Title: Effect of a stepwise lighting method termed “stage reduced lighting” using LED and metal halide fishing lamps in the Japanese common squid jigging fishery

Running title: Stage reduced lighting for squid jigging

Author and affiliations:

Yoshiki MATSUSHITA* and Yukiko YAMASHITA

Graduate School of Fisheries Science and Environmental Studies, Nagasaki University, Nagasaki, 852-8521, Japan

* Corresponding author. Tel.: +81 95 819 2803; fax.: +81 95 819 2803

E-mail address: yoshiki@nagasaki-u.ac.jp (Y. Matsushita).

Abstract

Lighting systems combining light emitting diodes (LEDs) and metal halide lamps (MHs) are expected to be energy-saving tools in Japan's squid jigging fishery. Previous research showed the necessity for light stronger than LEDs (9kW) and 36 MHs (108 kW) in catching Japanese common squid *Todarodes pacificus*. We tested a stepwise lighting method termed "stage reduced lighting" in the Tsushima Strait in January and February 2010 using 9 fishing boats. LEDs (9 kW) and 50 MHs (150 kW) were lit for 3.9 h on average, and then the number of MHs was reduced to either 30 or 36 until the end of fishing (7.3 h on average). This method reduced fuel consumption by 22-25 % compared to the continuous use of all fishing lamps (159 kW). We carried out catch analysis of 9 experimental boats and 21 commercial boats during the experiment period. Generalized linear modeling analysis suggests that squid catch can be explained by illuminated fraction of the moon and monthly change in squid abundance, with the lighting method. The stage reduced lighting using LEDs and MHs has a potential to reduce fuel consumption with maintaining the squid catch.

(189 words)

Keywords: catch performance, fishing light, fuel saving, Japanese common squid *Todarodes pacificus*, light emitting diode, squid jigging, stepwise lighting method

Introduction

A Japanese coastal squid jigging boat of 19 gross tons (GT) typically consumes approximately 60 l of fuel per hour during jigging with lamps at nighttime [1]; thus, this fishery uses an energy intensive fishing method. We conducted a series of fishing experiments on this fishery by equipping boats with arrays of light emitting diode panels (LEDs, 9 kW in total) and different numbers of conventional metal halide lamps (MHs, 3 kW each) to seek an economic balance between reduction in fuel consumption and squid catch. The largest catch of swordtip squid *Photololigo edulis* was observed when 24 MHs and LEDs were employed, but the optimum combination of MHs and LEDs was unclear for Japanese common squid *Todarodes pacificus*, because the largest catch was observed with the maximum number of MHs (36 MHs) and LEDs [2]. A greater catch might have been obtained if more MHs were used, but the number of MHs should be restrained, since the use of a greater number of MHs obviously increases fuel consumption. Accordingly, we tested a stepwise lighting method termed "stage reduced lighting" for Japanese common squid fishing in the Tsushima Strait in winter.

In this study, we examine the effectiveness of stage reduced lighting in terms of reduction in fuel consumption and catch performance. For fuel saving effect, we measured the fuel consumption of experimental boats and compared the observed fuel consumption with the estimated fuel consumption of commercial boats. To highlight the catch performance, we analyzed the catch of experimental boats that employed stage reduced lighting and catch of commercial boats by a generalized linear model (GLM) in consideration of other factors that potentially affect the catch amounts.

Materials and Methods

Nine squid jigging boats of 19 GT that were the same boats as previously reported [2] participated in the experimental fishing for 43 days between January 9 and February 24, 2010 in the Tsushima Strait (Fig. 1). Boats were equipped with 9 kW blue LEDs (Takagi Corporation, Kagawa, Japan) in addition to 46-50 MHs (3 kW each) and positive displacement flowmeters (Oval Corporation, Tokyo, Japan, LS4976-460A for main engines and LSF40PO-M1 for auxiliary engines). We obtained data on time, position, amount of fuel consumed in each operational process (e.g. until arrival at the fishing ground, start of the stage reduced lighting, reduction of lighting, end of lighting) and the catch amount of squid (number of boxes) from the captain’s log-books.

All MHs and LEDs (total 147-159 kW) were lit at the beginning of lighting for several hours (Fig. 2A, hereafter referred to as “full-lighting”), and then the number of MHs was reduced to either 30 (90 kW) or 36 lamps (108 kW) until the end of fishing (Fig. 2B, hereafter referred to as “30 MHs” or “36 MHs”) in stage reduced lighting. Thus, boats during the full-lighting period consume an equal amount of fuel as commercial operations and the fuel is then saved by subsequently reducing the amount of lighting.

Fuel consumption data for commercial boats was not available. Fuel consumption of the commercial boats was estimated by the average values of fuel consumption rate during the full-lighting period and the typical time schedule of fishing operations of experimental boats.

We compared catches of experimental boats to average catch of 21 commercial boats between January 9 and February 24, 2010. Experimental boats had to operate offshore of 12 nautical miles from the coast-line of Iki and Tsushima islands (Fig. 1) due to local regulations (lighting power must be less than 60 kW (20 MHs) within 12 nautical miles from the coast-line). On the other hand, commercial boats were able to choose their fishing locations at will. In addition, commercial boats sometimes reduce the number of MHs for about 1-2 h during the middle of the night to encourage squid to rise to a shallower layer. Catches of commercial boats are consequently influenced by differences in location and various lighting conditions (conventional lighting). However, we consider that the commercial data can be criteria for catch comparison because fishermen generally tried to maximize their fishery earnings in commercial operations.

GLM analysis was conducted for catch analysis. Catch C, in general, is expressed as a product of the catchability coefficient q, fishing effort E, and abundance of squid in the fishing ground N.

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

where E is the fishing effort expressed as one operation. Concerning N, we observed a clear difference in the catch amount of squid for the experimental and commercial boats between data for January and data for February. We therefore set a two-level categorical variable (January and February) for N.

We considered that the catchability coefficient q can be extracted as a product of several factors; q is influenced by the lighting method, direct and indirect impacts of lunar phase, and fishing power (ability) of each boat that originates from the fishermen's skills.

$$q = q_M q_L q_B \qquad (2)$$

where q_M is the fraction of the catchability coefficient that is governed by the lighting method. We defined q_M as a categorical variable, because it showed a nonlinear relationship between the catch and number of MHs used in the previous study [2]. q_L is the direct and indirect influence of the lunar phase on catchability coefficient and q_B is the fraction of catchability coefficient that originates from the difference in fishing power of each boat. In this study, we obtained catch data from 30 boats (9 experimental and 21 commercial boats) but we set 10 levels, consisting of 9 for the experimental boats and 1 for the mean fishing power of the 21 commercial boats, because too many levels require too many dummy variables, which reduce the degrees of freedom for analysis.

From these assumptions, we took 4 factors that explain catch C; *light* as a 3-level categorical variable (30 MHs, 36 MHs, and conventional lighting), *lunar* as a continuous variable explained from illuminated fraction of the moon between 0 and 1, *boat*; a 10-level categorical variable (9 experimental boats and the mean fishing power of commercial boats), and *month*; a 2-level categorical variable as an index of change in squid abundance (January and February).

Catch amounts were analyzed as a function of factors mentioned above by GLM. We assume the catch C_i (i.e., the number of boxes of squid caught during the *i*th operation) is a random variable having a negative binomial distribution [2];

$$C_i \sim NB(\mu_i, \theta) \quad (3)$$

θ (>0) is a potential dispersion parameter to be estimated [3]. Then, the expected value of C, $E(C)$ and its variance var(C) are expressed as;

$$E(C) = \mu \quad (4)$$

$$\mathrm{var}(C) = \mu + \mu^2/\theta \quad (5)$$

Overdispersion is expressed as the multiplicative factor 1+ μ/θ, which depends on μ.

C was modeled as;

$$\mathrm{Ln}C = \beta_0 + \beta_1 light + \beta_2 boat + \beta_3 lunar + \beta_4 month + \varepsilon \quad (6)$$

where β_0 is the intercept (constant), and β_1, β_2, β_3, and β_4 are the coefficients for the respective *light*, *boat*, *lunar*, *month*, and ε the error. Parameter estimation was performed by the maximum likelihood method (*glm.nb* function in the MASS package[4] in R ver. 2.13.0, R Development Core Team). We took the stepwise forward entry method for parameter estimation following Yamashita et al. [2]. 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.

Results

We obtained catch and fuel consumption data from the 9 experimental boats consisting of a total of 114 operations (57 operations with 30 MHs and 57 operations with 36 MHs) between January 9 and February 24, 2010. We also collected catch data of a total of 466 operations conducted by 21 commercial boats in the same period.

Three box and whiskers plots in Fig. 3 show durations of lighting, amounts of fuel consumed and fuel consumption rates according to lighting method. The average duration for the full-lighting was 3.9 h regardless of the number of lamps used after the full-lighting. Then experimental boats reduced the number of MHs to either 36 or 30 and continued fishing for 7.3 h on average. Experimental boats consumed approximately 242 l of fuel during the average 3.9 h duration of full-lighting, and during the ensuing stage reduced lighting period an average of 294 l with 36 MHs, and 273 l with 30 MHs. From these data, the average values of fuel consumption rates were 61.5 l/h during the full-lighting, 40.4 l/h with 36 MHs, and 37.6 l/h with 30 MHs.

Daily catch amount of boats that used the stage reduced lighting and conventional lighting is summarized in Fig. 4. Skewed distributions and wide range of variations were observed in catch amount regardless of lighting method. The median catch values were 72.5, 105, and 105 boxes for conventional lighting, 30 MHs, and 36 MHs, respectively. Non-parametric multiple comparison for all catch data suggested the catch amount by the conventional lighting was less than those by the stage reduced lighting with 30 and 36 MHs (Steel-Dwass test, $P<0.05$), and the number of MHs after the full-lighting did not affect the catch amount ($P>0.05$). When the time sequence is considered, catch amounts by the stage reduced lighting with two different treatments and the conventional lighting showed similar catch tendencies (Fig. 5); all boats suspended fishing for several days around the full moon (January 30) and catch amounts peaked around new moon days (January 15 and February 14).

GLM analysis revealed that the AIC value was smallest when parameters, *lunar*, *month*, and *light* were taken into the model as shown in Tables 1 and 2. The results of the GLM analysis demonstrated that *light* is less significant ($P<0.05$ only for 36 MHs) and *lunar* showed a significant negative effect ($P<0.001$), suggesting that catch would decrease during operation around the full moon period. In addition, catch was significantly larger in January than in February ($P<0.001$). Thus, GLM analysis adopted a model (Model 3-1 in Table 2) in which catch amount significantly depends on *lunar* and *month*, with less influence of *light*. Expected catch amounts from the adopted model were plotted against the observed catch amounts in Fig. 6. The range of catch amounts calculated from this model was between 41 and 206 boxes, and this model did not express larger and smaller catches beyond the range that was frequently observed in the experimental period.

Discussion

A merit of the stage reduced lighting is the potential from the fuel saving point of view. When a commercial operation is conducted with the full-lighting condition (159 kW) that is close to the maximum lighting power of the voluntary regulation (160 kW) for 11.2 h (average lighting duration in this study), total fuel consumption for lighting is estimated as 690 l. However fuel consumption amount during commercial operations is sometimes less than this value because fishermen occasionally reduce the number of MHs for about 1-2 h (pers. comm., with a captain who participated in the experiment). In this case, the amount of fuel reduction by this procedure is at least 123 l, which is the approximate amount of fuel consumed during full-lighting for a 2 h. When typical durations for the full-lighting (3.9 h) and lighting with 30 MHs or 36 MHs (7.3 h) are taken into account, it is estimated that the stage reduced lighting consumes 516 l for 30 MHs during jigging with lamps and 536 l for 36 MHs. These estimated values are 174 and 154 l (22 and 25%) less than the estimated maximum amount of fuel consumption during the conventional lighting. Unlike the summer fishing season [1], squid fishing grounds in the Tsushima Strait in winter are relatively close to the base ports and therefore fuel saving during jigging with lamps is a management priority to improve profitability.

Several studies have demonstrated that squid around a jigging boat are generally hooked in the shadow zone which is created by the boat hull [5-8]. These findings suggest that squid shelter from strong light around the boat although this fishing technique applies the principle of squid attraction to the light. We consider that full-lighting initially delivered light over a broad area and attracted squid schools around the boat at the beginning of fishing. Once the squid schools got closer to the boat after the full-lighting, strong light such as the maximum lighting power of the voluntary regulation (160 kW) may not be necessary.

By appearance, the stage reduced lighting led to better catch than the conventional lighting (Fig. 4), but the catch difference between conventional and the stage reduced lighting with 30 MHs was not significant in the GLM analysis (Table 2, P=0.086). Therefore, stage reduced lighting is considered to potentially have the same catch performance as the conventional lighting. The observed increase in catch amount with stage reduced lighting (Fig. 4) may be due to the difference in light sources between the experimental and commercial boats. Experimental boats partially employed LEDs that emit a certain range of wave-length (blue-blue green, 450-500 nm) that has good penetration into the water [7,9], whereas commercial boats use only MHs that emit other ranges of light. Light from LEDs penetrates into the water better than light from MHs and reaches squid that are distributed further and/or in a deeper area from the boat.

Unlike the results in our previous study on GLM analysis of squid catch in summer [2], we detected an influence of the illuminated fraction of the moon. Lunar rhythmicity in catch has been recognized among fishermen who operate fishing with artificial light and they generally suspend their fishing for several nights around the full moon. Our results demonstrated an influence of the lunar phase to catch by analyzing catch data during 2 cycles of lunar phase. Regardless of the lighting method, catch amount tended to increase from the full moon to the new moon and an opposite tendency was shown from the new moon to the full moon (Fig. 5). This tendency may be due to the direct influence of light in the environment but also due to the internal rhythm of squid governed by the lunar phase [10,11]. In addition, we did not detect any influence of fishing power due to differences in the fishermen's skills. This result probably reflects the unique characteristics of the fishing ground in Tsushima Strait in winter. Japanese common squid migrates from the north for spawning in this season and forms dense distributions in limited areas [12]. Many squid jigging boats concentrate in limited areas in this season to capture squid while maintaining a sufficient distance (at least 2 nautical miles, pers. comm., with a captain who participated in the experiment) from the next boat so as not to affect the area influenced by its lighting. Under such conditions, choice of preferable fishing position, which is one of the most important skills explaining the fishing power, may be restricted.

There may be other factors that we did not take into account to explain the catch amount, because the expected catch in the GLM analysis expressed a narrow range (41 to 206 boxes) against a range of observed catch amount (0 to 659 boxes, Fig. 6). One possibility is related to the influence of the weather and sea conditions. In a preliminary GLM analysis, we took hours of sunshine (Japan Metrological Agency Web: http://www.data.jma.go.jp/obd/stats/etrn/index.php, Accessed July 2011) just before starting the operation to describe the weather condition on the day, and the result suggested a significant influence on the catch. However, the number of hours of sunshine incidentally exhibited a positive correlation with the lunar phase so that we did not take this factor into account. Further research by accumulating data for longer durations is necessary to evaluate the influence of the weather and sea conditions. In addition, foraging behaviour of dolphins; generally, Pacific white-sided dolphin *Lagenorhynchus obliquidens* and bottlenose dolphin *Tursiops truncatus*, in the fishing ground is a concern among fishermen, since, once they arrive, the squid around the boat tend to disperse. Small catch data sometimes recorded by commercial boats may include the impact of dolphin behavior.

Thus, stage reduced lighting using LEDs and MHs has a potential to save fuel consumption by up to 25 % when compared to commercial lighting practice while maintaining the squid catch in Tsushima Strait in winter. We propose to fishermen that stage reduced lighting is a promising method for improving profitability through fuel saving.

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Table 1 Models considered in the study and results of fit

	Formula	Null deviance	Null d.f.	Residual deviance	Residual. d.f.	AIC	θ	(s.e.)
Model 0	*C* ~ 1	708.92	579	708.92	579	6464.4	0.5792	(0.0329)
Model 1-1	*C* ~ *light*	719.95	579	708.82	577	6457.4	0.5896	(0.0337)
Model 1-2	*C* ~ *lunar*	741.02	579	708.71	578	6434.9	0.6096	(0.0350)
Model 1-3	*C* ~ *boat*	725.88	579	708.79	570	6465.5	0.5952	(0.0340)
Model 1-4	*C* ~ *month*	736.54	579	708.75	578	6439.2	0.6053	(0.0347)
Model 2-1	*C* ~ *lunar* + *light*	748.29	579	708.73	576	6432.1	0.6165	(0.0355)
Model 2-2	*C* ~ *lunar* + *boat*	754.93	579	708.76	569	6439.9	0.6228	(0.0359)
Model 2-3	*C* ~ *lunar* + *month*	750.66	579	708.78	577	6427.9	0.6187	(0.0356)
Model 3-1	*C* ~ *lunar* + *month* + *light*	758.67	579	708.83	575	6424.5*	0.6264	(0.0362)
Model 3-2	*C* ~ *lunar* + *month* + *boat*	765.24	579	708.88	568	6432.5	0.6326	(0.0366)
Model 4	*C* ~ *lunar* + *month* + *light* + *boat*	765.24	579	708.88	567	6434.5	0.6326	(0.0366)

*Adopted as the model

Table 2 Coefficients estimated

Parameter	Estimate	(s.e.)	Wald statistic	*p*-value
Intercept *	4.5581	(0.1037)	43.944	< 0.001
lunar	-0.8504	(0.2232)	-3.810	< 0.001
month	0.3759	(0.1087)	3.457	< 0.001
light				
30 MHs	0.3063	(0.1787)	1.714	0.086
36 MHs	0.3940	(0.1779)	2.215	0.026

* coefficient for catch by conventional lighting in new moon of February

Figure captions

Fig. 1. Map of the fishing ground. Solid circles designate positions where stage reduce lighting with 30 MHs was carried out in January 2011, grey circles stage reduced lighting with 30 MHs in February, solid squares stage reduced lighting with 36 MHs in January, grey squares stage reduced lighting with 36 MHs in February.

Fig. 2. Squid jigging boat lighting LEDs and MHs. Full-lighting (a) and lighting with reduced numbers of MHs (b).

Fig. 3. Box and whisker plots for durations of full-lighting and lighting with reduced numbers of MHs by the 9 experimental boats using stage reduced lighting (a), amounts of fuel consumed during full-lighting and lighting with reduced numbers of MHs (b), and fuel consumption rate in full-lighting and in lighting with reduced numbers of MHs (c). The band in the box is the median values and the bottom and top of the box are the lower and upper quartiles, respectively. The ends of the whiskers represent the 1.5 interquartile range and plots depicted as open circles designate the outliners.

Fig. 4. Box and whisker plot for daily catch amount (boxes) of boats that used different lightings (stage reduced lighting with 30 MHs, stage reduced lighting with 36 MHs, and conventional lighting). The band in the box is the median values and the bottom and top of the box are the lower and upper quartiles, respectively. The ends of the whiskers represent the 1.5 interquartile range and plots depicted as open circles designate the outliners. These outliners are all used in catch analysis in the study.

Fig. 5. Average catch amounts of boats that used the different lighting (with 30 MHs after the full-lighting, with 36 MHs after the full-lighting, and conventional lighting) during January and February 2010.

Fig. 6. Expected catch (boxes) plotted against observed catch (boxes) for the adopted model (3-1). A solid line designates equal values.

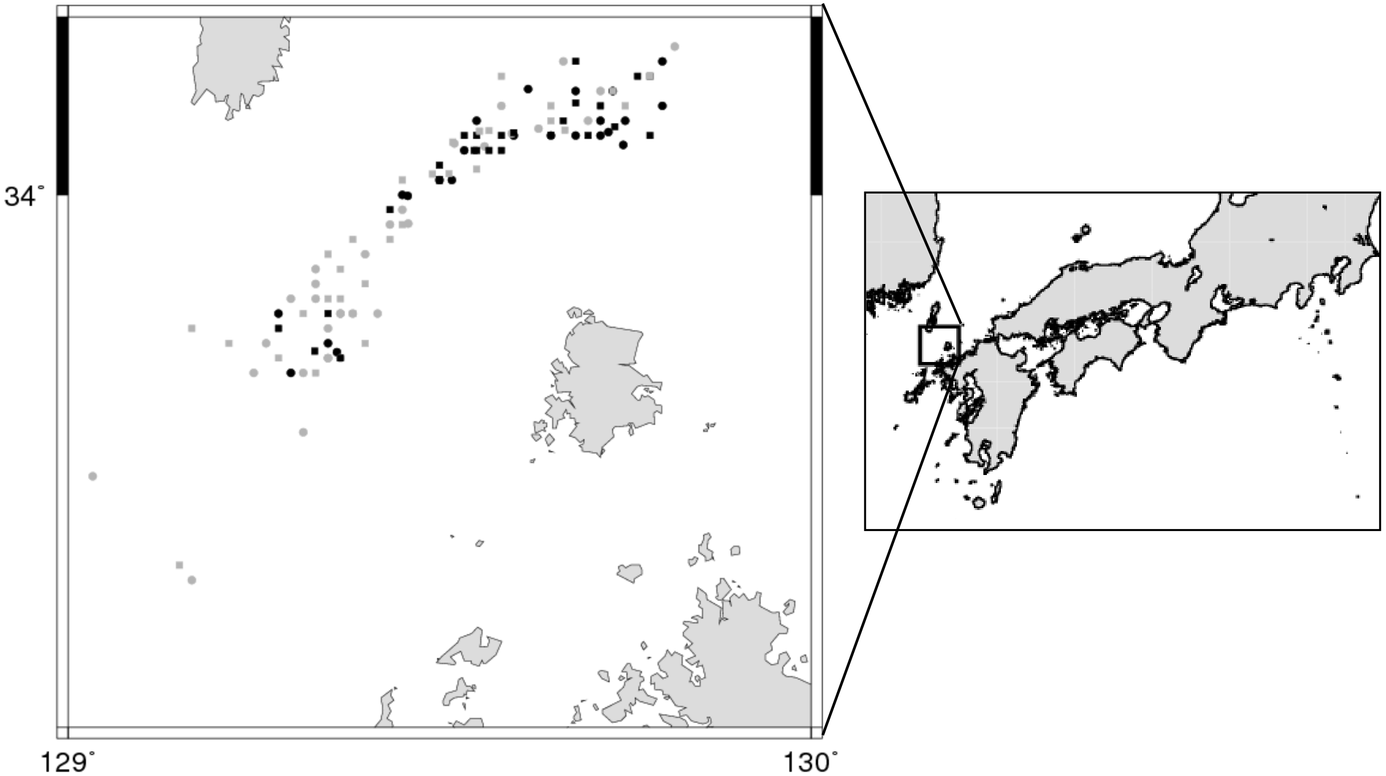

Fig. 1 Matsushita and Yamashita

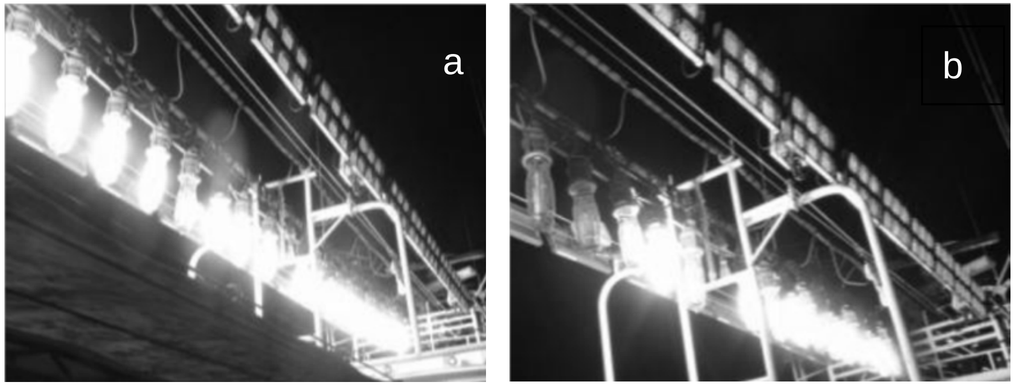

Fig. 2 Matsushita and Yamashita

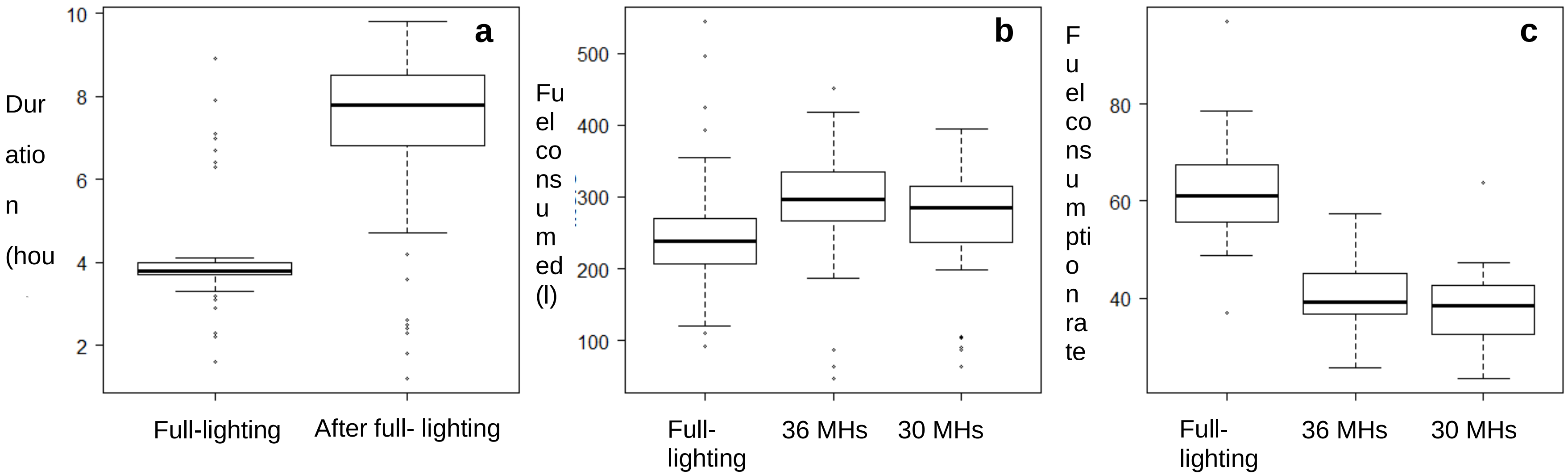

Fig. 3 Matsushita and Yamashita

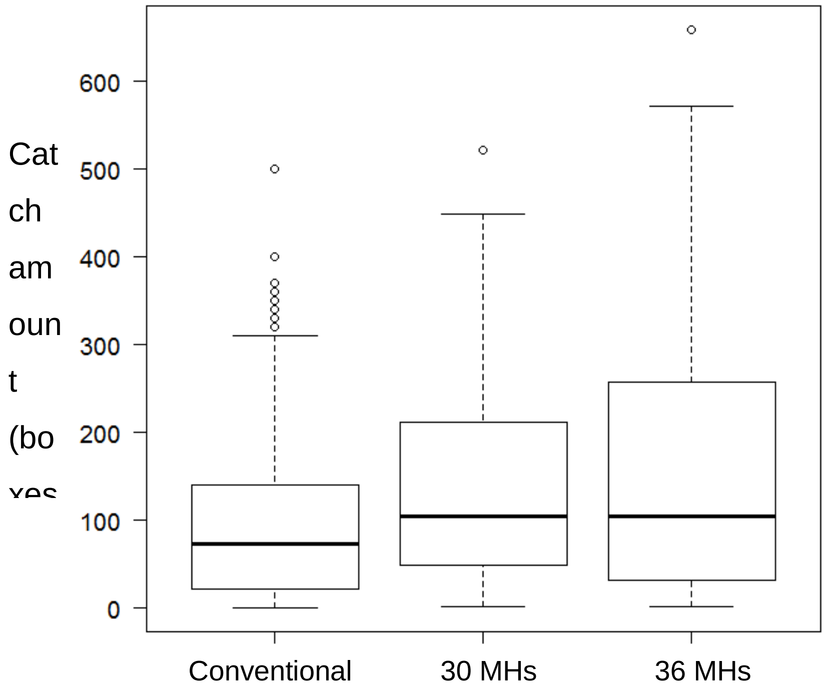

Fig. 4 Matsushita and Yamashita

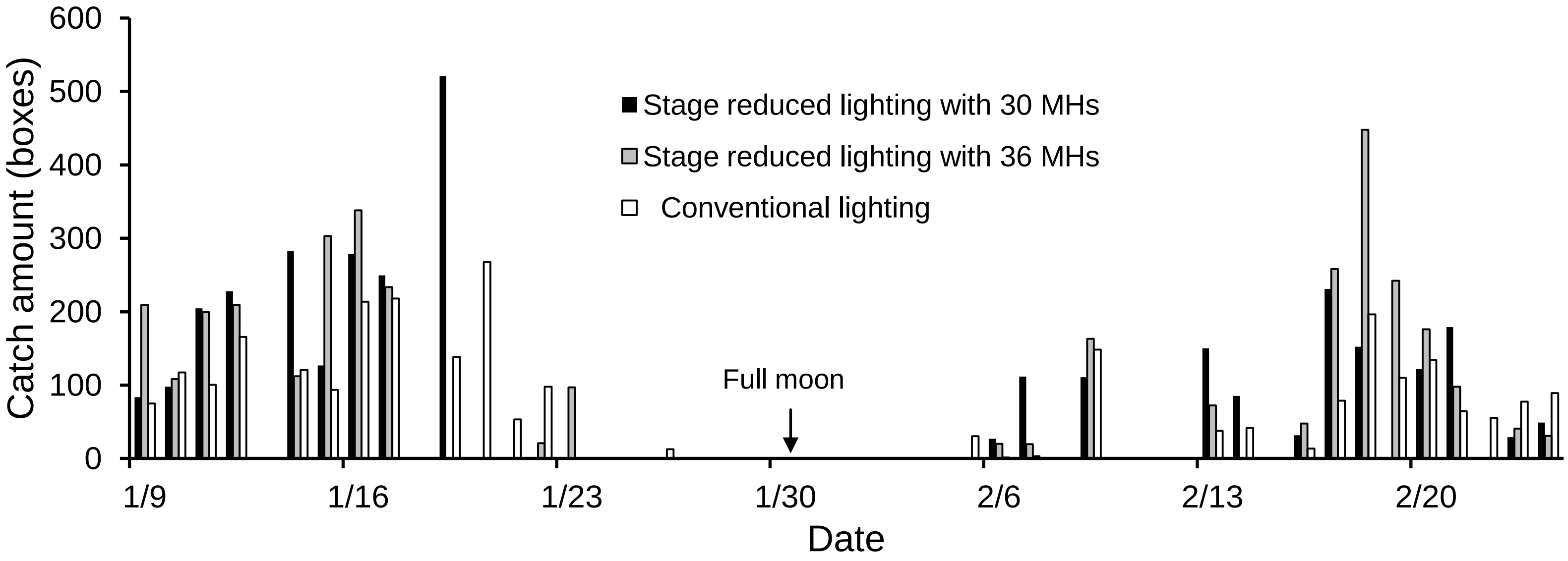

Fig. 5 Matsushita and Yamashita

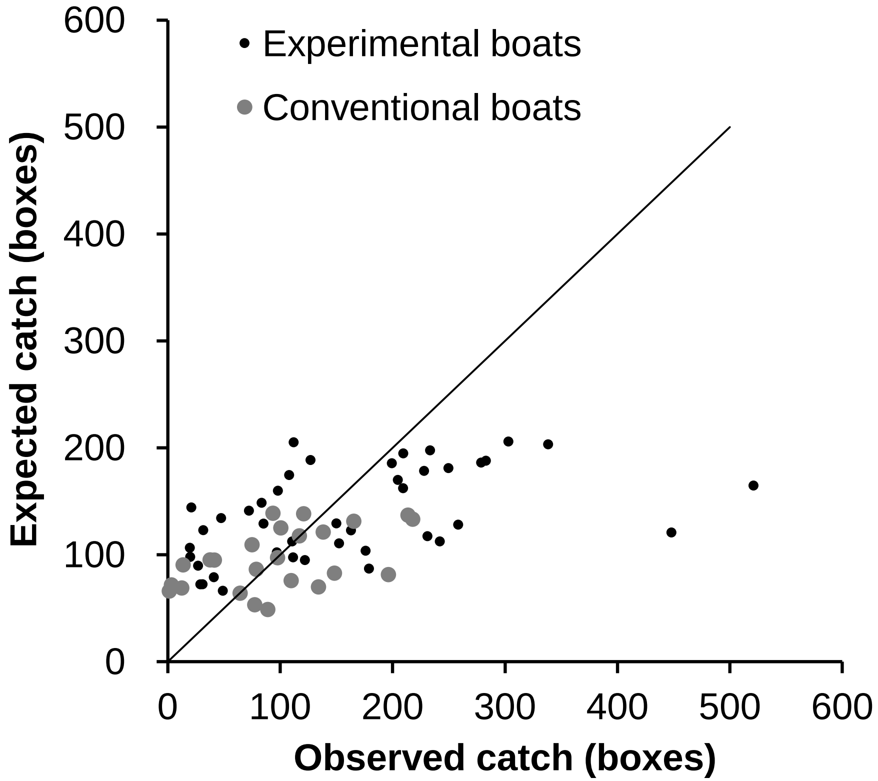

Fig. 6 Matsushita and Yamashita