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Sexual Dimorphism, Length-Weight Relationships, Fecundity, and Diet of the Striped Eel Catfish *Plotosus lineatus* (Plotosidae) on Taiwan's Southwest Coast

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Abstract

This study of feeding guild fish from the same coast of subtropics helps to suggest conservation of fishery resources. A total of 2,537 specimens of *Plotosus lineatus* (Plotosidae) were collected from July 2013 to March 2019 on the coast of Taiwan. The average total body length (TL) was 23.7 cm ± 4.7 cm and 20.3 cm ± 2.9 cm, and the average body weight (W) was 94.1 g ± 59.6 g and 56.6 g ± 30.8 g among 174 males and 630 females, respectively. The LWRs of male and female were $\ln(W)_M = 3.2914 \times \ln(TL) - 6.0395$, and $\ln(W)_F = 3.0917 \times \ln(TL) - 5.3629$. The male specimens were large than female in TL and W. The average OSW/TL ratios were 0.722 ± 0.044 and 0.649 ± 0.029 among 41 male and 49 female specimens, respectively. The OSW of the male head was wider than that of the female head ($F = 91.5$; $p < 0.001$), and the head widths of the male fish were significantly more than those of their female counterparts, causing the OSs to form granular protrusions. The average CFW/TL ratios were 0.198 ± 0.034 and 0.252 ± 0.032 among the male and female specimens, respectively. The CFW of the male specimens was narrower than that of the female specimens ($F = 58.9$; $p < 0.001$), and the CF gap of the male fish was narrower than that of the female fish. The *P. lineatus* exhibits significant sexual dimorphism. The average eggs number of each female was 2375.6 eggs/individual ± 1140.9 eggs/individual ($N = 161$). The major prey of *P. lineatus* were shrimps, crabs, and fishes; the total relative frequencies of occurrence of the prey were 57.1%, 32.6%, and 37.2%, respectively ($N = 282$), and their total relative abundance levels were 40.2%, 26.3%, and 25.8%, respectively ($N = 445$). Proper scientific knowledge management will improve the development of fisheries.

Keywords

Plotosus lineatus, Population Structure, Skull Development, Feeding Guild, Taiwan

1. Introduction

The striped eel catfish, *Plotosus lineatus* (Thunberg, 1787) (Plotosidae), is widely distributed in the Indo-Pacific and generally found in coral reef areas, shallow coastal areas, lagoons, estuaries, and the pores of wave-dissipating blocks in Japan, Taiwan, Samoa, East Africa, and the Mediterranean [1]-[6]. Juveniles form dense ball-shaped schools of approximately 100 fish; adults are solitary or living in smaller groups of around 30 individuals [7] [8] [9] [10] [11]. The *P. lineatus* is a top predator that feeds on crustaceans, fish, and mollusks [1] [2] and has high commercial value in the aquarium industry [12] [13]. But in Taiwan, it's a very low-priced trash fish, and they're usually discarded by fishermen. In addition, their 3 poisonous jagged spines often cause harm to the people [14] [15]. It is one of the four common poisonous fish on the west coast of Taiwan. Fishermen often sing songs to remind them to be careful when fishing.

The objective of this study was to evaluate linear length-to-weight relationships (LWRs) of *P. lineatus* by the natural logarithm. The evaluation results can serve as a reference for fishery assessments, fishing methods, attitudes, and management, and future comparisons between populations of the same species encountered in different environments [16] [17] [18] [19].

Knowledge of reproductive traits such as size at maturity, spawning rate, sex ratio, ova diameter, and fecundity is an essential basis for fishery management and conservation [20] [21]. A pair of mated fish would look for porous spaces, such as coral reefs and wave-breaking blocks. After spawning, the male fish takes care of the eggs when in the incubation stage [21]. Therefore, male fish often remain in pores on the coast during the breeding season, whereas female fish return to the small breeding group and wait for possible breeding opportunities. Fecundity is the number of eggs production or offsprings per unit length of and weight of the fish [22]. The fertility rates of Taiwan's population of *P. lineatus* may be similar to that of other regions.

The gonads of *P. lineatus* have an opaque, milky white color in both immature male and female individuals, but the mature female gonads are light pink, whereas the male gonads have a transparent, milky white color [23]. However, the ovaries of either immature female fish or the female during the nonbreeding season are often milky white, and such fish can be easily misjudged to be immature male fish [16]. The thin branches (fronds) of the testes of immature male fish appear very similar to the under-developed ovaries of females.

For fish, fundamental morphological traits such as sexual dimorphism can be used to estimate fish body size, population sex ratio, size structure, and reproductive potential [19] [24]. Sex-based differences in the operculum of *Scoloplax empousa* have been reported by Schaefer (1990) [25]. The male mosquitofish, *Gambusia affinis* (Poeciliidae), was osteologically different from the females by gonopodial suspensorium and modified vertebra [26]. Some bones in certain types of catfish exhibit sex-based variations [27].

Therefore, the male and female fish can be more accurately identified only when they grow to more than 13 cm [23]. It is not possible to distinguish between all males and immature females by the appearance of the gonads other than relying on some anatomy the appearance. Furthermore, the cranial fontanel (CF) and orbitosphenoid (OS) are not expanded; in subadult fish, the parieto-supraoccipital bone gradually expands outward dorsally, and some OS spines are formed upward (**Figure 1**).

Knowledge of skull development will help estimate the sex ratio. During the breeding season, the female-to-male ratio of *P. lineatus* is high, with the reported ratio being 1.4 in Korea [23]. Nevertheless, in Indonesia, the reported male-to-female ratio of *P. lineatus* was 4.5 [16]. Accordingly, the sex ratio of *P. lineatus* is a notable phenomenon that warrants exploration.

For example, in adult male auchenipterids, the parieto-supraoccipital bone is dorsally concave, and the OS bone forms a closed cylindrical tube and a flat skull [28] [29]. Of the many mechanisms that drive the evolution of sexual dimorphism, the most widely recognized is sexual selection, which enhances the fitness of each sex exclusively concerning reproduction [30] [31] [32] [33]. Male and female individuals may differ in their size, color, shape, and skeletal structure and their development of appendages, such as horns, teeth, or fins [34]. Mature male *P. lineatus* individuals have slightly wider heads than female *P. lineatus* individuals, which could be due to an altered width of either OS or CF.

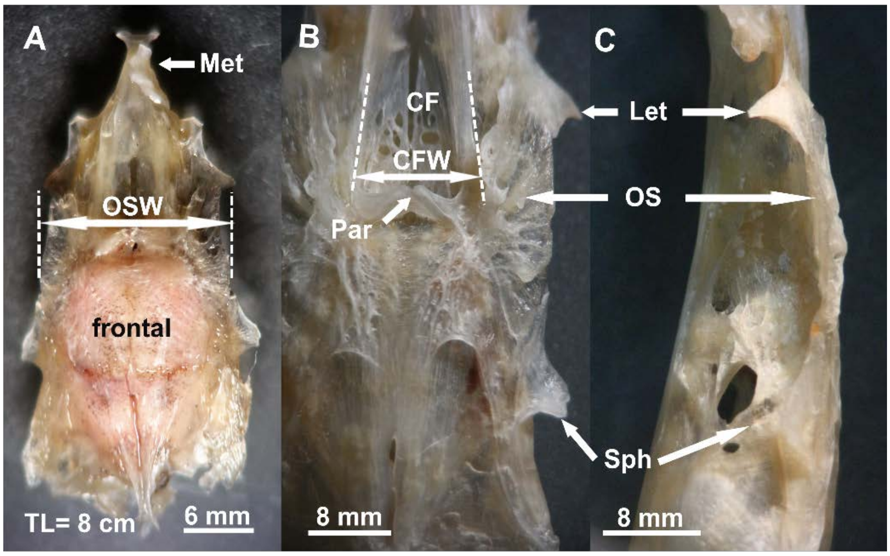

Figure 1. Crania of juvenile *Plotosus lineatus*. ((A), (B)) dorsal view; (C) lateral view; CF: cranial fontanel; CFW: cranial fontanel width; Let: lateral ethmoid; Met: mesethmoid; OS: orbitosphenoid; OSW: orbitosphenoid width; PAR: parasphenoid; SPH: sphenoid.

The major preys of *P. lineatus* are crustaceans, amphipods, isopods, crabs, shrimps, calanoid copepods, mollusks, worms, and fish [2] [35]. This species is "voracious", is "probably a top predator", and lives in different ecological habitats [1]. In the southwestern coastal habitat of Taiwan, crustaceans and fish constitute the main food source of *Pisodonophis cancrivorus* and *Pisodonophis boro* (Ophichthidae) [17]. Although these fish live in different geographic habitats, their prey utilization is similar. Following *Pisodonophis* spp. report [17], we study the basic information of other feeding guild fish—*P. lineatus.*

2. Materials and Methods

In this study, the fish was collected by the lift nets and trap nets in lagoons and estuaries in southern Taiwan, including Zhuoshui Estuary (Jhuoshuei River), Puzih Estuary (contain Dongshih Lagoon), and Beimen Lagoon (120˚05'04.9"E - 120˚15'50.4"E, 23˚16'18.7"N - 23˚50'46.2"N) from July 2013 to March 2019.

All specimens of *P. lineatus* were stored in a freezer at 0˚C and assessed in the laboratory. In the laboratory, sex, total body length (TL, cm), and total weight (W, g) were determined. Lastly, the specimens were preserved in 75% ethanol.

The LWR was calculated based on the linear length-to-weight equation: $\ln(W) = a\ln(TL) + b$, where TL and W represent natural logarithm-transformed variables, a represents the slope, and b represents the intercept [16] [18] [36] [37].

After the heads had been separated from the bodies of the fish, the TL (cm), orbitosphenoid width (OSW, precision = 0.1 mm), and cranial fontanel width (CFW, precision = 0.1 mm) were measured near the front end of the parasphenoid with a digital caliper, as documented in **Figure 1** [37].

For the estimation of fecundity, the ovaries or testes were removed and their wet weight was measured. The number of eggs (fecundity) was also counted under a microscope with a 10× objective. A total of 402 fish were examined for stomach contents under a microscope from May 2017 to March 2019.

All stomach and gut contents were preserved in 75% ethanol. The diet elements of fish otoliths, scales and bones; crab claws and carapace; shrimps carapaces and tails; mollusk shells; and mouthpart of a crustacean, were washed and compared with those of complete possible food individual collected for species identification (**Figure 2**) [38]-[45]. The data are presented as the mean ± standard deviation.

The data are presented as the mean ± standard deviation. The recorded data were analyzed using subroutines implemented in Resemblance and SIMPER (PRIMER v.6, PRIMER-E, Plymouth), both of which are statistical analysis programs (Krebs, 1999). One-way ANOVA was used to compare the ratios of the OSW/TL and CFW/TL of the male and female *P. lineatus*.

3. Results

Between July 2013 and March 2019, a total of 2537 *P. lineatus* specimens were caught along the southwest coast of Taiwan, and 1387 of those were analyzed.

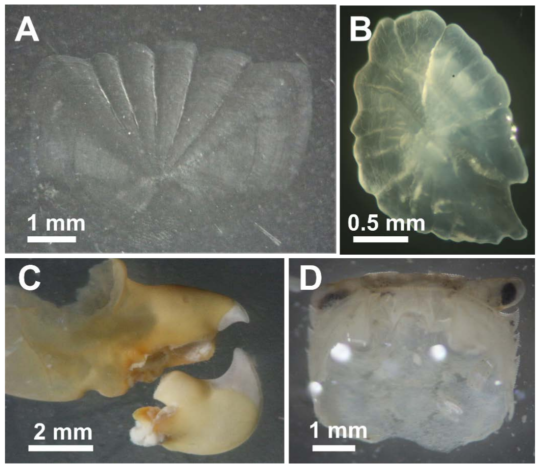

Figure 2. Stomach and gut contents. A: scale of a fish (Gobiidae). B: otolith of a fish (Sesarmidae: *Secutor ruconius*). C: major cheliped of alpheid shrimp (Alpheidae), D: Crab carapace (Grapsidae: *Pachygrapsus minutus*).

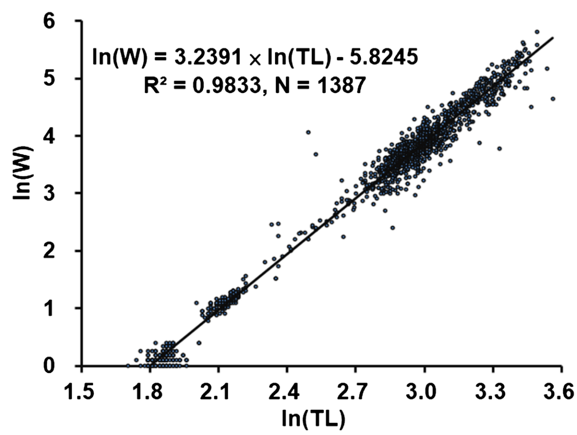

Figure 3. Relationships between total body length (TL) and weight (W) of *Plotosus lineatus* captured from the southwest coast of Taiwan.

The average TL of the *P. lineatus* was 17.7 cm ± 6.7 cm (range: 5.5 - 35.2 cm), and the average W was 49.2 g ± 46.9 g (range: 0.9 - 336.3 g) (N = 1387). The LWR was $\ln(W) = 3.2391 \times \ln(TL) - 5.8245$ ($R^2 = 0.9833$, N = 1387) (Figure 3).

3.1. Skull of *Plotosus lineatus*

The average OSW/TL ratio of the male *P. lineatus* specimens obtained from the southwest coast of Taiwan was 0.722 ± 0.044 (range: 0.642 - 0.825, N = 41), and that of the female specimens was 0.649 ± 0.029 (range: 0.579 - 0.698, N = 49). The linear relationship between TL and OSW was $OSW_M = 0.8864 \times TL - 4.2715$ ($R^2 = 0.863$, N = 41) for the male and $OSW_F = 0.5294 \times TL + 2.5703$ ($R^2 = 0.8328$, N = 49) for the female specimens (Figure 4). One-way ANOVA conducted on OSW/TL ratios indicated that the heads of the male fish were generally wider than those of the female fish ($F[1, 90] = 91.5$; $p < 0.001$), and the head widths of the male fish were significantly more than those of their female counterparts, causing the OSs to form granular protrusions. The average CFW/TL ratio of the male *P. lineatus* specimens was 0.198 ± 0.034 (range: 0.125 - 0.374, N = 41), and that of the female specimens was 0.252 ± 0.032 (range: 0.185 - 0.341, N = 49) (**Figure 4**). However, the CFW/TL ratios indicated that the female *P. lineatus* specimens were larger than the male specimens ($F[1, 90] = 58.9$ and $p < 0.001$), and the CF gap of the male fish was narrower than that of the female fish. This indicates that *P. lineatus* is sexually dimorphic.

Although the OS of female adult is also changeable, their cranial fontanel width is smaller that of male. In addition, both OS and parasphenoid (**Figure 1**) are not upturned and forming granular protrusions on the scalp. During the breeding period, the male adult of *P. lineatus* can swim below the female adult and hit the cloaca and paired successfully. The OS of the male *P. lineatus* extended outward to form a head wider than that of the female *P. lineatus*. The inner edges of the OSs of the male specimens had obvious upward tubulars and spines; the parasphenoids also extended forward and turned upward. The shapes of the OSs varied (**Figure 5**). These granular OSs and protrusions under the skin caused roughness of the skin on the top of the head (**Figure 6**). Male and female *P. lineatus* can be easily differentiated by these small protrusions under the scalp.

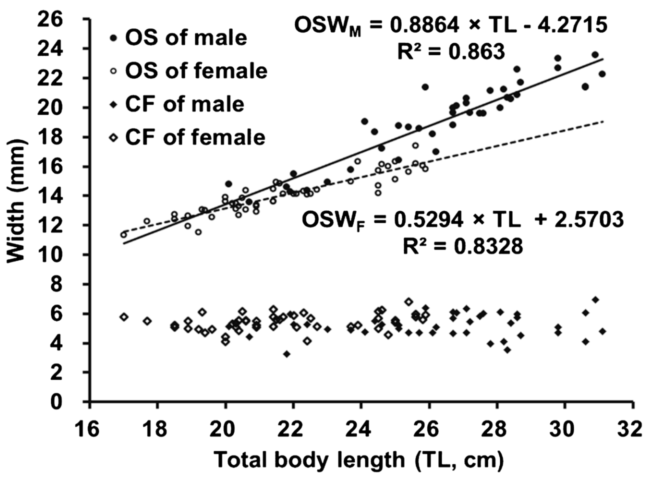

Figure 4. Distribution of total body length (TL), orbitosphenoid width (OSW), and cranial fontanel width (CFW) for male (N = 41) and female (N = 49) *Plotosus lineatus*.

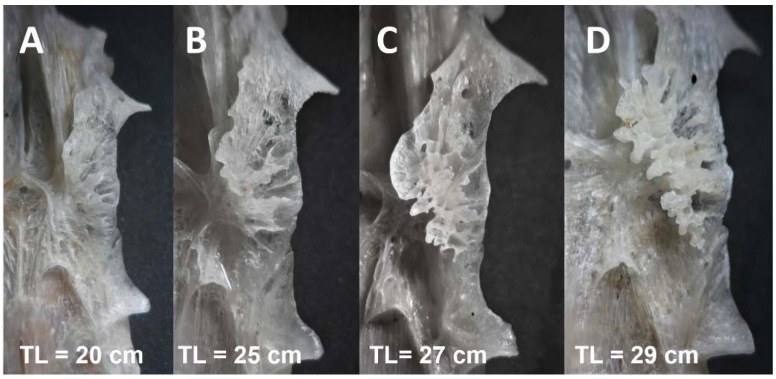

Figure 5. Right orbitosphenoid of male adult *Plotosus lineatus*. (A)-(D): dorsal views revealing the organism's multiple styles.

3.2. Sex-Based Differences of *Plotosus lineatus*

The gonads of the specimens were anatomically examined. The female-to-male ratio was 3.6:1. Among these fish, 174 male specimens had developed gonads; their average TL was 23.7 cm ± 4.7 cm (range: 9.1 - 32.9 cm), and the average W was 94.1 g ± 59.6 g (range: 4.5 - 267.0 g). The LWR of male *P. lineatus* was $\ln(W)_M = 3.2914 \times \ln(TL) - 6.0395$ ($R^2 = 0.9097$) (Figure 7). The gonads of 630 female specimens were developed; their average TL was 20.3 cm ± 2.9 cm (range: 12.5 - 35.2 cm), average W was 56.6 g ± 30.8 g (range: 14.8 - 189.0 g), and average ovarian weight was 8.7 g ± 6.4 g (range: 0.1 - 48.5 g). The LWR of female *P. lineatus* was $\ln(W)_F = 3.0917 \times \ln(TL) - 5.3629$ ($R^2 = 0.8124$) (Figure 7). Thus, the average length and weight of male specimens were greater than those of female specimens.

The number of eggs of 161 female *P. lineatus* was calculated; the average number of eggs per female was determined to be 2375.6 ± 1140.9 (range: 193 - 5750 eggs/individual), and the linear relationship between TL and number of eggs (fecundity) was $F = 334.6 \times TL - 4357.9$ ($R^2 = 0.5834$) (Figure 8). The average weight of each egg was 5.15 mg ± 3.32 mg (range: 1.08 - 35.00 mg; N = 159). Furthermore, no correlation was observed between egg weight/egg diameter and TL variables in any of the female fish.

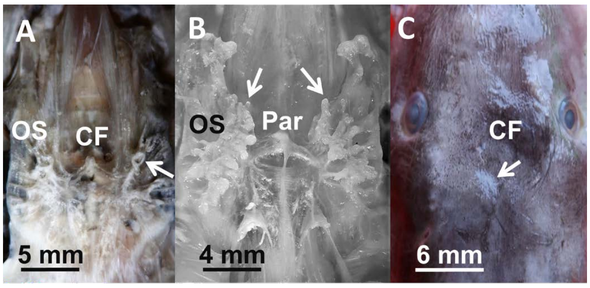

Figure 6. Cranial fontanel and orbitosphenoid of *Plotosus lineatus.* (A)-(C): dorsal view. CF—cranial fontanel; OS—orbitosphenoid; and Par—parasphenoid. Arrows: tubular, spinal, and granular protrusions, respectively.

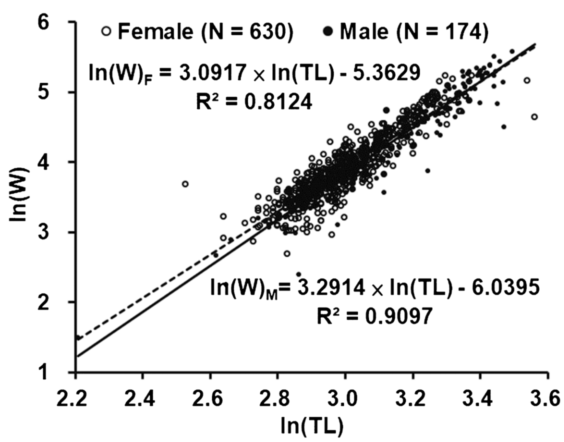

Figure 7. Relationships between total body length (TL) and weight (W) on both sexes of *Plotosus lineatus* specimens from the southwest coast of Taiwan.

The TLs of the female fish were mainly distributed in the ranges of 17 - 19, 19 - 21, and 21 - 23 cm, accounting for 29.4%, 30.0%, and 17.6% of all the female fish, respectively. The male fish TLs were greater and evenly distributed in the range of 15 - 31 cm; most TLs were in the ranges of 19 - 21, 21 - 23, and 27 - 29 cm, accounting for 16.7%, 13.2%, and 13.8% of all the male fish, respectively (**Figure 9**).

3.3. Monthly Change in Population of *Plotosus lineatus*

From July 2013 to March 2019 on the southwest coast of Taiwan, 2537 specimens of *P. lineatus* were caught and analyzed. The average monthly proportions of *P. lineatus* relative to the total fish population were highest in March, October, and April, at 17.7%, 17.6%, and 15.9%, respectively (N = 2537), less than 5% in December, January, and February, and only 1.5% in September, during the typhoon season (**Figure 10**). March to June was the main breeding season for the striped eel catfish. In October and November, after the typhoon season, juveniles joined the population, and the population increased substantially.

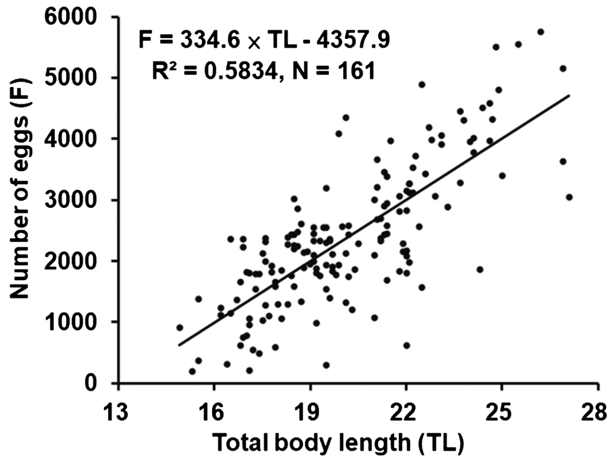

Figure 8. Relationship between total body length (TL) and fecundity (eggs) for female.

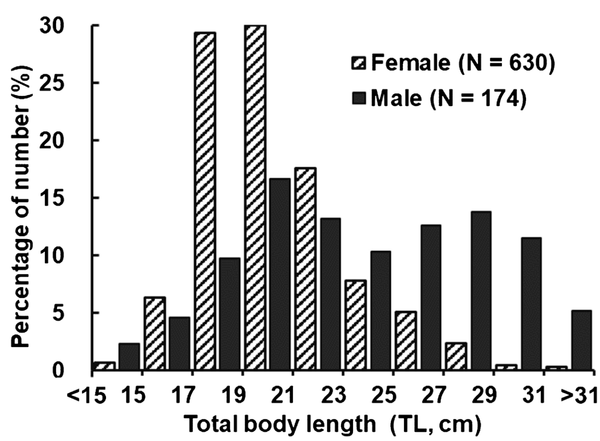

Figure 9. Frequency of size classes of total body length (TL) in both sexes of *Plotosus lineatus.*

3.4. Diet of *Plotosus lineatus*

In total, the stomach contents of 463 *P. lineatus* specimens were examined; the stomachs of 282 of these specimens contained food consumed by *P. lineatus*, and 181 were empty. The food items included fish, crustaceans, mollusks, and brachiopods. A total of 445 food items were retrieved. In the stomachs containing food (N = 282), the relative frequencies of occurrence of shrimp, crab, fish, mollusks, and all other food items were 57.1%, 32.6%, 37.2%, 6.4%, and 2.8%, respectively, and their proportions relative to the total number of food items were 40.2%, 26.3%, 25.8%, 4.3%, and 3.4% (Table 1).

The predominant prey types, identified to the family level, were shrimp (Palaemonidae and Penaeidae), crabs (Grapsidae [*Hemigrapsus penicillatus* and *Pachygrapsus minutus*], Ocypodidae [*Leipocten sordidulum*], Portunidae [*Portunus pelagicus*], and Sesarmidae [*Nanosesarma gordoni*]), fish (Gerreidae [*Gerres erythrourus*], Gobiidae [*Pseudogobius javanicus*], Leiognathidae [*Gerres erythrourus* and *Secutor ruconius*] and Plotosidae [*Plotosus lineatus*]), and mollusks (Laternulidae). At the same time, we also observed striped eel catfish eating their juveniles.

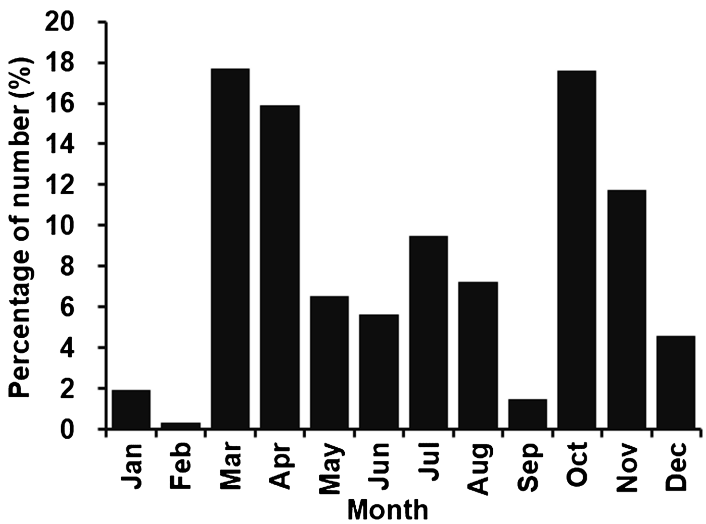

Figure 10. Monthly variation of *Plotosus lineatus* (N = 2537) collected from the southwest coast of Taiwan from March 2013 to March 2019.

Table 1. Frequency of occurrence (percentage of specimens containing the prey type) and proportions of prey items (relative to the total food items) of *Plotosus lineatus* caught on Taiwan's southwest coast from December 2017 to March 2019.

Food classification	Shrimp	Crab	Fish	Mollusk	Others
Frequency of occurrence	161	92	105	18	10
%	56.9	32.5	37.1	6.4	3.5
Proportions of prey item	179	117	115	19	17
%	40.2	26.3	258	4.3	3.8

The other types of prey included Alpheidae, Amphipod, Lingulidae (*Lingula anatine*), Ostracoda, Upogebiidae (*Austinogebia edulis*), and some crustaceans (**Figure 2(C)**). Additionally, the proportion of individuals with parasites (Isopoda, and Nematoda) was 6.5% (N = 463).

4. Discussion

The average slope of the LWR of *P. lineatus* was 3.2919 in males, 3.0917 in females, and 3.239 overall, which are like previous reports [18] [19] [36] [37] [46].

The primary reason for the differences in the head width between male and female *P. lineatus* is that as they grow, the males' OS grow faster than the females' OS, and the OSW/TL ratio is 0.722 > 0.649. However, the growth of CF was contradictory, and the CFW/TL ratio for the male fish was smaller than the female fish (0.198 < 0.252). In addition to differences among male and female *P. lineatus* individuals in size and OS bone structure (**Figure 6** and **Figure 7**), a higher female-to-male ratio greatly increases the number of reproductive options for this species. Although studies in Indonesia have reported that *P. lineatus* have a high male-to-female ratio, we speculate that some of the male individuals in their specimens (TL < 13 cm) may be immature or subadult individuals [16]. The sexually mature body length of this fish in Taiwan is slightly smaller than that from the north Andhra Pradesh coast [19].

After examining the adult fish gonads during the breeding season, we discovered that much more females had laid eggs than males had reproduced (loose gonads). We conjecture that the female fish return to the group after spawning while the male fish remain in the habitat of the wave-dissipating block and take care of the juveniles, resulting in a high female-to-male ratio [20] [47]. Moreover, a weak positive correlation was observed between egg number and TL variables for female fish (**Figure 8**), but not between egg diameter (or weight) and TL variables for each female fish. The fecundity of *P. lineatus* in Taiwan (2375.6 eggs/individual) was greater than that of Korea (831 eggs/individual) and Indonesia (1730 eggs/individual) [21] [23].

At the left and right sides of the vertebrae is a pair of ova in the form of pouches in close contact with the body wall. The gonads of mature females are light pink, and those of males are transparent/milky white. However, during the nonbreeding season, they have an opaque milky white color in both immature male and female *P. lineatus*. Therefore, when studying the sex ratio of different populations, researchers must rely on anatomy to differentiate between the sexes.

The aim of the present study was to develop a quick method for differentiating between male and female *P. lineatus* according to the feel of the skin on the top of the adult fish's head and the characteristics of the orbitosphenoid bone, as felt through the fish's skin (**Figure 6(C)**). Additionally, the head dorsal width was slightly greater among the male than among the female and exhibited considerable sexual dimorphism. This approach helps to determine the gender of individual fish and calculate sex ratios during field research, especially during the nonbreeding season [48] [49].

The Palaemonidae and Penaeidae shrimps accounted for the dominant species in the lagoons and estuaries of Taiwan's southwestern coast. Members of the Grapsidae family (*Hemigrapsus penicillatus* and *Pachygrapsus minutus*) were also in high abundance in oyster cultivation areas [38]. Although the striped eel catfish *P. lineatus* has high commercial value in the aquarium industry [12] [13], its meat quality and taste are not widely appreciated in Taiwan and East Asia. However, the diet of this species is highly similar to that of the rice-paddy eel *Pisodonophis boro*, which has high economic value in East Asia.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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