigo edulis* catch off Iki

	Formula	Null deviance	Null d.f.	Residual deviance	Residual. d.f.	AIC	θ (s.e)
Model 0	$C \sim 1$	158.78	138	158.78	138	1348.6	1.17 (0.134)
Model 1	$C \sim MH$	190.45	138	156.92	135	1324.2	1.43 (0.168)
Model 2	$C \sim MH + Month$	302.00	138	155.24	134	1254.8	2.38 (0.304)
Model 3	$C \sim MH + Month + Boat$	353.49	138	156.01	130	1240.5*	2.84 (0.376)
Model 4	$C \sim MH + Month + Boat + Lunar$	355.24	138	155.72	129	1241.5	2.86 (0.378)

*Lowest AIC value.

Table 3 Parameter estimates, standard errors (s.e.), Wald's statistics (*W*), and their p-value in the optimal generalized linear model (Model 3) fitted to *P. edulis* catch off Iki

Parameter	Estimate	(s.e.)	*W*	*p*-value
Intercept	2.144	(0.1603)	13.374	< 0.001*
MH				
4 MHs	0.539	(0.1516)	3.557	< 0.001*
24 MHs	0.996	(0.1503)	6.626	< 0.001*
30 MHs	0.939	(0.1513)	6.206	< 0.001*
Month				
September	1.112	(0.1082)	10.273	< 0.001*
Boat				
Boat B	0.453	(0.1606)	2.821	0.005*
Boat C	0.456	(0.1636)	2.786	0.005*
Boat D	0.255	(0.1755)	1.453	0.146
Boat E	-0.216	(0.1648)	-1.308	0.191

*Statistically significant ($p < 0.05$). Estimate of intercept includes effects of the basis of incorporated factors as categorical variables (*MH*: 0 MH, *Month*: August, *Boat*: Boat A).

Table 4 The values of statistics from GLMs fitted to *Todarodes pacificus* catch off Hokkaido

	Formula	Null deviance	Null d.f.	Residual deviance	Residual. d.f.	AIC	θ	(s.e)
Model 0	$C \sim 1$	113.42	104	113.42	104	1118.8	1.91	(0.253)
Model 1	$C \sim MH$	134.56	104	112.20	101	1104.4	2.29	(0.308)
Model 2	$C \sim MH + Boat$	154.01	104	111.34	98	1094.5*	2.63	(0.360)
Model 3-1	$C \sim MH + Boat + Month$	154.13	104	111.34	97	1096.4	2.63	(0.360)
Model 3-2	$C \sim MH + Boat + Lunar$	154.08	104	111.35	97	1096.4	2.63	(0.360)
Model 4	$C \sim MH + Boat + Month + Lunar$	154.15	104	111.34	96	1098.4	2.63	(0.360)

*Lowest AIC value.

Table 5 Parameter estimates, standard errors (s.e.), Wald's statistics (*W*), and their p-value in the optimal generalized linear model (Model 2) fitted to *T. pacificus* catch off Hokkaido

Parameter	Estimate	(s.e.)	*W*	*p*-value
Intercept	3.760	(0.1605)	23.434	< 0.001*
MH				
12 MHs	0.127	(0.1753)	0.726	0.468
24 MHs	0.260	(0.1714)	1.514	0.130
36 MHs	0.811	(0.1724)	4.702	< 0.001*
Boat				
Boat G	0.202	(0.1715)	1.178	0.239
Boat H	0.215	(0.1714)	1.253	0.210
Boat I	0.687	(0.1761)	3.902	< 0.001*

*Statistically significant ($p < 0.05$). Estimate of intercept includes effects of the basis of incorporated factors as categorical variables (*MH*: 8 MHs, *Boat*: Boat F)