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New discovery of two subtropical and one boreal marine fish species in Korean waters during summer reveals their habitat range expansion

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Abstract

This study presents the first Korean records of two subtropical fish species, *Pseudojuloides paradiseus* and *Diplogrammus xenicus*, collected around Jeju-do Island, as well as one boreal fish species, *Erilepis zonifer*, collected in Busan (approximately 200 km away from Jeju-do Island). In this study, we discuss the implications of the species' habitat range expansion. Previously, *P. paradiseus* was known as an endemic species of Japan, while *D. xenicus* was known to inhabit the Eastern Indian Ocean and the Pacific Ocean excluding around the equator, and *E. zonifer* was only known to inhabit the Pacific Ocean between eastern Japan and the western USA. Their habitat range expansions might be attributed to the expansion of the Tsushima Warm Current at the surface layer and/or the North Korean Cold Current at the bottom layer. Our findings may suggest that habitat of marine fish is being changed continuously by climate change or oceanic currents. Therefore, it needs to conduct integrated and systematic monitoring of fish fauna to response changing marine biodiversity.

Introduction

The Korean Peninsula, located in the marginal sea of the northwest Pacific, is surrounded by unique waters on three sides, each of which shows quite different oceanographic features. The Korean Peninsula exhibits a variety of environmental characteristics, with noticeable climatic differences in all cardinal directions (Lee *et al.*, 2005). Additionally, complex ocean currents and water masses influence the Korean Peninsula, as it is situated between subtropical and subarctic waters (Rebstock & Kang, 2003). Each sea surrounding Korean Peninsula has formed independent marine ecosystems because of their heterogeneous characteristics (Figure 1). The East Sea, also called Japan Sea, has a monotonous coastline with few Islands and bays and has developed a deep-sea ecosystem due to its average depth of about 1700 m and the maximum depth of 4049 m (Barnes & Mann, 1991; Kang *et al.*, 2014). In the East Sea, the East Korea Warm Current (EKWC) and North Korean Cold Current (NKCC) meet, forming a subpolar front (Gong & Son, 1982; Cho *et al.*, 2004; Kang *et al.*, 2014). The Jeju Warm Current (JWC), which splits from the Tsushima Warm Current (TWC), flows clockwise around Jeju-do Island and transports warm and saline water to the Korea Strait through the Jeju Strait, while the Yellow Sea Bottom Cold Water (YSBCW) expands to the east from the southern Yellow Sea by baroclinic conditions and southerly monsoon winds (Wang *et al.*, 2014; Yang *et al.*, 2014; Kim *et al.*, 2022). Since the southern part of Jeju-do Island is directly affected by the high-temperature and -salinity water of the TWC, subtropical fish are highly abundant and diverse (Kim & Rho, 1994; Ko *et al.*, 2003; Kim, 2009). Marine biodiversity serves as an indicator of a healthy marine ecosystem and plays a crucial role in supporting the structure and function of ecosystems (Costanza & Mageau, 1999; Worm & Lotze, 2009; Johnson *et al.*, 2011). Therefore, considerable efforts need to be made to monitor changes in marine biodiversity and biological responses to global warming in these areas.

During our field survey monitoring fish species around Jeju-do Island and Busan, we discovered three previously unrecorded fish species, *Diplogrammus xenicus* (Callionymidae), *Erilepis zonifer* (Anoplopomatidae), *Pseudojuloides paradiseus* (Labridae). *E. zonifer*, North Pacific boreal species, inhabits the sea surface at juvenile stages but it descends deeper as it grows (Orlov *et al.*, 2012). Although *D. xenicus* and *P. paradiseus* are subtropical species, they tend to avoid high-temperature water around the equator (Briggs, 1999; Tea *et al.*, 2020). Furthermore, both of them show sexual dimorphism, males are splendid and females are relatively monotonous.

Their first records in Korean waters suggest an expansion of their habitat range, which might be related to climate change. The purpose of this study is to describe morphological and molecular characteristics of the species, confirm their taxonomic status, and discuss the implications of these findings in Korean waters.

Materials and methods

P. paradiseus specimen was collected with a lift net in Seogwipo-si, southern Jeju-do Island on 25 May 2022. *D. xenicus* specimen was collected with a scoop net in Seogwipo-si, southern

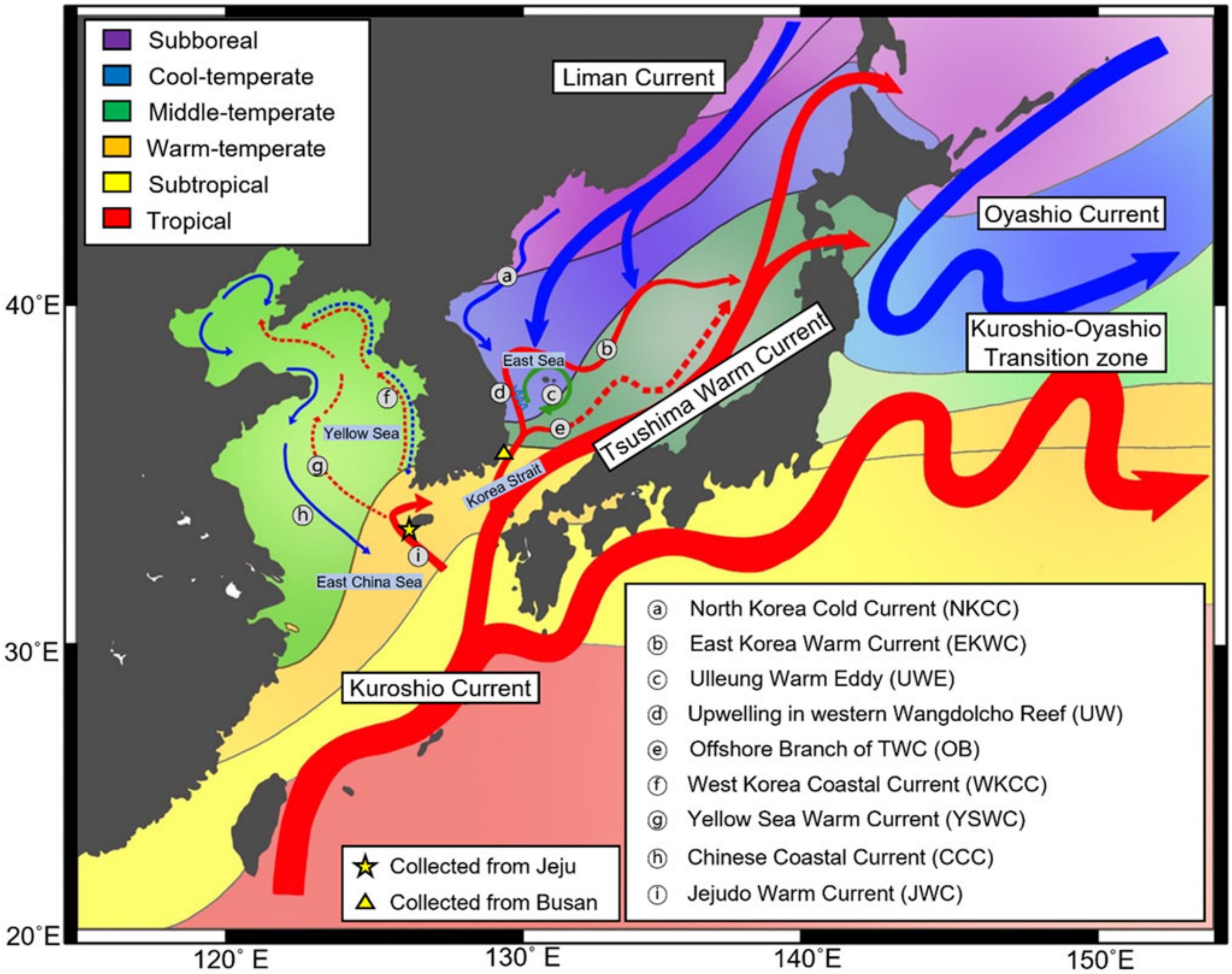

Figure 1. Schematic diagram showing diverse oceanic currents and water masses affecting the seas around the Korean peninsula cited from Yu & Kim (2018) and Nakayama (2022).

Jeju-do Island on 14 August 2022. *E. zonifer* specimen was collected with a gill net in Busan, which is located at the boundary between the Korea Strait and the East Sea, on 18 July 2022. The specimens were transported to the Ichthyology laboratory at Pukyong National University (PKU) and identified following Nakabo (1983, 2013) and Tea *et al.* (2020). They were fixed in 10–15% formalin, and preserved in 70% ethanol after washing. Three specimens were deposited in National Marine Biodiversity Institute of Korea (MABIK). Meristic characters were conducted following Lockington (1880), Fricke & Zaiser (1982), Orlov *et al.* (2012), and Tea *et al.* (2020). The specimens were measured using a tapeline and vernier callipers, and measurements were converted into ratios (%) relative to total length (TL) or SL (Figure 2). Molecular analysis was performed to confirm morphology-based species identifications. Total genomic DNA was extracted from muscle tissue using 10% Chelex 100 resin (Bio-Rad, Hercules, CA, USA). The mitochondrial DNA (mtDNA) cytochrome c oxidase subunit I (COI) was amplified using the universal primer set developed by Ward *et al.* (2005). We used the PCR conditions sas follows: predenaturation at 95 °C for 5 min; 35 cycles of denaturation at 95 °C for 30 s, annealing at 52 °C for 45 s, extension at 72 °C for 45 s; final extension at 72 °C for 7 min. The amplified sequences were deposited in the National Center for Biotechnology Information (NCBI) database. Sequence alignments were conducted using CLUSTALW (Thompson *et al.*, 1994) within BioEdit version 7 (Hall, 1999). Subsequently, genetic divergence was calculated using the Kimura two-parameter model (Kimura, 1980), and a neighbour-joining tree was constructed to infer the phylogenetic relationships among specimens.

Results

Diplogrammus xenicus *(Jordan & Thompson, 1914) (Perciformes: Callionymidae) (×Figure 3A)*

Material examined. MABIK PI00061773 (PKU 62992), 1 specimen, male, 123.8 mm TL, Seogwipo-si, Jeju-do Island, Korea (33°13’21.1”N 126°14’30.9”E)

Diagnosis. D. IV-8; A. 7; P_1. ii+15~17; mouth small; infraorbital canals branched; preopercle not barbed; body with dermal fold; opercle with flap; caudal fin not protruding; diagonal patterns on anal fin (no pattern in female).

Description (in males). Body compressed and elongated. Head and mouth small in proportion to body length. Lower lip with few fleshy papillae. Infraorbital canals branched. Posterior tip of preopercle not barbed. Opercle with flap. Both lateral lower sides of body with a dermal fold-like ridge. First dorsal spine elongated. All caudal fin rays branched. Lateral line reaching to caudal fin rays. Head and body brownish. Eye yellowish.

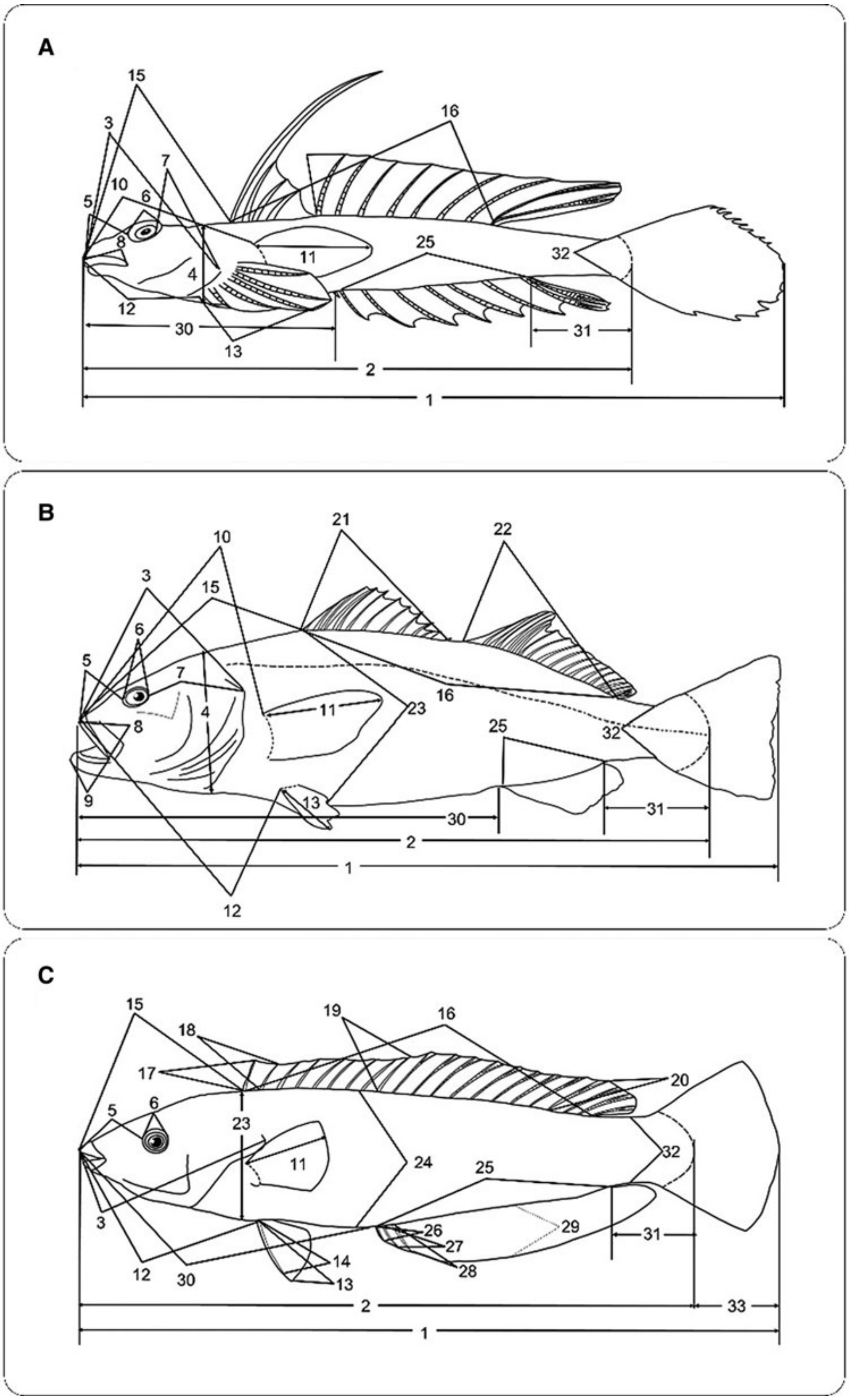

Figure 2. Diagrams of the measurements: A. *D. xenicus*; B. *E. zonifer*; C. *P. paradiseus* (1, total length; 2, standard length; 3, head length; 4, head depth; 5, snout length; 6, orbital diameter; 7, postorbital length; 8, upper jaw length; 9, lower jaw length; 10, prepectoral length; 11, pectoral length; 12, prepelvic length; 13, pelvic length; 14, pelvic spine length; 15, predorsal length; 16, dorsal fin base length; 17, first dorsal spine length; 18, second dorsal spine length; 19, last dorsal spine length; 20, longest dorsal ray length; 21, first dorsal fin base length; 22, second dorsal fin base length; 23, body depth; 24, greatest body depth; 25, anal fin base length; 26, first anal spine length; 27, second anal spine length; 28, third anal spine length; 29, longest anal ray length; 30, preanal length; 31, caudal peduncle length; 32, caudal peduncle depth; 33, caudal length).

Posterior preopercle with dark blue speckle. Blue blotches and spots on head to caudal fin. Upper of pectoral fin whitish and lower part blackish with blue spots. Dorsal fin dark yellowish with translucent oblique patterns. Anal fin black with light lines and spots. Upper half of caudal fin yellow and lower part blackish.

Distribution. Korea (Present study), Southern Japan, Philippines, Indonesia, and Western Australia (Sonoyama *et al.*, 2020; GBIF Secretariat, 2023).

Remarks. *D. xenicus* can be distinguished from closely related species, such as *D. goramensis*, by the shape of the infraorbital

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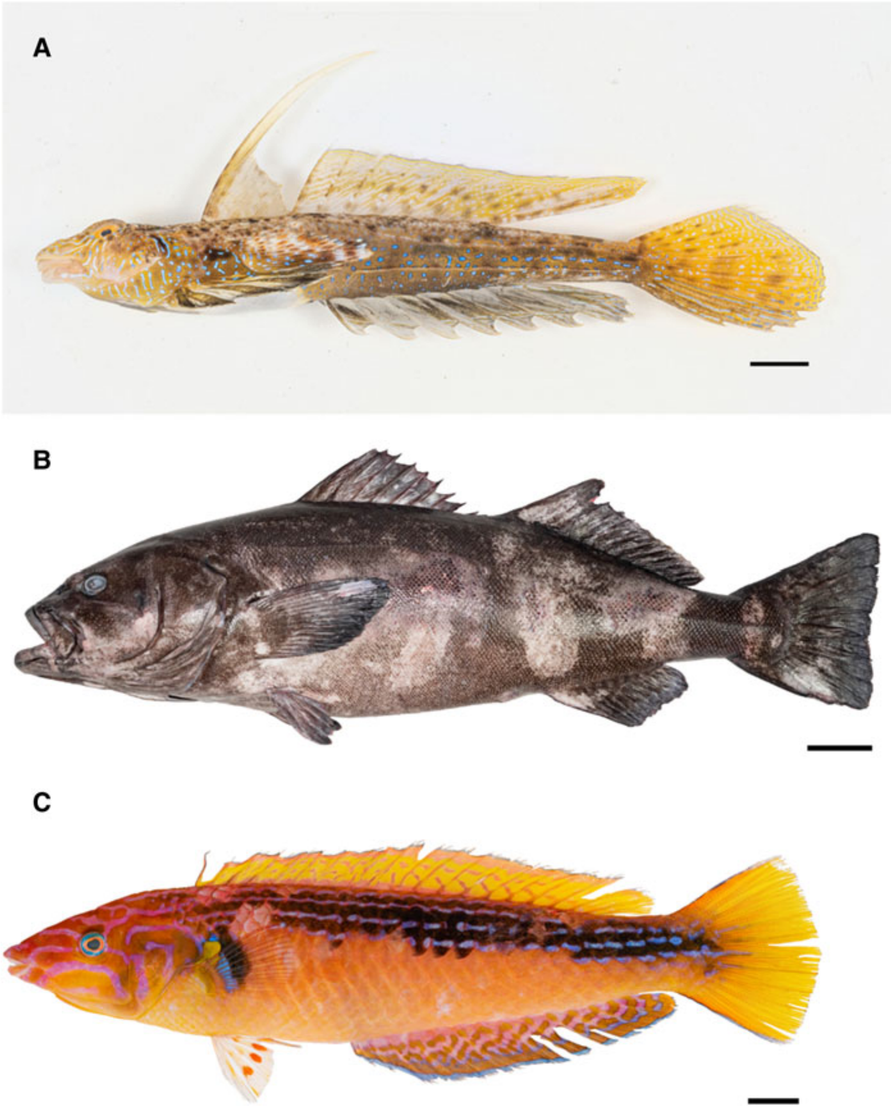

Figure 3. Photographs of unrecorded fish species collected from Korea: A, *D. xenicus*, MABIK PI00061773 (PKU 62992), 94.5 mm SL, collected from Jeju-do Island; B, *E. zonifer*, MABIK PI00061776 (PKU 63131), 116 cm SL, collected from Busan; C, *P. paradiseus*, MABIK PI00061777 (PKU 63132), 144.4 mm SL, collected from Jeju-do Island. The scale bars of A and C indicate 1 cm, and a bar of B indicates 10 cm.

canal. *D. goramensis* has no branched infraorbital canal, unlike *D. xenicus* (Nakabo, 2013). These species exhibit sexual dimorphism, so species identification based on morphological traits can be challenging (Fricke & Zaiser, 1982). In adult males, the colouration of the lower anal fin rays differs. *D. xenicus* has short oblique black lines on the anal fin, while *D. goramensis* has many small dark spots. The counts and measurements are well-matched with previous studies (Jordan & Thompson, 1914; Fricke & Zaiser, 1982) (Table 1). Also, molecular identification based on mtDNA COI sequences supported the morphology-based results of *D. xenicus* (Figure 4). As this is the first record in Korea, we suggest the new Korean name of the genus and species, 'Ju-reum-dot-yang-tae-sok' and 'Ju-reum-dot-yang-tae'.

Erilepis zonifer *(Lockington, 1880)* *(Perciformes: Anoplopomatidae)* *(Figure 3B)*

Material examined. MABIK PI00061776 (PKU 63131), 1 specimen, 1310 mm TL, Busan, Korea (35°09'02.6"N 129°09'10.6"E)

Diagnosis. D. XII~XIV-I~II, 16~21; A. II~III, 11~14; P_1. 16~19; LL. 120~130; body deep and short; the first and second dorsal fins proximal; white spots on side of body (uniformly dark as they grow).

Description. Body slightly deep and stout-like. Head and mouth large. Lips thick. Eyes small. Nostrils below midline of eye. Upper jaw not reaching to eye. No spine on preopercle and opercle. Pectoral fin ahead of pelvic fin. Pectoral fin reaching to between the 6^{th} and 7^{th} spine of the first dorsal fin. The first and second dorsal fins proximal. Anal fin base short. Caudal fin truncated. Lateral line reaching to caudal peduncle. Scales small and ctenoid. Head and body deep dark. Large dark spots and blots on the lateral side of body. All fin ray black.

Distribution. Korea (Present study), Japan, Russia, USA (East of around 138° E) (Mecklenburg, 2003; Nakabo, 2013; GBIF Secretariat, 2023).

Remarks. The family Anoplopomatidae comprises only two genera and two species worldwide (Froese & Pauly, 2023): *Anoplopoma fimbria* (Pallas, 1814) and *E. zonifer*. Anoplopomatidae species can be distinguished by their body shape and the distance between the first and second dorsal fins. *A. fimbria* has a slender and slightly compressed body with well-separated first and second dorsal fins. Our specimen of the first dorsal fin base length is 22.1% in TL (25.0% SL), other specimens are 17.7% in TL by Jordan & Thompson (1914) and 13.2–15.7% in SL by Lockington (1880) and Orlov *et al.* (2012) (Table 2). Because we investigated only one specimen, it seems to be an individual variation. Molecular identification based on mtDNA COI sequences supported morphology-based results of *E. zonifer* with a high degree of confidence (Figure 4). As this species was named as 'Keun-eun-dae-gu' by NIFS (2010) previously, we followed the name, and suggest the new Korean name for the family and genus, 'Eun-dae-gu-gwa', 'Keun-eun-dae-gu-sok', respectively.

Table 1. Comparison of the morphometrics and meristic characters of *D. xenicus*

Morphological character	Present study MABIK PI00061773		Jordan & Thompson (1914)	Fricke & Zaiser, (1982)
Number of individuals	1		1	8
Total length (mm)	123.8		135	–
Standard length (mm)	94.5		–	30.8–105.5
Counts				
Dorsal fin rays	IV-8		IV-8	IV-8
Anal fin rays	7		7	7
Pectoral fin rays	ii + 15		19	i–iii + 14–16
Pelvic fin rays	I, 5		–	I, 5
% of	In TL (%)	In SL (%)	In TL (%)	In SL (%)
Body depth	10.0	13.2	13.3	11.7–15.9
Head length	23.0	30.1	28.6	22.5–24.6
Head depth	9.1	12.0	–	–
Orbital diameter	4.8	6.3	5.7	–
Interorbital width	1.3	1.7	–	–
Upper jaw length	7.1	9.2	–	–
Snout length	3.8	5.0	–	–
Postorbital length	10.8	14.2	–	–
Prepelvic length	17.5	23.0	–	–
Prepectoral length	24.9	32.6	–	–
Predorsal length	20.7	27.1	–	26.5–30.1
Preanal length	36.4	47.7	–	45.3–49.5
Dorsal fin base length	38.3	50.1	–	–
Anal fin base length	25.0	32.7	–	–
Pectoral fin length	20.6	16.6	–	–
Caudal peduncle depth	4.1	5.4	–	6.5–7.6
Caudal peduncle length	17.1	22.4	–	20.2–22.9

Pseudojuloides paradiseus *Tea, Gill & Senou, 2020 (Perciformes: Labridae) (Figure 3C)*

Material examined. MABIK PI00061777 (PKU 63132), 1 specimen, male, 162.8 mm TL, Seogwipo-si, Jeju-do Island, Korea (33°13'21.1"N 126°14'30.9"E)

Diagnosis. D. IX, 12-13; A. III, 12; median predorsal scales lack; large canine tooth on corner of mouth; colour of male: body bright yellow to orangish pink, dorsal of body black with blue dashed line; female: body reddish orange to dark red, dorsal unmarked.

Description (in males). Body compressed and elongated. Head moderately large and convex. Mouth and eyes small. Teeth well-developed. Upper jaw slightly protruded. Anal fin bases long. Caudal fin slightly round. Scales large and ctenoid. Lateral line continuous. Head with purplish wavy stripes. Body yellowish orange to pinkish orange. Blue and Black blotches under pectoral fin. Metallic blue or purplish stripes that broke into spots on upper lateral side in males. Pelvic fin pale with orange spots. Dorsal fin yellow with orange mark. Anal fin pink to orange with blue margin. Caudal fin yellow.

Distribution. Korea (Present study), Japan (Sagami Bay) (Tea *et al*., 2020).

Remarks. *P. paradiseus* closely resembles its congeners *P. elongatus* and *P. crux*. All three species have overlapping meristic and morphometric ranges, and their genetic divergence shows an extremely close level of 0.1–1.5%. However, despite their morphological and genetic similarities, *P. elongatus*, *P. crux*, and *P. paradiseus* are recognized as valid species due to their distinct distribution differences. *P. elongatus* is found only around eastern Australia, *P. crux* is found only around western Australia, and *P. paradiseus* is found in the northwest Pacific, specifically around Japan. We identified our specimen as *P. paradiseus* based on morphological, molecular characteristics, and distribution (Figure 4; Table 3). This genus of species is the first record in Korea, so we suggest the new Korean name of the genus and species, 'Pa-ra-da-i-seu-nol-rae-gi-sok' and 'Pa-ra-da-i-seu-nol-rae-gi', respectively.

Discussion

As a result of monitoring a fish fauna around the Korean waters during the summer, we firstly found three unrecorded fish species belonging to the subtropical and boreal fishes. The two subtropical species collected from Jeju-do Island, *D. xenicus* and *P. paradiseus*, are generally known to prefer temperatures of 27–28 °C (Froese & Pauly, 2023). Since *D. xenicus* is a bottom-dwelling fish that inhabits shallow waters at depths of 9–27 m (Fricke & Zaiser, 1982), it may have a limited migratory range. *P. paradiseus* has been considered an endemic species of Japan, but the recent discovery of the species in Korean waters suggests the possibility of its range expansion. *P. paradiseus* was previously considered a synonym of *P. elongatus* but was recognized as a new species with a distinct distribution by Tea *et al*. (2020). In their study, Tea *et al.*

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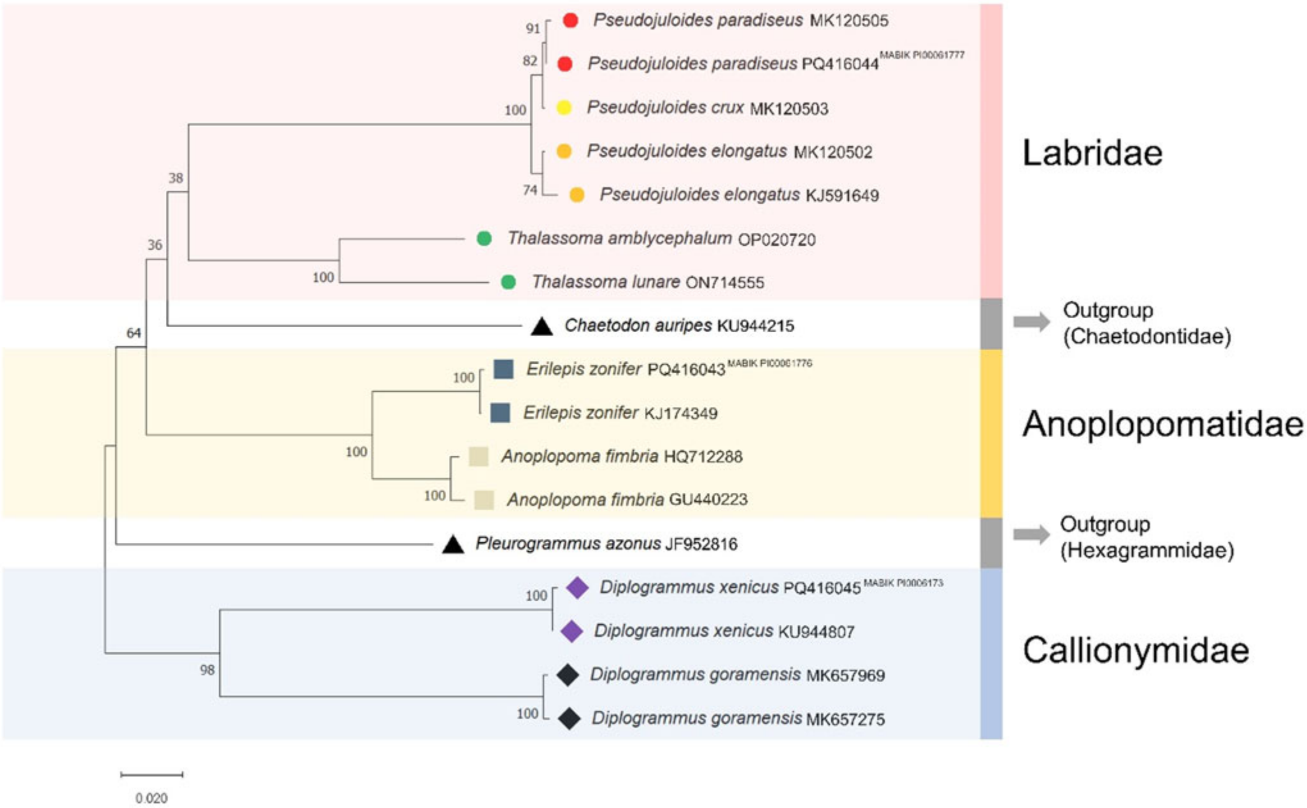

Figure 4. Neighbor-Joining tree based on mtDNA COI sequences. Each mark indicates the family of species and the colour indicates distinct species: circle (●), Labridae; Square (■), Anoplopomatidae; Diamond (◆), Callionymidae; Triangle (▲), outgroups.

Table 2. Comparison of the morphometrics and meristic characters of *E. zonifer*

Morphological character	Present study MABIK PI00061776		Lockington (1880)	Orlov et al. (2012)
Number of individuals	1		1	12
Total length (mm)	1310		298.45	71–1130
Standard length (mm)	1160		–	–
Counts				
1st dorsal spine	13		12	11–13
2nd dorsal fin (spine + rays)	18 (I, 17)		16 (I, 15)	16–19
Anal fin rays (spine + rays)	13 (II, 11)		13 (II, 11)	12–15
Pelvic fin rays (spine + rays)	6 (I, 5)		6 (I, 5)	6–7
Pectoral fin rays	17		18	16–19
% of	In TL (%)	In SL (%)	In TL (%)	In SL (%)
Body depth	23.7	26.7	27.7	28.4–32.5
Head length	27.5	31.0	25.7	29.2–37.2
Head depth	22.1	25.0	–	24.5–36.6
Orbital diameter	3.7	4.1	4.9	4.7–6.2
Interorbital width	10.3	11.6	8.9	9.7–12.4
Upper jaw length	11.5	12.9	9.8	10.1–14.1
Lower jaw length	9.9	11.2	12.1	10.8–17.2
Snout length	10.4	11.7	6.6	8.2–13.3
Postorbital length	15.3	17.2	–	–
Prepelvic length	31.3	35.3	28.3	–
Prepectoral length	28.2	31.9	25.5	–
Predorsal length	33.9	38.3	34.3	37.0–42.5

(*Continued*)

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Table 2. (*Continued.*)

Morphological character	Present study MABIK PI00061776		Lockington (1880)	Orlov *et al.* (2012)
Preanal length	60.3	68.1	54.9	65.0–74.3
Pelvic fin length	10.7	12.1	12.8	12.0–16.9
Pectoral fin length	17.0	19.1	7.7	16.8–24.7
Dorsal fin base length	45.0	50.9	–	–
First dorsal fin base length	22.1	25.0	17.7	13.2–15.7
Second dorsal fin base length	22.9	25.9	22.1	21.7–27.6
Anal fin base length	14.1	15.9	13.8	13.2–15.7
Caudal peduncle depth	9.2	10.3	8.3	7.8–10.1
Caudal peduncle length	15.3	17.2	–	–

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Table 3. Comparison of the morphological characters of *P. paradiseus, P. elongatus*, and *P. crux*

	P. paradiseus				
		Tea *et al.* (2020)		Tea *et al.* (2020)	
Morphological character	Present study MABIK PI00061777	Holotype	Paratypes	*P. elongatus*	*P. crux*
Number of individuals	1	1	9	11	13
Standard length (mm)	144.4	103.0	43.2–130.0	48.6–121.8	65.6–111.4
Counts					
Dorsal fin rays	IX, 12	IX, 12	IX, 12–13	IX, 12–13	IX, 12
Anal fin rays	III, 12	III, 12	III, 12	III, 12	III, 12–13
Pectoral fin rays	11	12	12	12	11–13
Pelvic fin rays	I, 5	I,5	I,5	I, 5	I, 5
Caudal fin rays	22	25	24–26	24–26	24–26
Lateral line scales	27	27	27	26–27	26–27
TRb	8	8–9	9	8–10	8–10
In standard length (%)					
Greatest body depth	21.1	22.8	18.8–22.	18.8–23.3	20.5–23.1
Body depth at dorsal origin	20.1	20.7	17.1–21.6	16.6–21.3	19.1–21.7
Body width	10.9	10.9	8.8–12.0	9.7–11.1	9.1–11.6
Head length	29.2	28.6	29.7–31.5	28.9–31.8	29.7–33.0
Snout length	11.3	10.2	10.0–11.2	9.3–11.4	9.5–11.9
Orbit diameter	4.20	5.0	4.4–6.9	4.4–6.5	4.9–6.6
Interorbital width	6.9	5.6	5.6–6.2	5.6–6.5	5.4–6.4
Prepelvic length	29.8	32.6	30.3–32.6	30.4–33.3	30.6–34.5
Predorsal length	28.1	27.3	27.1–30.6	27.8–30.9	28.0–31.1
Preanal length	46.9	50.6	49.3–53.1	49.7–53.1	49.0–54.3
Pectoral-fin length	12.8	14.7	13.9–15.0	12.7–14.6	13.9–16.6
Pelvic-fin length	12.4	14.0	12.8–13.9	11.9–13.6	12.3–14.1
Pelvic-spine length	8.2	9.3	7.9–8.8	7.1–9.0	7.7–9.4
Dorsal fin base length	54.6	59.6	55.6–62.1	55.1–59.6	54.0–59.6
First dorsal-fin spine	4.0	5.1	3.7–4.8	3.5–4.6	3.8–5.6
Second dorsal-fin spine	6.5	6.9	4.5–6.6	5.1–6.4	5.3–7.5
Last dorsal-fin spine	8.7	10.9	8.3–9.6	8.1–9.6	8.6–10.9

(*Continued*)

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Table 3. (*Continued.*)

Morphological character	*P. paradiseus*				
	Present study MABIK PI00061777	Tea *et al.* (2020)		Tea *et al.* (2020)	
		Holotype	Paratypes	*P. elongatus*	*P. crux*
Longest dorsal-fin ray (number)	12.5 (9)	12.1 (9)	11.8–13.9 (9)	11.6–12.9 (9)	12.0–13.9 (9)
Anal fin base length	37.4	41.7	37.9–41.0	37.0–40.4	35.1–41.3
First anal-fin spine	3.0	3.4	2.7–3.5	2.7–4.0	2.5–4.0
Second anal-fin spine	4.0	5.6	4.6–6.9	4.7–6.8	4.4–5.9
Third anal-fin spine	5.7	8.3	6.8–9.0	6.1–9.2	5.8–8.4
Longest anal-fin ray	10.9	12.2	11.5–12.3	9.6–12.8	11.0–14.6
Caudal-peduncle depth	9.9	11.5	9.7–11.8	9.4–11.5	10.4–11.6
Caudal-peduncle length	11.1	10.0	9.2–11.0	8.8–11.0	7.9–11.1
Caudal-fin length	19.4	22.0	21.1–25.5	20.5–22.3	20.4–23.4

(2020) divided *P. elongatus* into three species: *P. elongatus sensu stricto* from Eastern Australia, *P. crux* from western Australia, and *P. paradiseus* from Japan. They exhibit vicariance, with their distribution extending from the far northern hemisphere to the far southern hemisphere. It has also been suggested that *D. xenicus* belongs to a group of representative anti-tropical species, in contrast to similar species such as *D. goramensis* which inhabits tropical waters (Fricke, 1988; Briggs, 1999, 2005). In the case of anti-tropical species, allopatric speciation might have occurred due to water temperature barriers after the species migrated across the equator to the opposite hemisphere during the last glacial maximum, during which SST decreased (Burridge, 2002; Briggs, 2003; Le Port *et al.*, 2013; Kai & Motomura, 2022).

The boreal species *E. zonifer* was collected from Busan, located at the boundary between the East Sea and the Korea Strait. Except for a single immature specimen of 50 cm SL occurring in waters off Shizuoka on the Pacific side of Japan (34.9° N, 138.5° E) (Orlov *et al.*, 2012; Zolotov *et al.*, 2014), it has been almost exclusively recorded in the North Pacific Ocean above 36° N (GBIF Secretariat, 2023). The present study demonstrates that the distribution of *E. zonifer* extends to the southwest of the East Sea. The collected depth of *E. zonifer* is in relatively deep water at 100–200 m. The water temperature at 100–105 m was approximately 4.41–5.31 °C at that time. The SST of the Korea Strait, where *E. zonifer* was collected, is known to be highest during summer due to the TWC, while the sea bottom temperature is lowest during the same period due to the NKCC (Lim & Chang, 1969; Cho & Kim, 1998). The range expansion of this species might be related to the southward expansion of the NKCC, as the TWC strengthens to the north due to the compensation effect (Lim, 1971; Mitta & Ogawa, 1984; Isobe *et al.*, 1994). Global warming promotes large-scale changes in atmospheric circulation, including the strengthening of the North Pacific gyre and changes in the Hadley and Ferrell circulations or Kuroshio and Kuroshio extensions (Cheon *et al.*, 2012; Choi *et al.*, 2013). These changes eventually impact the strength of the TWC. Due to these complex shifts in physical processes, we carefully suggest that the southern boundary of *E. zonifer* might be expanding southward.

The simultaneous appearance of two subtropical species and one boreal species implies that the waters around the Korean Peninsula are exposed to quite complex marine shifts. The Intergovernmental Panel on Climate Change (IPCC) has reported that global ocean warming due to climate change has more than doubled from 1993 to 2017 in comparison to 1969 to 1993, and they predict that the trend of increasing water temperatures will be higher in the western Pacific, including Korean waters, than the global average (Shukla *et al.*, 2019). Over the past 130 years (1880–2009), global sea temperatures increased by 0.6 °C. In comparison, the SST of Korean waters has increased by 0.9–1.5 °C, i.e. up to three times faster than the global average (Kim *et al.*, 2011). Recently, the number of unrecorded fish species in Korea has been increased rapidly. Korean fish diversity has increased by 37%, i.e. from 872 species (Chyung, 1977) to 1193 species (Jeong & Kim, 2023; MABIK, 2023) within 46 years, which might be related, at least in part, to the rapid increase in SST in Korea (Kang & Jeong, 2000; Seo & Yoon, 2008; Kim, 2009; Jung *et al.*, 2013; Yoo *et al.*, 2014). These findings indicate that Korean waters are undergoing significant change.

To conserve global biodiversity in light of future climate change, fish species composition and metapopulation dynamics should be monitored continuously. Specifically, it needs to focus on the frontal area (e.g. East Sea), which is characterized by dramatic temperature and salinity changes that serves as a biogeographical barrier by the intersection of subtropical and boreal waters; this leads to adaptive responses of local populations, and finally speciation (Kim *et al.*, 2002, 2010a, 2010b; Gwak & Nakayama, 2011; Myoung & Kim, 2014; Bae *et al.*, 2020a, 2020b; Song *et al.*, 2020a, 2020b).

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