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Sorting the wheat from the chaff: a review of BINs associated with groupers of Vietnam and the implications for species identification from DNA barcoding

Jean-Dominique Durand¹, Manh Hung Pham², Thanh Thi Viet Tran³, Duc Huy Hoang², Quang Van Vo⁴

The Epinephelidae is a marine fish family that has been the focus of worldwide taxonomical attention due to its economic value. Recent molecular-based phylogenies have improved understanding of species diversity within this family. Nonetheless, species misidentification or hybridization has led to a barcode index number (BIN) being associated with several species, which hampers a clear species identification within the BOLD system. In this study, grouper diversity in Vietnam was investigated to check the species inventory, provide a DNA barcode library for Vietnam, and reevaluate BINs associated with some species that are present in Vietnam. To this end, 157 specimens were barcoded corresponding to 30 species and 31 BINs. Nine species were new records, bringing to 49 the number of species inventoried for Vietnam. In BOLD, these species are associated with 75 BINs, 31 species being represented by more than one BIN. A careful review of these BINs, considering the present results from Vietnam, the species composition and frequency of each BIN in BOLD, and reference species sequences from phylogenetic studies, revealed those misidentified or hybrid specimens that artificially increased the number of BINs per species. After appropriate revision, 15 species still remained associated with more than one BIN. A phylogeographic analysis of these species demonstrated that most of the BINs derived from evolutionary lineages with geographic distributions that match well known biogeographic units in the Indo-Pacific. Beyond the species identification, these multiple BINs of each species can be used to track the biogeographic origin of each of the associated specimens.

Keywords Cytochrome oxidase I · BOLD · Misidentification · Biogeography · Epinephelidae

Introduction

DNA barcoding in fishes is now widely used for taxonomical investigations (Hubert and Hanner 2015), biodiversity evaluations (Galdino Brandao et al. 2016; Shen et al. 2016; Durand et al. 2017), and food control (Barcaccia et al. 2015; Brito et al. 2015). One of the main results of the broad scan of fish diversity across geographic areas, using cytochrome oxidase I (COI) polymorphisms, has been the revelation of numerous species complexes or cryptic species, leading to a profound change to our vision of biodiversity (Hubert et al. 2012, 2017; Jaafar et al. 2012; Winterbottom et al. 2014; Durand and Borsa 2015; Williams and Viviani 2016; Habib et al. 2018; Delrieu-Trottin et al. 2019). This important result justifies more barcoding investigations because gaps in taxonomical coverage limit accuracy of the species identification based on a DNA barcode. However, if the BOLD database is used as reference library and is continuously enriched with new barcodes, then there is also an increase in mis-labelled

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sequences due to misidentification, which is a serious concern (Vilgalys 2003; Ward et al. 2009). By comparing sequences of a marine fish family from a reference library to those available in Genbank, an important source of barcodes for BOLD, Durand et al. (2017) demonstrated that misidentified species of a fish family were more frequent in barcoding studies than other types of studies like molecular phylogeny and phylogeography. This may be due to the difficulties of developing reliable systematic expertise for a wide range of fish taxa, for studies that do not target specific families.

As a consequence, while barcoding studies are still necessary to fill taxonomical knowledge gaps and solve some taxonomical issues, it is also necessary to review the DNA barcodes in BOLD, to better define species boundaries and track species misidentification. To reach this objective, new barcoding projects could be (1) more taxonomically restricted so as to limit potential species identification problems, (2) increase the number of specimens and sampling localities over the species distribution range so as to better estimate levels of intraspecific diversity, and (3) consider all DNA barcodes stored in the BOLD library, to track both mislabelled sequences and putative undescribed or cryptic species. While individual review of DNA barcodes in the BOLD library would be particularly tedious, the process could be facilitated by the barcode index number (BIN) provided by BOLD system that corresponds to an operational taxonomical unit (OTU). This OTU consists of barcodes that are identical or phylogenetically closely related and separated from others in the library by a barcode gap. OTUs are delimited in BOLD, using the Refined Single Linkage (RESL) algorithm (Ratnasingham and Hebert 2013). The BIN was created to circumvent taxonomical issues linked to identification problems, undescribed species or, more generally, to reveal cryptic diversity (Ratnasingham and Hebert 2013).

The grouper, Epinephelidae, is a marine fish family present in all temperate and tropical marine coastal waters. They comprise economically important species that are the target of fisheries and aquaculture. For this reason, the family has been the focus of a series of molecular phylogenetic and barcoding studies (Craig and Hastings 2007; Craig et al. 2011; Chu et al. 2011; Sachithanandam et al. 2012; Alcantara and Yambot 2016; Ma et al. 2016, 2018; Basheer et al. 2017). Among these studies, molecular phylogenetic or phylogeographic studies highlighted systematics issues such as the paraphyly of *Cephalopholis* (Bloch & Schneider, 1801) and *Epinephelus* (Bloch, 1793) genera, and the presence of cryptic species (Craig and Hastings 2007; Ma et al. 2016; Borsa et al. 2016; Ma and Craig 2018). In contrast, although all region-based barcoding studies provided new COI barcodes for groupers collected in countries such as India (Sachithanandam et al. 2012; Basheer et al. 2017), Malaysia (Chu et al. 2011), or the Philippines (Alcantara and Yambot 2016), none considered the barcodes in BOLD in order to review intraspecific diversity over a

broader geographic scale than their barcoded species or the BIN diversity per species, which represent an alternative way to both track mis-labelling sequences or polyphyletic species.

Within global grouper diversity, 34 to 39 species may occur in Vietnamese waters (Heemstra and Randall 1993, 1999; Craig et al. 2011). Among these species, some are uncommon or have a limited distribution range. Due, however, to the difficulty in identifying some species by morphometric or phenotypic characters (Heemstra and Randall 1993; Guo et al. 2014; Alcantara and Yambot 2016) the species inventory should be considered with caution. Furthermore, new grouper species are still being described, such as *Epinephelus kupangensis* Tucker et al., 2016, *Epinephelus craigi* Frable et al., 2018 and *Epinephelus fuscomarginatus* Johnson & Worthington Wilmer, 2019. Other species have debatable taxonomic status, such as *Epinephelus moara* (Temminck & Schlegel, 1843) that is considered as valid by several authors (Guo et al. 2009; Liu et al. 2013; Guo et al. 2014) but a junior synonym of *Epinephelus bruneus* (Bloch, 1793) by others (Heemstra and Randall 1993; Craig et al. 2011; Fricke et al. 2019). For all these reasons, phylogenetic and barcoding studies are needed to clarify the species diversity present in Vietnam where barcoding analyses are rare (Thai et al. 2007; Tran et al. 2016; Ha et al. 2018; Huang et al. 2018) and missing for the Epinephelidae family.

In this context, this study aimed to create a reference barcoding library for Vietnam and test whether this approach can be used to update the species checklist and flag cryptic or undescribed species. Our ambition with this region-based barcoding study was also to review all BINs in BOLD for species present in Vietnam and determine significance of the presence of several BINs associated with a species. The last goal requires combining all available data to determine the congruency between species name associated with a BIN and some species' sequence considered as a reference (see hereafter), and investigate the phylogeographic structure of species associated with more than one BIN. Finally, this study represents a good opportunity to review the BOLD library and tracked misidentified specimens that can limit accuracy of species identification.

Material and methods

Taxonomy and species checklist for Vietnam

The taxonomy and classification of groupers is debated (Ma and Craig 2018) because successive molecular phylogenetic studies have highlighted a number of inconsistencies, such as the non-monophyly of the Serranidae family and of some genera within the Epinephelinae subfamily (Maggio et al. 2005; Ding et al. 2006; Craig and Hastings 2007; Craig et al. 2011; Zhuang et al. 2013; Schoelincx et al. 2014; Ma

et al. 2016). To resolve this issue, some authors have proposed an updated taxonomy (Smith and Craig 2007; Ma and Craig 2018). Within this, the subfamily “Epinephelinae” (sensu Johnson 1983) was elevated to family status and the tribes Diploprionini, Epinephelini, Grammistini, and Liopropomini to subfamilies within Epinephelidae (sensu Smith and Craig 2007). Furthermore, the species classification of the Epinephelinae (sensu Smith and Craig 2007) was revised according to their molecular phylogeny (Ma et al. 2016).

In the current study, the taxonomy proposed by Smith and Craig (2007) has been adopted but we have conserved the “traditional” genus naming of species of the Epinephelinae, since this has not yet been adopted by Eschmeyer’s Catalog of Fishes (Fricke et al. 2019) and thus not recognized by BOLD or GenBank. However, in Table 1, the second column has the revised taxonomic nomenclature of Ma and Craig (2018), involving the genus replacement of *Aethaloperca* by *Cephalopholis*, *Anyperodon*, and *Cromileptes* by *Epinephelus*; *Triso* by *Hyporthodus*; and *Epinephelus* by *Mycteroperca* for the following species: *E. epistictus*, *E. heniochus*, *E. morrhua*, and *E. poecilonotus*.

The species checklist of Epinephelidae present in Vietnam (Table 1) has been established on the basis of two references, Heemstra and Randall (1993) and Craig et al. (2011). One additional species have been added to this list, *Epinephelus craigi* because it was recently described in the South China Sea, probably including Vietnamese waters (Nha Trang) according to Frable et al. (2019).

Sampling

Grouper specimens were collected between 2015 and 2017 from major fish landings and markets at 18 locations belonging to 11 provinces in Vietnam (Fig. 1). We strived to obtain as many species as possible, to provide the broadest overview of diversity in Vietnam. When possible, several specimens from the same species were collected at different locations, to provide some information about intraspecific diversity and distribution ranges in Vietnam. A total of 157 groupers were collected, plus one specimen of *Diploprion bifasciatum* belonging to the *Diploprioniae* subfamily, used as outgroup (Table S1). An initial species identification was performed on site using the FAO identification sheet (Heemstra and Randall 1993) and Craig et al. (2011). Each specimen was photographed and a small section of the pectoral fin stored in ethanol 70° in a 1.5 ml Eppendorf, which were then stored at –20 °C in the laboratory.

DNA extraction and barcoding

Genomic DNA was isolated from fins using the G-Spin Total DNA extraction mini kit (iNtRON biotechnology, Korea) following the manufacturer’s recommendations. Approximately

655 base pairs (bp) of the cytochrome oxidase I (COI) were amplified using the reverse primer FishR1 and the two forward primers in cocktail: FishF1 and FishF2 (Ward et al. 2005). The 40 µl PCR reaction mixes included 20 µl of MyTaq PCR Mastermix (Bioline), 16 µl of ultrapure water, 0.8 µl of BSA (Euromedex), 0.6 µl of each primers (3 µM), and 2 µl of DNA template. Amplifications were performed in a PTC-100 BIORAD Thermal cycler. The thermal regime consisted of an initial step of 2 min at 92 °C followed by 35 cycles of 45 s at 92 °C, 45 s at 52 °C, and 1 min at 72 °C, followed in turn by 5 min at 72 °C and then held at 4 °C. PCR products were visualized on 1–2% agarose gels and the most intense products were selected for sequencing by MacroGen (<https://dna.macrogen.com/>).

Electropherograms were visually checked using 4Peaks by A. Griekspoor and Tom Grootuis, nucleobytes.com, and sequences aligned using MUSCLE implemented in MEGA7 (Kumar et al. 2016). DNA barcodes and specimens’ data are available in the project file DS-SERV: Epinephelidae of Vietnam on BOLD systems site dx.doi.org/10.5883/DS-SERV. Each DNA barcode was assigned to a BIN by the BOLD system and deposited in GenBank under accession number MN708800 to MN708957 (Table S1). Sequence divergences (Table S2) were calculated using the Kimura two parameters (K2P) distance model (Kimura 1980). Neighbor-joining (NJ) trees of K2P distances were drawn to highlight pattern of divergence between species (Saitou and Nei 1987). A bootstrapping test was performed in MEGA3 (Kumar et al. 2004) with 500 replications, to test the relevance of the tree’s nodes.

Species identification and species boundaries

The accuracy of the OTU delineation provided by BOLD using the RESL algorithm was first evaluated by comparing BINs to OTUs identified by the Automatic Barcode Gap Delineation (ABGD) algorithm (Puillandre et al. 2012). These two methods used DNA alignments as inputs, consisting of ABGD, of all DNA barcodes (with a core segment of a 502 bp) constituting BINs associated with species name listed in Table 1, plus all Vietnamese barcodes generated in this study (Table S3). The final fasta file contained 1648 sequences and was uploaded to the website that hosted the ABGD algorithm to run the analyses (<https://bioinfo.mnhn.fr/abi/public/abgd/abgdweb.html>).

The first phylogenetic analyse was performed on a dataset composed exclusively of DNA barcodes obtained in this study, i.e., the groupers sampled in Vietnam. The tree was rooted with *Diploprion bifasciatum*. The species name recovered using the morphology and the BIN provided by BOLD was mapped onto this tree, to flag polyphyletic species and to reveal intraspecific and interspecific diversity within the Epinephelidae.

Table 1 Epinephelidae species inventoried in Vietnam according Heemstra and Randall (1993), BIN's BOLD column, number of public members present in the BIN/number of members labeled Craig et al. (2011), and this study. In bold, species name that represent new records for Vietnam. For with the species name are mentioned in brackets, probable species misidentifications are in italics each species, the associated BINs in BOLD, in Ma et al. (2016) and in this study, are listed. In the (see Table S3 for the rationale)

Classification "Catalog of Fishes"	Classification according Ma and Craig (2018)	Forsskål, 1775	Heemstra and Randall 1993 (FAO)	Craig et al. 2011	This study	BIN's BOLD	Ma et al. (2016)	BIN present in Vietnam (this study)	Multi-BIN species	Phylogeographic pattern
<i>Aethaloperca rogaa</i>	<i>Cephalopholis rogaa</i>	Forsskål, 1775	X	X	X	BOLD:AAD9665 [16/15], BOLD:ACC0322 [3/3]	BOLD:AAD9665 NA	NA	Y?	N
<i>Anypserodon leucogrammicus</i>	<i>Epinephelus leucogrammicus</i>	Valenciennes in Cuvier & Valenciennes, 1828	X	X	X	BOLD:AAAC8327 [7/6], BOLD:AAAC8327 [5/5]	BOLD:AAAC8328 NA	NA	Y	Y
<i>Cephalopholis argus</i>	-	Bloch & Schneider, 1801	X	X	X	BOLD:AAAC4474 [26/24], BOLD:AAAC0217 [21/1], BOLD:AAD4737 [26/1]	BOLD:AAAC4474 NA	NA	N	N
<i>Cephalopholis boenak</i>	-	Bloch, 1790	X	X	X	BOLD:ACT7478 [32/31], BOLD:AAB3684 [7/7], BOLD:ACT7479 [1/1]	BOLD:ACT7478 BOLD:ACT7478	BOLD:ACT7478	Y	Y
<i>Cephalopholis cyanostigma</i>	-	Valenciennes in Cuvier & Valenciennes, 1828	X	X	X	BOLD:AAAC0217 [21/15]	BOLD:AAAC0217 BOLD:AAAC0217	BOLD:AAAC0217	N	N
<i>Cephalopholis formosa</i>	-	Shaw & Nodder, 1812	X	X	X	BOLD:AAF0621 [29/27]	BOLD:AAF0621 BOLD:AAF0621	BOLD:AAF0621	N	N
<i>Cephalopholis leopardus</i>	-	Lacépède, 1802	X	X	X	BOLD:AAD9032 [7/7]	BOLD:AAD9032 NA	NA	N	-
<i>Cephalopholis microprion</i>	-	Bleeker, 1852	X	X	X	BOLD:AAAC0217 [21/4], BOLD:AAF0629 [4/4]	<i>BOLD:AAAC0217</i> NA	NA	N	-
<i>Cephalopholis miniata</i>	-	Forsskål, 1775	X	X	X	BOLD:AAAC0216 [28/28], BOLD:AAAC0217 [21/1]	BOLD:AAAC0216 BOLD:AAAC0216	BOLD:AAAC0216	N	N
<i>Cephalopholis sonnerati</i>	-	Valenciennes in Cuvier & Valenciennes, 1828	X	X	X	BOLD:AAD4737 [26/25], BOLD:AAB5431 [15/14], BOLD:ACC0647 [5/5], BOLD:AAB5432 [6/2]	BOLD:AAD4737 BOLD:AAD4737	BOLD:AAD4737	Y	Y
<i>Cephalopholis urodeta</i>	-	Forster in Bloch & Schneider, 1801	X	X	X	BOLD:AAAC4202 [23/4/93]	BOLD:AAAC4202 BOLD:AAAC4202	BOLD:AAAC4202	N	N
<i>Cromileptes altivelis</i>	<i>Epinephelus altivelis</i>	Valenciennes, 1828	X	X	X	BOLD:AAAC1876 [16/16]	BOLD:AAAC1876 NA	NA	N	-
<i>Epinephelus akaara</i>	-	Temminck & Schlegel, 1842	X	X	X	BOLD:AAF1053 [83/81], BOLD:AAAC5362 [50/1]	BOLD:AAF1053 NA	NA	N	-
<i>Epinephelus amblycephalus</i>	-	Bleeker, 1857	X	X	X	BOLD:AAAB1345 [67/48], BOLD:AAAB1346 [3/3], BOLD:ADA9689 [1/1]	<i>BOLD:AAAB1345</i> BOLD:AAAB1346	BOLD:AAAB1346	N	N
<i>Epinephelus areolatus</i>	-	Forsskål, 1775	X	X	X	BOLD:AAA9821 [37/36], BOLD:AAA9822 [25/23], BOLD:ACC0344 [3/3]	BOLD:AAA9821 BOLD:AAA9821, BOLD:AA-A9822	BOLD:AAA9821, BOLD:AA-A9822	Y	Y
<i>Epinephelus awoara</i>	-	Temminck & Schlegel, 1842	X	X	X	BOLD:AAF0829 [8/7], BOLD:AAB8391 [113/2]	BOLD:AAF0829 BOLD:AAF0829	BOLD:AAF0829	N	-

Table 1 (continued)

Classification "Catalog of Fishes"	Classification according Ma and Craig (2018)	Heemstra and Randall 1993 (FAO)	Craig et al. 2011	This study	BIN's BOLD	Ma et al. (2016)	BIN present in Vietnam (this study)	Multi-BIN species	Phylogeographic pattern
<i>Epinephelus bleekeri</i>	-	Vaillant, 1878	X	X	BOLD: AAC5362 [50/48]	BOLD: AAC5362	BOLD: AAC5362	N	N
<i>Epinephelus bruneus</i>	-	Bloch, 1793	X	X	BOLD: AAJ0588 [6/6], BOLD: ACS0266 [3/3]	BOLD: AAJ0588	BOLD: ACS0266	N	N
<i>Epinephelus chlorostigma</i>	-	Cuvier & Valenciennes, 1828	X	X	BOLD: AAC5363 [19/14], BOLD: ABA7404 [5/5], BOLD: ADE3544 [1/1]	BOLD: AAA9822	BOLD: AAC3591	Y	-
<i>Epinephelus coioides</i>	-	Hamilton, 1822	X	X	BOLD: AAB8391 [113/76], BOLD: AAB8389 [35/1], BOLD: AAC2802 [19/1]	BOLD: AAB8391	BOLD: AAB8391	N	N
<i>Epinephelus corallicola</i>	-	Valenciennes in Cuvier & Valenciennes, 1828	X	X	BOLD: AAD8682 [9/9]	BOLD: AAD8682	BOLD: AAD8682	N	-
<i>Epinephelus craigi</i>	-	Frable, Tucker & Walker, 2019			The name "craigi" is not in BOLD but the sequence match BOLD: AAB1345	NA	NA	-	-
<i>Epinephelus cyanopodus</i>	-	Richardson, 1846	X	X	BOLD: AAD1767 [16/3]	BOLD: AAD1767	NA	N	-
<i>Epinephelus epistictus</i>	<i>Mycteroperca cyanopodus</i>	Temminck & Schlegel, 1842	X	X	BOLD: ADB3169 [13/13], BOLD: AAF1066 [4/4]	BOLD: AAF1066	NA	Y	Y
<i>Epinephelus erythrurus</i>	-	Valenciennes in Cuvier & Valenciennes, 1828	X	X	BOLD: ACC0501 [15/11]	NA	BOLD: ACC0501	N	N
<i>Epinephelus fasciaticaudatus</i>	-	Peters, 1866	X	X	BOLD: AAC5392 [11/2], BOLD: AAF0829 [8/1], BOLD: AAF1053 [83/2]	BOLD: AAC5392	NA	N	-
<i>Epinephelus fuscoguttatus</i>	-	Forsskål, 1775	X	X	BOLD: AAB1332 [30/29], BOLD: AAB1334 [23/18], BOLD: AAB1333 [4/3], BOLD: AAB1335 [1/1]	BOLD: AAB1333	BOLD: AAB1332	Y	Y
<i>Epinephelus heniochus</i>	<i>Mycteroperca heniochus</i>	Forsskål, 1775	X	X	BOLD: AAB1333 [4/3], BOLD: AAB1335 [1/1]	NA	NA	-	-
<i>Epinephelus hexagonatus</i>	-	Fowler, 1904	X	X	BOLD: AAD8872 [23/18], BOLD: AAD8873 [6/3], BOLD: AAD3855 [5/5]	BOLD: AAD8872	BOLD: AAD8872	N	Y
<i>Epinephelus lanceolatus</i>	<i>Mycteroperca heniochus</i>	Fowler, 1904	X	X	BOLD: AAD3458 [11/10]	NA	NA	-	-
<i>Epinephelus latifasciatus</i>	-	Forster in Bloch & Schneider, 1801	X	X	BOLD: AAD8914 [6/6], BOLD: AAD8872 [23/1]	BOLD: AAD8914	BOLD: AAD8914	N	-
<i>Epinephelus macrospilus</i>	-	Bloch, 1790	X	X	BOLD: AAD8911 [9/9], BOLD: ADM3791 [5/5]	BOLD: ADM3791	NA	Y	Y
<i>Epinephelus malabaricus</i>	-	Temminck & Schlegel, 1842	X	X	BOLD: AAE1882 [11/9], BOLD: AAB8386 [42/4]	BOLD: AAE1882	NA	N	-
	-	Bloch & Schneider, 1801	X	X	BOLD: AAB8389 [35/27], BOLD: AAB8391 [113/1]	BOLD: AAB8389	BOLD: AAB8389	N	Y

Table 1 (continued)

Classification "Catalog of Fishes"	Classification according Ma and Craig (2018)	Heemstra and Randall 1993 (FAO)	Craig et al. 2011	This study	BIN's BOLD	Ma et al. (2016)	BIN present in Vietnam (this study)	Multi- BIN species	Phylogeographic pattern
<i>Epinephelus merra</i>	-	X	X	X	BOLD:AAB8386 [42/38], BOLD:AAB8387 [13/4]	BOLD:AAB8386 NA	NA	Y	Y
<i>Epinephelus morhua</i>	<i>Mycteroperca morhua</i>	X	X	X	BOLD:ACE6821 [15/14], BOLD:ADL0994 [13/4], Valenciennes, Cuvier & 1833	BOLD:ACE6821	BOLD:ACE6821	Y	N
<i>Epinephelus poecilnotus</i>	<i>Mycteroperca poecilnotus</i>	X	X	X	BOLD:ADC2027 [1/1]	BOLD:AAD3854 NA	NA	N	-
<i>Epinephelus</i>	-	X	X	X	BOLD:AAD3854 [30/28], BOLD:AAD3855 [5/1]	BOLD:AAD8873	BOLD:AAD8873	Y	Y
<i>polyphekaion</i>	-	X	X	X	BOLD:ABX5597 [9/9]	BOLD:AAC2809	BOLD:AAC2809	N	Y
<i>Epinephelus quoyanus</i>	-	X	X	X	BOLD:AAC2809 [18/18], BOLD:AAC362 [50/1]	BOLD:AAC2809	BOLD:AAC2809	N	Y
<i>Epinephelus rivulatus</i>	-	X	X	X	BOLD:ACZ9919 [22/17], BOLD:AAF0433 [3/1]	BOLD:ACZ9919	BOLD:AAF0433	Y	Y
<i>Epinephelus sexfasciatus</i>	-	X	X	X	BOLD:AAC5392 [11/9], BOLD:ACM3827 [13/13]	BOLD:AAC5392	BOLD:ACM3827	N	N
<i>Epinephelus stictus</i>	-	X	X	X	BOLD:AAB1345 [67/18]	NA	NA	-	-
<i>Epinephelus trimaculatus</i>	-	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-
<i>Plectropomus leopardus</i>	-	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-
<i>Plectropomus maculatus</i>	-	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-
<i>Plectropomus oligacanthus</i>	-	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-
<i>Plectropomus maculatus</i>	-	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-
<i>Plectropomus oligacanthus</i>	-	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-
<i>Triso dermopterus</i>	<i>Hyporhamphus dermopterus</i>	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-
<i>Variola albimarginata</i>	-	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-
<i>Variola louti</i>	-	X	X	X	BOLD:AAJ0586 [6/4]	BOLD:AAJ0586	NA	N	-

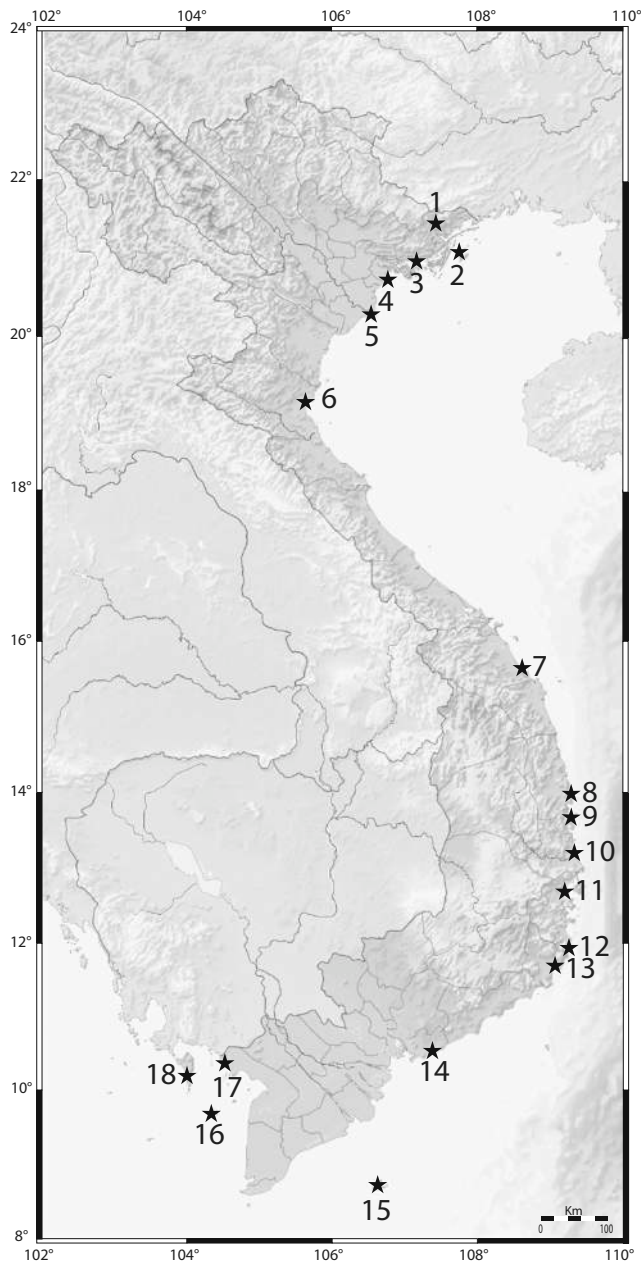


Fig. 1 Sampling locations in Vietnam for the DNA barcoding of the Epinephelidae subfamily. 1 Tien Yen, Quang Ninh; 2 Co To Island, Quang Ninh; 3 Ha Long bay, Quang Ninh; 4 Do Son, Hai Phong; 5 Xuan Thuy, Nam Dinh; 6 Hau Loc, Thanh Hoa; 7 Nui Thanh, Quang Nam; 8 Quy Nhon, Binh Dinh; 9 Cu Mong, Phu Yen; 10 Thuy Hoa, Phu Yen; 11 Nha Trang, Khanh Hoa; 12 Binh Ba Island, Khanh Hoa; 13 Ninh Thuan, Ninh Thuan; 14 Loc An, Ba Ria Vung Tau; 15 Con Dao, Ba Ria Vung Tau; 16 Nam Du, Kien Giang; 17 Ha Tien, Kien Giang; 18 Phu Quoc, Kien Giang

The second phylogenetic analysis was performed on a large dataset that comprised:

- One sequence representative of each species and lineage (BIN) observed in this study.

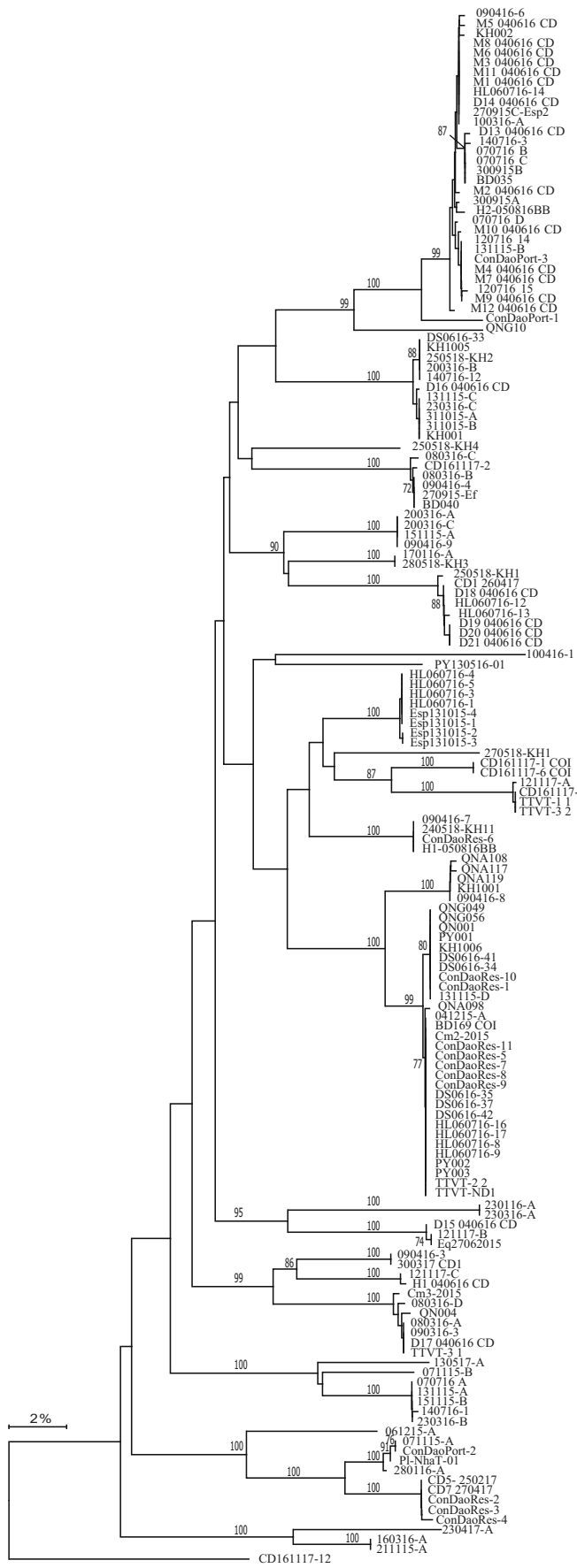
- All sequences published by Ma et al. (2016) that represent 87% of the known species diversity in the Epinephelidae and that may be considered as the reference.
- The COI sequences of *Epinephelus moara* resurrected by Liu et al. (2013), *Epinephelus craigi* described by Frable et al. (2019), and *Epinephelus fuscomarginatus* + *E. magniscuttis* described and redescribed respectively by Johnson and Worthington Wilmer (2019).
- One COI barcode of each BIN associated with a species name in BOLD, i.e., those present in the updated species checklist for Vietnam. BINs have been identified through the public data portal of BOLD (consultation 29/11/2018).

The aim of this second phylogenetic tree was to check concordance between species identification based on morphological criteria (present data) and DNA barcode (BOLD), to reveal misidentification or introgression in BINs associated with grouper species present in Vietnam and, finally, to highlight species that are polyphyletic due to the presence of several BINs. Species misidentification or introgression is responsible for more than one species name within a BIN. However, it is possible to determine specimens in a BIN that were misidentified or a hybrid, by considering:

- the number and origin (laboratory and geography) of specimens of different species within a BIN: the more barcodes were similarly identified by independent laboratories from various locations, the more the species identification may be considered reliable,
- the phenotype of the specimen when a picture is available in BOLD,
- the phylogeny, by considering the phylogenetic position of reference species sequence and BINs.

Following this rationale, we reassigned BINs to a probable species.

A phylogeographic analysis was used to further investigate processes responsible for intraspecific diversity in the groupers. A special attention was paid to polyphyletic species, those that present several BINs that form a clade in the phylogenetic tree, in order to determine the evolutionary significance of these BINs. All public COI barcodes belonging to BINs associated with a species name were uploaded and added to “Vietnamese” grouper data (Table S4). Haplotypic networks were estimated using the TCS method of Clement et al. (2002) implemented in PopART (French et al. 2014; <http://popart.otago.ac.nz>), and the geography and BIN were mapped



BOLD:AAA9821 *Epinephelus areolatus*

BOLD:AAA9822 *Epinephelus areolatus*
BOLD:AAC3591 *Epinephelus chlorostigma*

BOLD:AAC5362 *Epinephelus bleekeri*

BOLD:AAD3458 *Epinephelus hexagonatus*

BOLD:AAB1332 *Epinephelus fasciatus*

BOLD:AAB1346 *Epinephelus amblycephalus*

BOLD:AAF0829 *Epinephelus awoara*

BOLD:ACM3827 *Epinephelus sexfasciatus*

BOLD:AAD9769 *Triso dermatopterus*
BOLD:ACE6821 *Epinephelus morrhua*

BOLD:ACS0266 *Epinephelus bruneus*

BOLD:AAD8873 *Epinephelus polyphekadion*
BOLD:ACC0501 *Epinephelus erythrurus*

BOLD:AAD8682 *Epinephelus corallicola*

BOLD:AAD8872 *Epinephelus fuscoguttatus*

BOLD:AAB8389 *Epinephelus malabaricus*

BOLD:AAB8391 *Epinephelus coioides*

BOLD:AAF0433 *Epinephelus rivulatus*

BOLD:AAC2809 *Epinephelus quoyanus*

BOLD:AAF0621 *Cephalopholis formosa*

BOLD:AAC0217 *Cephalopholis cyanostigma*

BOLD:ACT7478 *Cephalopholis boenak*

BOLD:AAC0216 *Cephalopholis miniata*

BOLD:AAC4202 *Cephalopholis urodeta*

BOLD:AAD4737 *Cephalopholis sonnerati*

BOLD:AAL4434 *Plectropomus oligacanthus*

BOLD:AAC9348 *Plectropomus leopardus*

BOLD:ACK7859 *Plectropomus maculatus*

BOLD:AAC5719 *Variola louti*

BOLD:AAC9675 *Variola albigarginata*

BOLD:AAC9922 *Diploprion bifasciatum*

◀ **Fig. 2** Phylogenetic relationships among cytochrome oxidase I barcodes and BINs recovered among Vietnamese groupers. The pattern of divergence between species is represented by a neighbor-joining (NJ) tree based on K2P distances. The relevance of tree nodes are highlighted by bootstrap values (only values >70% are indicated). The tree is rooted using *Diploprion bifasciatum*

onto these TCS networks to determine a phylogeographic structure.

Results

Known diversity of groupers in Vietnam and their associated BINs

By compiling knowledge from two major grouper species checklists for the West Pacific or worldwide (Heemstra and Randall 1993; Craig et al. 2011) and reviewing all recent grouper species description or redescription (Liu et al. 2013; Tucker et al. 2016; Frable et al. 2019), 40 species were recorded for Vietnam (Table 1). These species belong to either six or four different genera, according Eschmeyer's Catalog of Fishes (Fricke et al. 2019) or Ma and Craig (2018), respectively (Table 1). With the exception of *Epinephelus craigi* described recently (Frable et al. 2019) and still not referenced in BOLD, all these species names were associated with one or several BINs (up to 4, Table 1). Only 1/3 of the species were associated with only a single BIN.

Species diversity and BINs recovered in Vietnam

A total of 158 DNA barcodes (with a core segment of a 603 bp) were uploaded to the DS-SERV project (dx.doi.org/10.5883/DS-SERV). These DNA barcodes correspond to 31 species matching 32 BINs (Fig. 2), only one species *Epinephelus areolatus* presented haplotypes that belonged to two BINs (Tables 1 and 2). With the exception of *Epinephelus areolatus* that presented 3.5% of divergence between the two BINs, the intraspecies diversity (similar to the intra BIN) was extremely low and ranged from 0% for several species sampled more than one time to 0.4% for *Cephalopholis boenak* (Table S2). Interspecies divergence ranged from 3.8% between *Epinephelus malabaricus* and *Epinephelus coioides* to 24.3% between *Epinephelus malabaricus* and *Diploprion bifasciatum* (Table S2)

Among the species identified, nine were new records for Vietnam: *Epinephelus bruneus*, *Epinephelus fuscoguttatus*, *Epinephelus hexagonatus*, *Epinephelus polyphkadion*, *Plectropomus maculatus*, *Plectropomus oligacanthus*, *Triso dermatopterus*, *Variola albimarginata*, and *Variola louti*. The grouper checklist for Vietnam therefore now includes 49 species. These species were associated with 76 BINs. The ABGD

algorithm identified 77 OTUs that broadly matched the RESL delineation (i.e., BINs) (Table S3). Actually, if we exclude three cases, there are no differences between OTUs delineated by the ABGD or RESL algorithms. The OTU6 included sequences belonging to two BINs BOLD:AAD4737 and BOLD:AAB5431 while one sequence of this last BIN is highlighted as a distinct OTU: OTU7 (Table S3). All sequences belonging to OTU6, OTU7, BOLD:AAD4737, and BOLD:AAB5431 come from specimens identified as *Cephalopholis sonnerati*. The last discrepancy concerned a unique sequence that belonged to the BIN BOLD:AAC5719 but was assigned by ABGD to a specific OTU (OTU72). Because the RESL algorithm appeared more conservative by comparison to ABGD, which was able to create a specific OTU for only one sequence, we hereafter only considered BINs for further analyses.

Multi-BIN species may correspond to polyphyletic species, but specimens that were misidentified or hybridized would also artificially increase the number of BIN per species. For these latter cases, the careful reexamination revised the species associated with them (Table 2). For 23 BINs, it was possible to sort hybrids and misidentified specimens, and thus limit these BINs to one species name (see Table S5 for rationale). For one BIN (BOLD:ADE3544) originally assigned to *E. chlorostigma*, it was not possible to check the species identification because no picture was provided for any BIN members while its phylogenetic position did not show any close relationships with either *E. chlorostigma* lineages or the species barcode reference.

In the phylogenetic tree (Fig. 3) we also noticed some issues for a number of barcodes published by Ma et al. (2016). The COI sequence corresponding to *E. chlorostigma* in Ma et al. (2016) is grouped with sequences identified as *E. areolatus* in BOLD and the present study (Fig. 3 (5)). The Ma et al. (2016) COI sequence of *E. bruneus* matched the sequence of the resurrected species *E. moara* published by Liu et al. (2013) but not the *E. bruneus* sampled in Vietnam that belonged to the BIN BOLD:ACS0266 that was also associated with *E. bruneus*. (Fig. 3 (3)). Their sequence labelled as *E. sexfasciatus* was not different to their sequence labelled as *E. fasciatomaculosus* while, in this study, we identified a specimen as *E. sexfasciatus* that presented a different sequence that belonged to the BIN BOLD:ACM3827 that only comprised *E. sexfasciatus* members (Fig. 3 (6)). Their sequence of *E. amblycephalus* corresponded to the DNA barcode later described as *E. craigi* (Frable et al. 2019) (Fig. 3 (6)). Their COI sequence corresponding to *E. irroratus* was phylogenetically extremely close to *E. fasciatus* that comprised 4 BINs. Similarly, no genetic divergence was observed between their sequence of *Cephalopholis nigripinnis* and *C. urodeta* (Fig. 3 (7)), or between *C. cyanostigma* and *C. microprium* (Fig. 3 (8)). Considering this revision, several conditions can be highlighted:

Table 2 List of BINs present in the Table 1 and associated species name after revision (see rationale in Table S5) or in BOLD

BIN	According to this review	In BOLD			
	Species name	Species 1	Species 2	Species 3	Species 4
BOLD:AAB1332	<i>Epinephelus fasciatus</i>	<i>Epinephelus fasciatus</i>			
BOLD:AAB1333	<i>Epinephelus fasciatus</i>	<i>Epinephelus fasciatus</i>	<i>Epinephelus irroratus</i>		
BOLD:AAB1334	<i>Epinephelus fasciatus</i>	<i>Epinephelus fasciatus</i>			
BOLD:AAB1335	<i>Epinephelus fasciatus</i>	<i>Epinephelus fasciatus</i>			
BOLD:AAB3684	<i>Cephalopholis boenak</i>	<i>Cephalopholis boenak</i>			
BOLD:ACT7478	<i>Cephalopholis boenak</i>	<i>Cephalopholis boenak</i>	<i>Cephalopholis</i> <i>igarashiensis</i>		
BOLD:ACT7479	<i>Cephalopholis boenak</i>	<i>Cephalopholis boenak</i>			
BOLD:AAB5431	<i>Cephalopholis sonnerati</i>	<i>Cephalopholis</i> <i>sonnerati</i>			
BOLD:AAD4737	<i>Cephalopholis sonnerati</i>	<i>Cephalopholis</i> <i>sonnerati</i>	<i>Cephalopholis argus</i>		
BOLD:ACC0647	<i>Cephalopholis sonnerati</i>	<i>Cephalopholis</i> <i>sonnerati</i>			
BOLD:AAA9821	<i>Epinephelus areolatus</i>	<i>Epinephelus areolatus</i>			
BOLD:AAA9822	<i>Epinephelus areolatus</i>	<i>Epinephelus areolatus</i>			
BOLD:ACC0344	<i>Epinephelus areolatus</i>	<i>Epinephelus areolatus</i>			
BOLD:AAC6284	<i>Epinephelus morrhua</i>	<i>Epinephelus morrhua</i>			
BOLD:ACE6821	<i>Epinephelus morrhua</i>	<i>Epinephelus morrhua</i>			
BOLD:ADC2027	<i>Epinephelus morrhua</i>	<i>Epinephelus morrhua</i>			
BOLD:AAD9665	<i>Aethaloperca rogaa</i>	<i>Aethaloperca rogaa</i>			
BOLD:ACC0322	<i>Aethaloperca rogaa</i>	<i>Aethaloperca rogaa</i>			
BOLD:AAC8327	<i>Anyperodon leucogrammicus</i>	<i>Anyperodon</i> <i>leucogrammicus</i>			
BOLD:AAC8328	<i>Anyperodon leucogrammicus</i>	<i>Anyperodon</i> <i>leucogrammicus</i>			
BOLD:AAC3591	<i>Epinephelus chlorostigma</i>	<i>Epinephelus spilotoceps</i>			
BOLD:ABA7404	<i>Epinephelus chlorostigma</i>	<i>Epinephelus</i> <i>chlorostigma</i>			
BOLD:AAF1066	<i>Epinephelus epistictus</i>	<i>Epinephelus epistictus</i>			
BOLD:ADB3169	<i>Epinephelus epistictus</i>	<i>Epinephelus epistictus</i>			
BOLD:AAD8911	<i>Epinephelus latifasciatus</i>	<i>Epinephelus</i> <i>latifasciatus</i>			
BOLD:ADM3791	<i>Epinephelus latifasciatus</i>	<i>Epinephelus</i> <i>latifasciatus</i>			
BOLD:AAB8386	<i>Epinephelus merra</i>	<i>Epinephelus merra</i>	<i>Epinephelus</i> <i>macrospilos</i>		
BOLD:AAB8387	<i>Epinephelus merra</i>	<i>Epinephelus merra</i>	<i>Epinephelus faveatus</i>		
BOLD:AAD8873	<i>Epinephelus polyphkadion</i>	<i>Epinephelus</i> <i>polyphkadion</i>	<i>Epinephelus</i> <i>fuscoguttatus</i>		
BOLD:ABX5597	<i>Epinephelus polyphkadion</i>	<i>Epinephelus</i> <i>polyphkadion</i>			
BOLD:AAF0433	<i>Epinephelus rivulatus</i>	<i>Epinephelus rivulatus</i>			
BOLD:ACZ9919	<i>Epinephelus rivulatus</i>	<i>Epinephelus rivulatus</i>			
BOLD:ACK7859	<i>Plectropomus maculatus</i>	<i>Plectropomus</i> <i>maculatus</i>			
BOLD:ADL8508	<i>Plectropomus maculatus</i>	<i>Plectropomus</i> <i>maculatus</i>			
BOLD:AAC5719	<i>Variola louti</i>	<i>Variola louti</i>			
BOLD:AAC5720	<i>Variola louti</i>	<i>Variola louti</i>			
BOLD:AAB1346	<i>Epinephelus amblycephalus</i>	<i>Epinephelus</i> <i>amblycephalus</i>			
BOLD:AAJ0588	<i>Epinephelus moara</i>	<i>Epinephelus bruneus</i>			

Table 2 (continued)

BIN	According to this review	In BOLD			
	Species name	Species 1	Species 2	Species 3	Species 4
BOLD:ACS0266	<i>Epinephelus bruneus</i>	<i>Epinephelus bruneus</i>			
BOLD:AAC4474	<i>Cephalopholis argus</i>	<i>Cephalopholis argus</i>			
BOLD:AAB5432	<i>Cephalopholis aurantia</i>	<i>Cephalopholis aurantia</i>	<i>Cephalopholis sonnerati</i>	<i>Cephalopholis spiloparaea</i>	
BOLD:AAC0217	<i>Cephalopholis cyanostigma</i>	<i>Cephalopholis cyanostigma</i>	<i>Cephalopholis microprion</i>	<i>Cephalopholis miniata</i>	<i>Cephalopholis argus</i>
BOLD:AAF0621	<i>Cephalopholis formosa</i>	<i>Cephalopholis formosa</i>			
BOLD:AAD9032	<i>Cephalopholis leopardus</i>	<i>Cephalopholis leopardus</i>			
BOLD:AAF0629	<i>Cephalopholis microprion</i>	<i>Cephalopholis microprion</i>			
BOLD:AAC0216	<i>Cephalopholis miniata</i>	<i>Cephalopholis miniata</i>			
BOLD:AAC1876	<i>Cromileptes altivelis</i>	<i>Cromileptes altivelis</i>			
BOLD:AAF1053	<i>Epinephelus akaara</i>	<i>Epinephelus akaara</i>	<i>Epinephelus fasciatomaculosus</i>		
BOLD:AAF0829	<i>Epinephelus awoara</i>	<i>Epinephelus awoara</i>	<i>Epinephelus fasciatomaculosus</i>		
BOLD:AAC5362	<i>Epinephelus bleekeri</i>	<i>Epinephelus bleekeri</i>	<i>Epinephelus quoyanus</i>	<i>Epinephelus akaara</i>	
BOLD:ADL0994	<i>Epinephelus coeruleopunctatus</i>	<i>Epinephelus coeruleopunctatus</i>	<i>Epinephelus morrhua</i>		
BOLD:AAB8391	<i>Epinephelus coioides</i>	<i>Epinephelus coioides</i>	<i>Epinephelus tauvina</i>	<i>Epinephelus awoara</i>	<i>Epinephelus malabaricus</i>
BOLD:AAD8682	<i>Epinephelus corallicola</i>	<i>Epinephelus corallicola</i>			
BOLD:AAB1345	<i>Epinephelus craigi</i>	<i>Epinephelus amblycephalus</i>	<i>Epinephelus stictus</i>		
BOLD:ACC0501	<i>Epinephelus erythrurus</i>	<i>Epinephelus erythrurus</i>	<i>Epinephelus coeruleopunctatus</i>		
BOLD:AAC5392	<i>Epinephelus fasciatomaculosus</i>	<i>Epinephelus sexfasciatus</i>	<i>Epinephelus fasciatomaculosus</i>		
BOLD:AAD8872	<i>Epinephelus fuscoguttatus</i>	<i>Epinephelus fuscoguttatus</i>	<i>Epinephelus lanceolatus</i>		
BOLD:AAD3855	<i>Epinephelus heniochus</i>	<i>Epinephelus heniochus</i>	<i>Epinephelus poecilonotus</i>		
BOLD:AAD3458	<i>Epinephelus hexagonatus</i>	<i>Epinephelus hexagonatus</i>			
BOLD:AAD8914	<i>Epinephelus lanceolatus</i>	<i>Epinephelus lanceolatus</i>			
BOLD:AAE1882	<i>Epinephelus macrospilos</i>	<i>Epinephelus macrospilos</i>			
BOLD:AAB8389	<i>Epinephelus malabaricus</i>	<i>Epinephelus malabaricus</i>	<i>Epinephelus coioides</i>		
BOLD:AAC2802	<i>Epinephelus ongus</i>	<i>Epinephelus ongus</i>	<i>Epinephelus coioides</i>		
BOLD:AAD3854	<i>Epinephelus poecilonotus</i>	<i>Epinephelus poecilonotus</i>			
BOLD:AAC5363	<i>Epinephelus polylepis</i>	<i>Epinephelus chlorostigma</i>	<i>Epinephelus polylepis</i>		
BOLD:AAC2809	<i>Epinephelus quoyanus</i>	<i>Epinephelus quoyanus</i>			
BOLD:ACM3827	<i>Epinephelus sexfasciatus</i>	<i>Epinephelus sexfasciatus</i>			
BOLD:ADA9689	<i>Epinephelus stictus</i>	<i>Epinephelus amblycephalus</i>			
BOLD:ADE3544	<i>Epinephelus</i> sp. 1	<i>Epinephelus chlorostigma</i>			
BOLD:AAJ0586	<i>Epinephelus trimaculatus</i>	<i>Epinephelus trimaculatus</i>	<i>Epinephelus fario</i>		
BOLD:AAC9348	<i>Plectropomus leopardus</i>	<i>Plectropomus leopardus</i>	<i>Plectropomus areolatus</i>	<i>Plectropomus maculatus</i>	<i>Plectropomus pessuliferus</i>

Table 2 (continued)

BIN	According to this review	In BOLD			
	Species name	Species 1	Species 2	Species 3	Species 4
BOLD:AAL4434	<i>Plectropomus oligacanthus</i>	<i>Plectropomus oligacanthus</i>			
BOLD:AAD9769	<i>Triso dermopterus</i>	<i>Triso dermopterus</i>			
BOLD:AAC9675	<i>Variola albimarginata</i>	<i>Variola albimarginata</i>			
BOLD:AAC4202	<i>Cephalopholis urodeta</i> / <i>C. nigripinnis</i>	<i>Cephalopholis urodeta</i>	<i>Cephalopholis nigripinnis</i>		
BOLD:AAD1767	<i>Epinephelus cyanopodus</i> / <i>E. flavocaeruleus</i>	<i>Epinephelus flavocaeruleus</i>	<i>Epinephelus cyanopodus</i>		

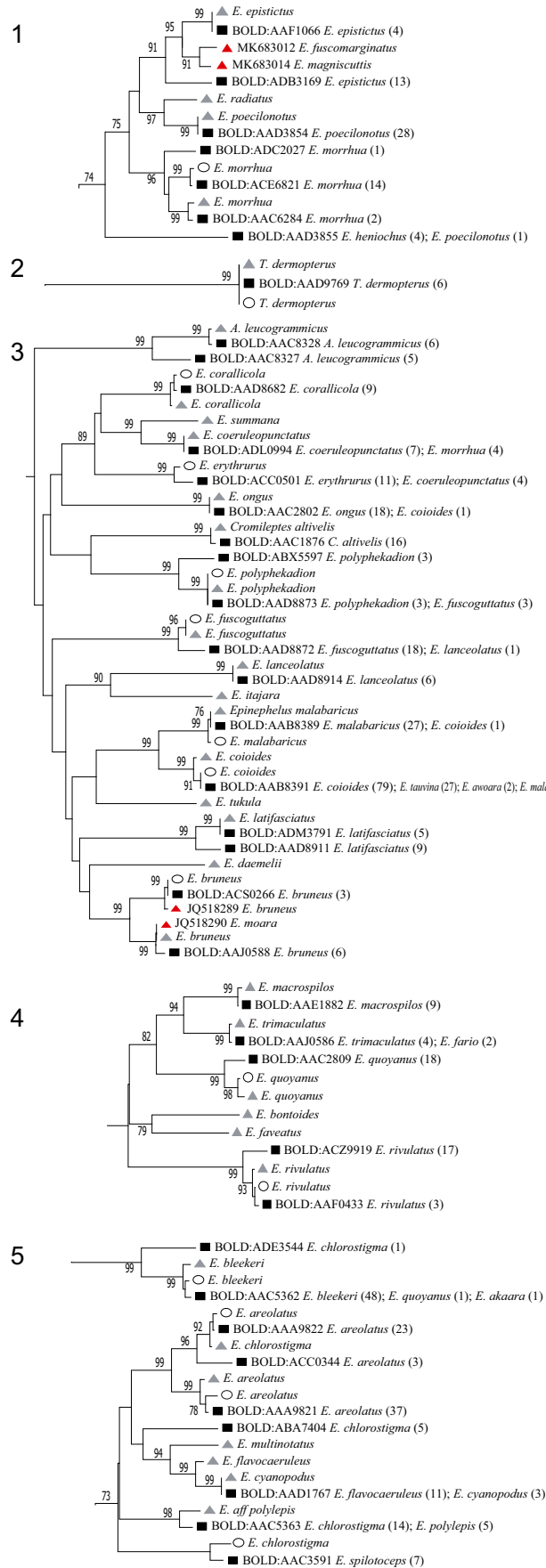
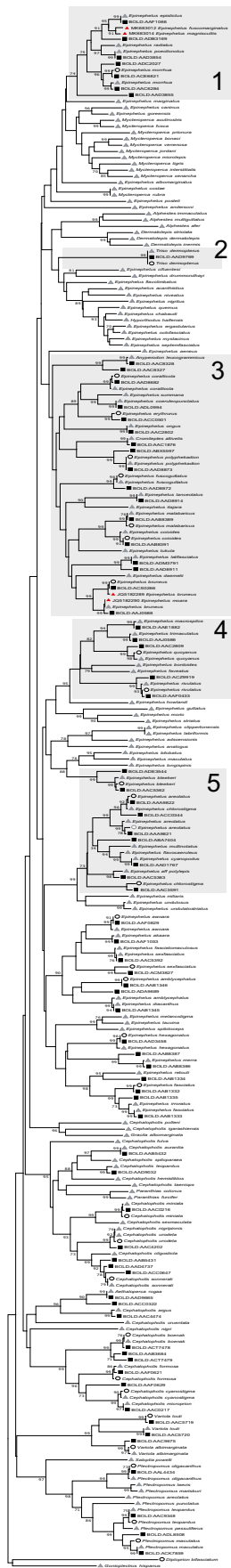
- One BIN–several species: Only two BINs corresponded to this situation where there was no apparent misidentification: BOLD:AAD1767 composed of members either identified as *E. cyanopodus* or *E. flavocaeruleus*, and BOLD:AAC4202 composed of members that can either corresponded to *Cephalopholis urodeta* or *C. nigripinnis*.
- One BIN–one species: This concerned 37 species listed in Table 2. *Chromileptes altivelis*, *Cephalopholis argus*, *C. aurantia*, *C. cyanostigma*, *C. formosa*, *C. leopardus*, *C. microprion*, *C. miniata*, *Epinephelus akaraa*, *E. amblycephalus*, *E. awoara*, *E. bleekeri*, *E. bruneus*, *E. coioides*, *E. corallicola*, *E. craigii*, *E. heniochus*, *E. coeruleopunctatus*, *E. erythrurus*, *E. hexagonatus*, *E. fasciatomaculosus*, *E. fuscoguttatus*, *E. lanceolatus*, *E. malabaricus*, *E. macrospilos*, *E. moara*, *E. oncus*, *E. poecilonotus*, *E. polylepis*, *E. quoyanus*, *E. sexfasciatus*, *E. stictus*, *E. trimaculatus*, *Plectropomus leopardus*, *P. oligacanthus*, *Triso dermopterus*, *Variola albimarginata*.
- One species–several BINs: This concerned 15 species: *Aethaloperca rogaea*, *Anyperodon leucogrammicus*, *Cephalopholis boenak*, *C. sonnerati*, *Epinephelus areolatus*, *E. chlorostigma*, *E. epistictus*, *E. fasciatus*, *E. latifasciatus*, *E. merra*, *E. morruha*, *E. polyphkadion*, *E. rivulatus*, *Plectropomus maculatus*, *Variola louti*.
- One geographic location (East Australia for BOLD:ADC2027 and the South China Sea for BOLD:AAC6284) while the third was widespread and present in the whole Indo-Pacific Ocean (Fig. 4l).
- A strict allopatric/parapatric distribution for at least one BIN associated with a species. This was observed for: *Aethaloperca rogaea*, *Epinephelus areolatus* and *Plectropomus maculatus* with the BINs BOLD:ACC0322, BOLD:ACC0344, and BOLD:ADL8508 respectively, restricted to the Andaman Islands (Fig. 4a, f, o); *Cephalopholis sonnerati* with BINs BOLD:AAB5431 and BOLD:ACC0647 restricted to SW Indian Ocean and the Andaman Islands, respectively (Fig. 4d); *Epinephelus epistictus* with the BIN BOLD:ADB3169 and the BIN BOLD:AAF1066 restricted to the Indian Ocean and the South China Sea, respectively (Fig. 4h); *E. fasciatus* and *E. rivulatus* with their BINs (BOLD:AAB1334 and BOLD:ACZ9919, respectively) restricted to the West Indian Ocean and the Red Sea (Fig. 4i, k); *E. polyphkadion* for which the distribution of the two BINs showed a clear geographic barrier located in the central part of the Indian Ocean (Fig. 4m), and *Variola louti* with the BIN BOLD:AAC5720 restricted to the Central Pacific Ocean: (Fig. 4p).
- Partial parapatry corresponded to species that presented several BINs at one location that, elsewhere, were in parapatry. This was the case for: *Anyperodon leucogrammicus* with two BINs present in Taiwan whereas BOLD:AAC8328 presented a distribution usually

Phylogeographic structure of polyphyletic species

The TCS networks built for species that remained polyphyletic (several BINs for a unique species name) after BIN/species reassignment showed various phylogeographic patterns.

- A geographic overlap of BINs/clades associated with a species name. This was only observed for *Epinephelus morruha*. However, it is noticeable that, among the three clades corresponding to 3 BINs, two are limited to one

Fig. 3 Phylogenetic relationships among all BINs recovered in Vietnam (white dot), BINs associated with species inventoried in Vietnam (black square), and some species COI sequence references from Ma et al. (2016, gray triangle), Frable et al. (2019, red triangle), Liu et al. (2013, red triangle), and Johnson and Worthington Wilmer (2019, red triangle). The pattern of divergence among species is represented by a neighbor-joining (NJ) tree based on K2P distances. The relevance of tree nodes are highlighted by bootstrap values (only value > 70% are indicated). *Flags polyphyletic species (more than one BIN but phylogenetically close); °flags parapatric species



- | *Epinephelus epistictus*^o
- | *Epinephelus fuscomarginatus*
- | *Epinephelus magniscutis*
- | *Epinephelus epistictus*^o
- | *Epinephelus radiatus*
- | *Epinephelus poecilonotus*
- | *Epinephelus morrhua**
- | *Epinephelus heniochus*
- | *Triso dermopterus*
- | *Anyperodon leucogrammicus**
- | *Epinephelus corallicola*
- | *Epinephelus summana*
- | *Epinephelus coeruleopunctatus*
- | *Epinephelus erythrurus*
- | *Epinephelus ongus*
- | *Cromileptes altivelis*
- | *Epinephelus polyphkadion**
- | *Epinephelus fuscoguttatus*
- | *Epinephelus lanceolatus*
- | *Epinephelus itajara*
- | *Epinephelus malabaricus*
- | *Epinephelus coioides*
- | *Epinephelus tukula*
- | *Epinephelus latifasciatus**
- | *Epinephelus daemeli*
- | *Epinephelus bruneus*
- | *Epinephelus moara*
- | *Epinephelus macrospilos*
- | *Epinephelus trimaculatus*
- | *Epinephelus quoyanus*
- | *Epinephelus bontoides*
- | *Epinephelus faveatus*
- | *Epinephelus rivulatus**
- | *Epinephelus sp.*
- | *Epinephelus bleekeri*
- | *Epinephelus areolatus**
- | *Epinephelus chlorostigma*^o
- | *Epinephelus multinotatus*
- | *E. cyanopodus / E. flavocaeruleus*
- | *Epinephelus polylepis*
- | *Epinephelus chlorostigma*^o

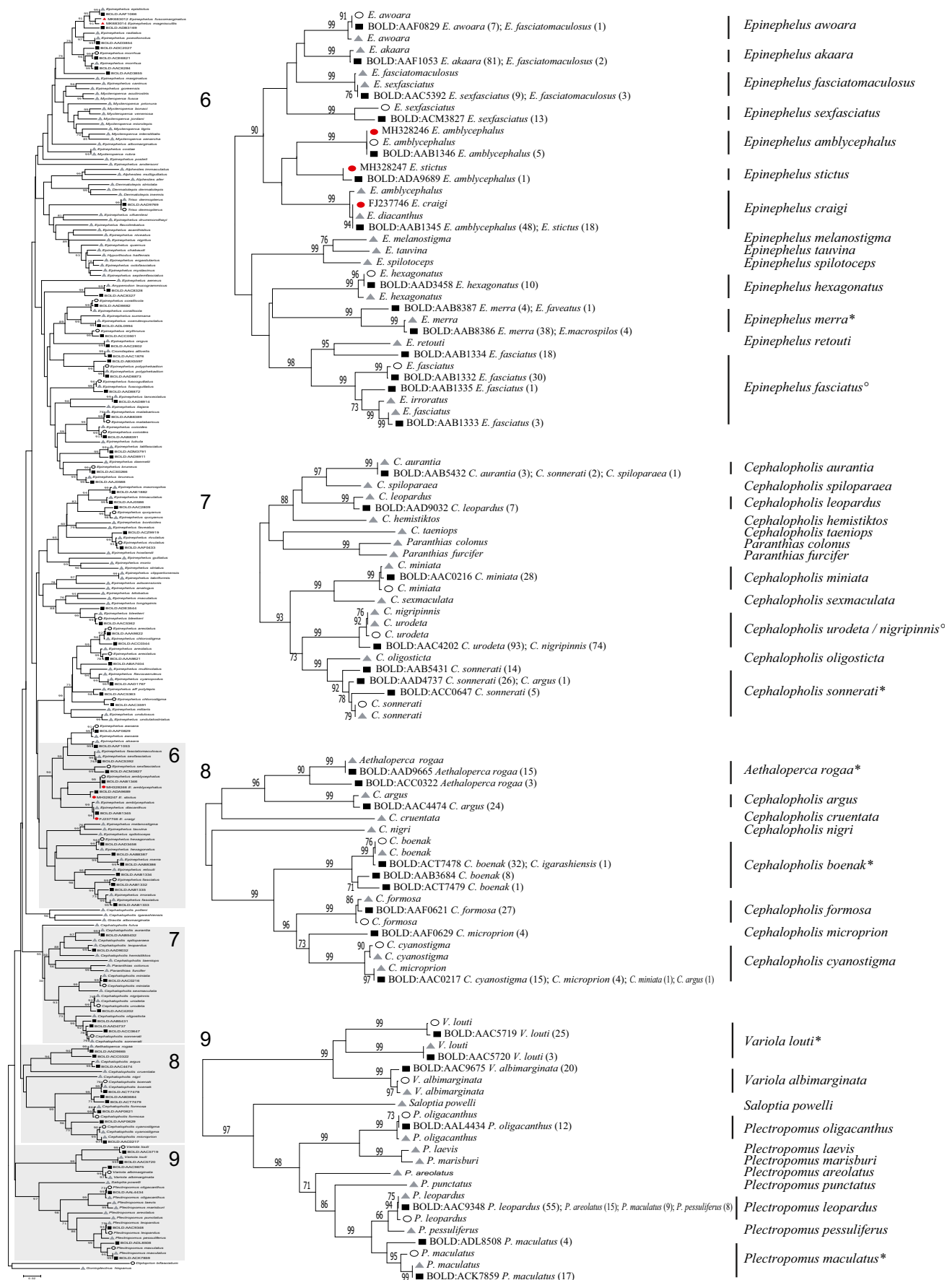


Fig. 3 (continued)

restricted to the Indian Ocean (Fig. 4b); *Cephalopholis boenak* with two BINs present in Western Australia whereas BOLD:AAB3684 was restricted to Australian shores (Fig. 4c); *Epinephelus areolatus* with two BINs present in Vietnam while BIN BOLD:AAA9822 was mainly observed in the Indian Ocean (Fig. 4f), and *E. merra* (Fig. 4k) with two BINs observed in Indonesia while their distribution range were allopatric outside this location and presented a clear separation between the Indian and the Pacific Oceans.

- Lastly, for some multi BIN species a phylogeographic structure was also observed within a BIN. This was the case for: *Plectropomus maculatus* (Fig. 4o) with the BIN BOLD:ACK7859 that showed two sets of haplotypes either distributed along the Australian shore or in the South East Asia, and *Variola louti* (Fig. 4p) with the BIN BOLD:AAC5719 that presented three subclades restricted to the Red Sea, the Andaman Islands and the Indian Ocean.

Discussion

Grouper diversity in Vietnam

To date, the species checklist for Vietnam consisted of 40 groupers and, while this study identified 30 species, up to nine are new records. As a result, up to 50% of known Vietnamese grouper diversity was not recovered in this study, despite sampling on a large spatial and temporal scale. Several species listed are, however, uncommon and can present a patchy geographical distribution or occurrence in Vietnam that is limited to some provinces. This is the case for *Anyperodon leucogrammicus*, *Cephalopholis leopardus*, *C. microprion*, *Epinephelus akaara*, *E. craigi*, *E. cyanopodus*, etc. Furthermore, the absence of some species may be a consequence of the intense fishing pressure on many groupers. In 1996, 43.5% of groupers were considered as threatened and two, *Cromileptes altivelis* and *Epinephelus akaara* as endangered, in the IUCN red list (Moriss et al. 2000). These two endangered species were not observed in the present study despite historical records in Vietnam. Consequently, our results suggest that more grouper species may be locally endangered but the absence, in Vietnam, of temporal series of fish biomass landing hampers our ability to monitor population dynamics and evaluate species status (Stocks et al. 2019). Life history traits of groupers, such as large body size, slow growth, long life-span, late reproduction, plus behaviors such as territoriality and spawning aggregations, make their survival uncertain and the chances of local population collapse high (Moriss et al. 2000; Sadovy de Mitcheson et al. 2012).

Beyond biological reasons that render groupers vulnerable to over-exploitation, pollution, and habitat destruction are also a major threat. Urbanization of coastal areas in Vietnam has degraded and even destroyed many aquatic habitats. Mangrove forests, known to be important nursery areas for marine fishes including groupers, declined dramatically from 4000 km² in 1950 to 1570 km² in 1994 (Son and Thuoc 2003), due to conversion for agriculture or pond aquaculture, and unsustainable use for timber (Hong 1993). Similarly, coral reefs that concentrate a high proportion of grouper species have decreased to 15–20% of their original surface due to pollution, siltation, and blast fishing (Lutaenko 2011). For all these reasons, it is likely that many groupers species in Vietnam have become rare, so explaining their absence in the present sampling.

Curiously, up to nine species are new records for Vietnam. This contrasts with the species rarefaction described above. These new records may also, however, be explained by exploitation. Vietnamese fisheries are primarily small-scale and inshore, but, due to the decline of many high-value inshore resources, many fishermen now focus on deeper waters (Thuoc 2001). As a consequence, some species that are not present inshore and thus were not targeted historically by the small scale fisheries, have become more visible on fish markets (Sadovy de Mitcheson et al. 2012). Among the nine new records up to six (*E. bruneus*, *P. maculatus*, *P. oligacanthus*, *T. dermatrus*, *V. albimarginatus* and *V. louti*) present a vertical distribution extending into deep water below above 100 m. None are, however, strictly restricted to deep waters, which limits this interpretation such that it cannot by itself explain why these species were not previously recorded. Nevertheless, in recent Vietnamese investigations, six of these species were observed (Le et al. 2011; Tran et al. 2015; Vo et al. 2016; Vo 2018) while *E. fuscoguttatus* is known to be reared in aquaculture at Quang Ninh based on larvae fished in the wild (Le 2004). Last, there are still two species: *E. polyphkadion* and *V. albimarginata* that remain new records for Vietnam whatever species checklist is considered and regardless of any aquaculture practices in Vietnam. The distribution range of some groupers are known to be very patchy, such as *E. polyphkadion*, such that they may be limited to small areas in Vietnam and have therefore not been recorded before. Concerning *V. albimarginata*, it is more difficult to explain why it was not recorded before because the species seems abundant in Vietnam (pers obs) and is difficult to misidentify with other groupers.

BIN diversity in Indo-Pacific groupers present in Vietnam

Specimens mislabelled in BOLD may have two origins: taxonomic confusion or hybridization. Grouper taxonomy is traditionally based on color patterns, morphological

distinctiveness, and osteological characters (Heemstra and Randall 1993) but, for some species, these criteria overlap from a species to another leading to confusion (Alcantara and Yambot 2016; Qu et al. 2018). Furthermore, recent taxonomical investigations describing new species confound with other species in previous DNA barcoding studies. This is the case for *E. craigi* recently described by Frabe et al. (2018) and previously confounded or still misidentified with *E. amblycephalus* and *E. stictus*. Similarly, despite the redescription of *E. moara* by Liu et al. (2013), this species is still ignored in BOLD and its BIN:BOLD:AAJ0588 is associated with *Epinephelus bruneus*.

In addition, hybridization within groupers can produce specimens with atypical body coloration, influencing our ability to recognize overall species. Several studies already identified grouper hybrids in the wild (Bostrom et al. 2002; Frisch and van Herwerden 2006; Randall and Justine 2008; Payet et al. 2016; Qu et al. 2018). Genetic characterization of a hybrid requires the comparison of its phylogenetic position estimated by a mitochondrial marker such as the COI (maternally inherited) against a nuclear marker (bi-parentally inherited), as proposed by Payet et al. (2016) or Qu et al. (2018). However, hybridization does not necessarily lead to conflicting phylogenies since an absence of interspecies differentiation by genetic markers can also be interpreted as a consequence of hybridization and introgression. This was already pointed out for two couples of species that share a unique BIN:BOLD:AAC4202 for *Cephalopholis urodeta* and *C. nigripinnis* and BOLD:AAD1767 for *E. cyanopodus* and *E. flavocaeruleus*. Despite clear differences of color pattern, these species share a unique BIN and are indistinguishable with nuclear markers (Payet et al. 2016; Qu et al. 2018). According to Payet et al. (2016), such absence of interspecies differentiation maybe due either to hybridization and introgression, taxonomical characters that are phylogenetically irrelevant, or incomplete lineage sorting. While Qu et al. (2018) suggested that *E. cyanopodus* and *E. flavocaeruleus* may be considered as a unique species, Payet et al. (2016) considered *Cephalopholis urodeta* and *C. nigripinnis* as real species that able to interbreed because these authors depicted various intermediate phenotypes between the two species where they occur in sympatry.

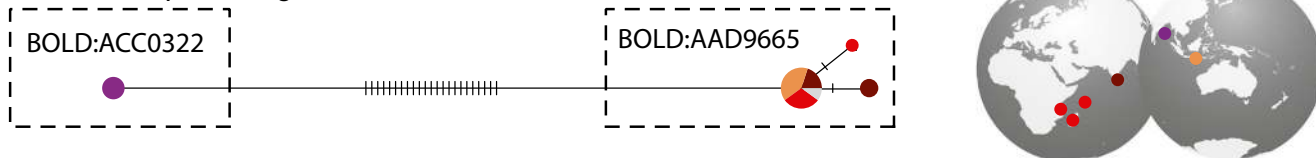
The question that arises for species that present two to four specific BINs is of their evolutionary significance. Among 15 species presenting this situation, only three, *E. chlorostigma*, *E. fasciatus*, and *E. epistictus* were associated with BINs that does not form monophyletic clade. Identification of *E. chlorostigma* seems confused in light of the phylogenetic tree based on sequences of various origin (Fig. 3). While the COI barcode of the specimen of Ma et al. (2013) corresponded to *E. areolatus* (for this study and for BOLD), among the BINs associated with *E. chlorostigma* in BOLD, none corresponded to the Vietnamese specimens that have been

Fig. 4 Haplotypic networks recovered in multi BIN grouper species for which BINs form a clade in Fig. 3. Dot color in the network represents the geographic origin of the haplotypes, while its size represents the abundance in BOLD. **a** *Aethaloperca rogoa*; **b** *Anyperodon leucogrammicus*; **c** *Cephalopholis boenak*; **d** *Cephalopholis sonnerati*; **e** *Epinephelus amblycephalus*, *Epinephelus stictus*, *Epinephelus craigi*; **f** *Epinephelus areolatus*; **g** *Epinephelus bruneus*, *Epinephelus moara*; **h** *Epinephelus epistictus*; **i** *Epinephelus fasciatus*; **j** *Epinephelus latifasciatus*; **k** *Epinephelus merra*; **l** *Epinephelus morrhua*; **m** *Epinephelus polyphkadion*; **n** *Epinephelus rivulatus*; **o** *Plectropomus maculatus*; **p** *Variola louti*

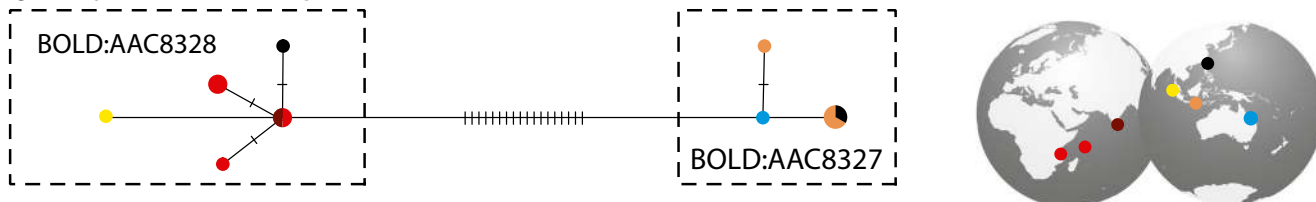
unambiguously identified as *E. chlorostigma*. By contrast, the BIN of the Vietnamese *E. chlorostigma* (BOLD:AAC3591) was associated in BOLD to seven specimens identified by the same institute as *E. spilotoceps* and collected in the South China Sea close to the Vietnamese sampling location. These specimens have been misidentified considering that (1) available pictures do not present the four blackish brown saddle-blotches at the base of the dorsal fin that are characteristic of *E. spilotoceps* (FAO), (2) the specimen identified by Ma et al. (2016) as *E. spilotoceps* belongs to a different phylogenetic lineage (Fig. 3), and (3) there is a BIN (BOLD:AAC3590) consisting of 17 members (including the specimen of Ma et al. 2016) that was unambiguously identified by BOLD as *E. spilotoceps*. Finally, there are two unrelated BINs (BOLD:AAC3591 and BOLD:ABA7404) associated to the name *E. chlorostigma* which suggest that there is a cryptic species in this taxon. Considering the type locality of *E. chlorostigma* (Seychelles), and BIN's geographic distributions which are based on only a few specimens, more work is needed to determine the BIN that corresponds to *E. chlorostigma*.

Concerning BINs recovered in specimens identified as *E. fasciatus*, they form a monophyletic clade that is paraphyletic with *E. retouti* and *E. irroratus* (Fig. 3). *E. irroratus* is endemic to the Marquesas Island and shares the BIN BOLD: AAB1333 with *E. fasciatus*, which is mainly observed in the SW and Central Pacific (Fig. 4i). By contrast, the Indo-Pacific *E. retouti* was associated with a BIN (BOLD:AAX8350) that did not correspond to any BINs identified in *E. fasciatus* but was closely phylogenetically related to the *E. fasciatus* BIN (BOLD: AAB1334). This last BIN (BOLD:AAB1334) diverged deeply from all other *E. fasciatus* BINs (Fig. 3) and presented a strong allopatric distribution limited to the Red Sea and the West Indian Ocean (Fig. 4i). All these results stress the presence of a species complex in *E. fasciatus* and, because the type locality of this species is the Red Sea, this suggests that the valid *E. fasciatus* should be limited to the Red Sea and the West Indian Ocean (= the BIN BOLD:AAB1334). All other BINs associated with the name *E. fasciatus* may correspond to another species for which phylogenetic relationships with *E. irroratus* is not clear. More taxonomic and phylogenetic work is necessary to solve

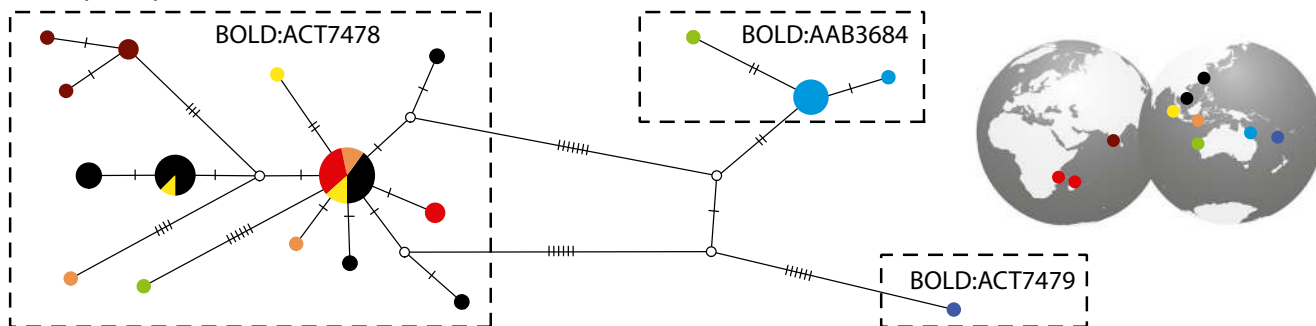
a *Aethaloperca rogae*



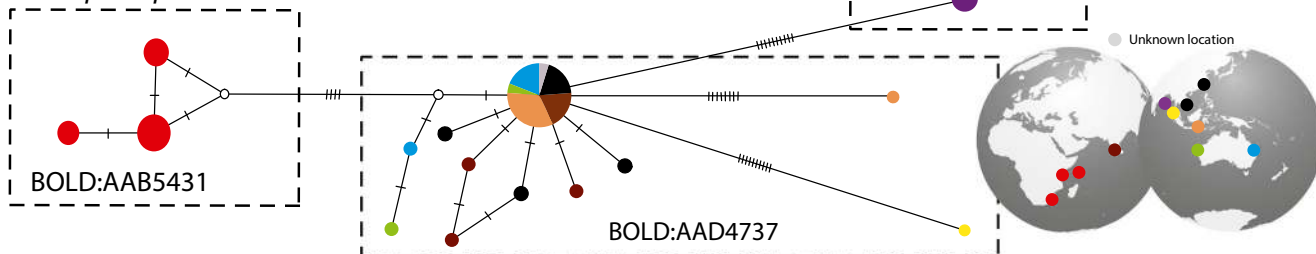
b *Anyperodon leucogrammicus*



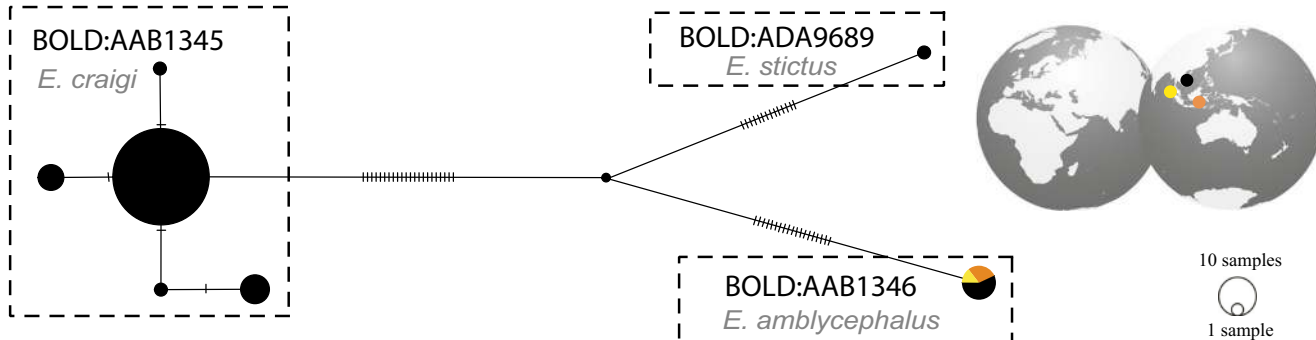
c *Cephalopholis boenak*



d *Cephalopholis sonnerati*



e *Epinephelus amblycephalus* / *E. craigi* / *E. stictus*



10 samples

 1 sample

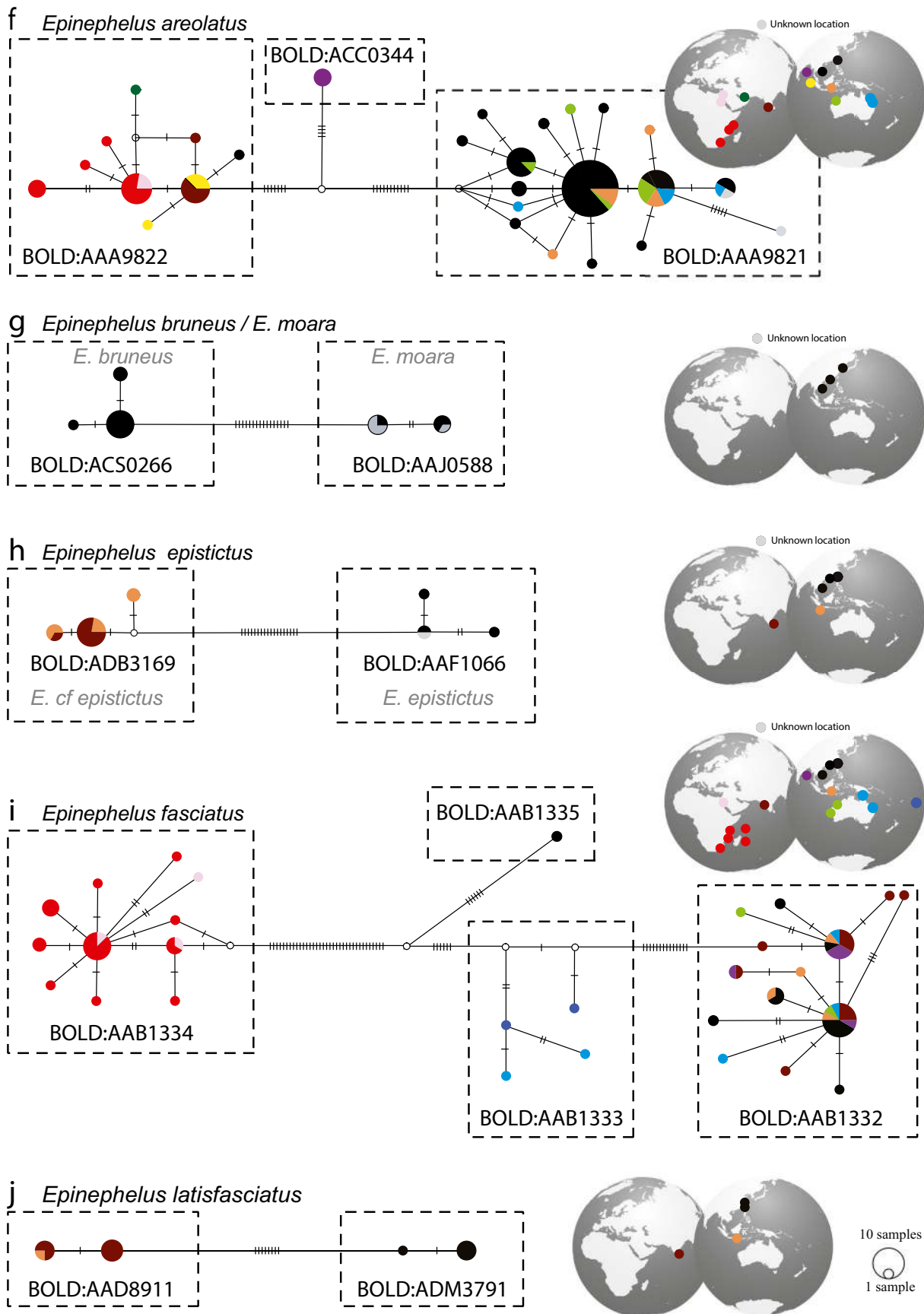


Fig. 4 (continued)

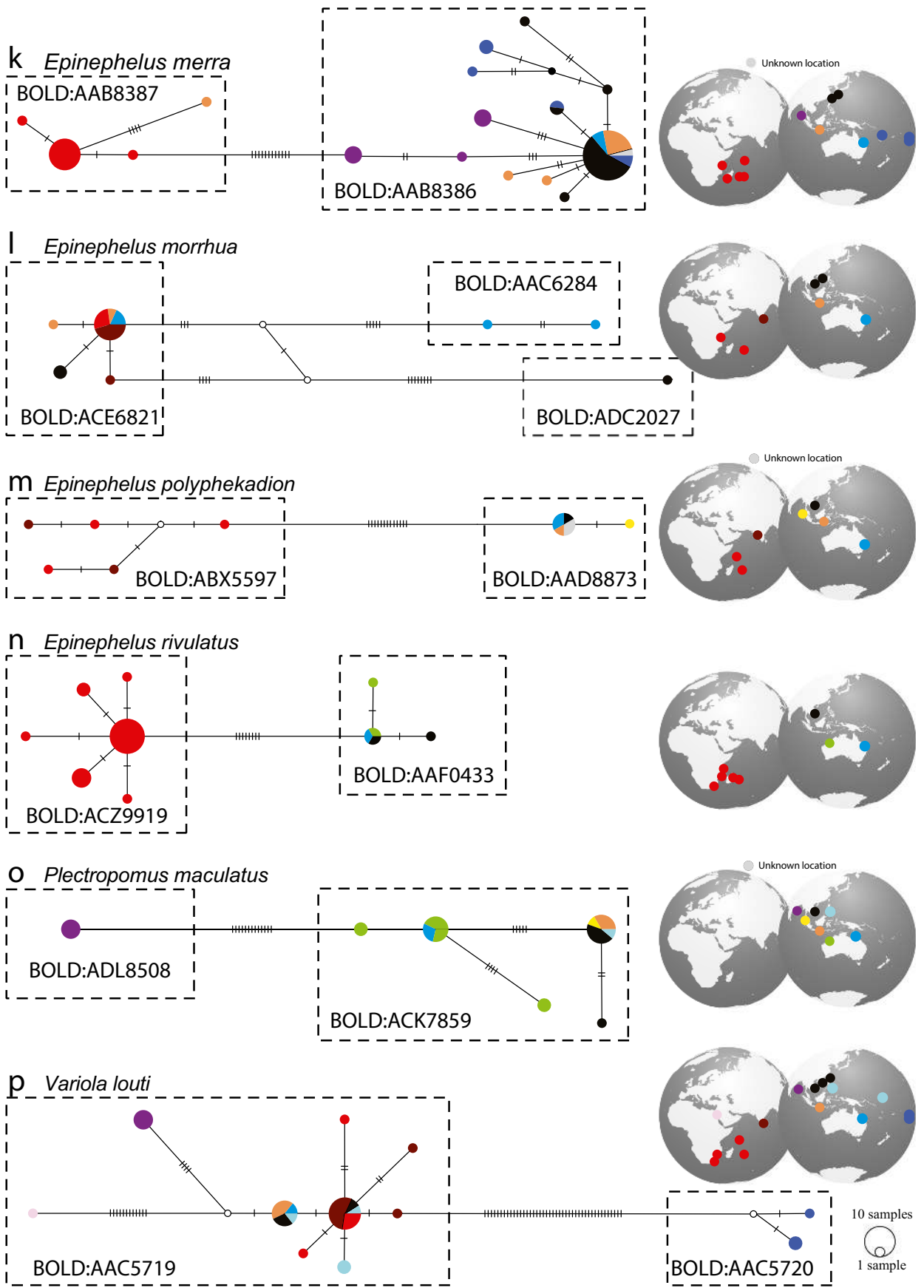


Fig. 4 (continued)

this question, given that genetic data concerning *E. retouti* is limited to only 7 COI barcodes.

Last, the two BINs (BOLD:AAF1066 and BOLD:ADB3169) associated with specimens identified as *E. epistictus* form a well-supported clade that also included the recent described species *E. fuscomarginatus* and its sister species *E. magniscuttis* (Fig. 3). This result confirmed findings of Johnson and Worthington Wilmer (2019) who demonstrated that *E. epistictus* is a species complex composed of at least 4 species. Because the type locality is Nagasaki, Japan, it is probable that the BIN BOLD:AAF1066 observed in specimens collected in the NW Pacific (Taiwan and China) corresponds to *E. epistictus*, but see Johnson and Worthington Wilmer (2019) for a more detailed and complete analysis.

For all other polyphyletic species or multi-BIN species, the present study demonstrated that their BINs form well supported clades in the majority of cases (Fig. 3). This result may be interpreted in three ways: BINs of a species correspond to (1) undescribed or cryptic sister species; (2) intraspecific biogeographic lineages, or (3) artifacts due to bad nucleotide scoring in the sequencing file (ab1 file) generated by the sequencing apparatus. This last situation cannot be excluded when a BIN is observed at only one location and thus consists of few members analyzed by only one institute. Up to seven BINs correspond to this situation and, curiously, 4 of them were described only in the Andaman Islands, such as BOLD:ACC0322 (*Aethaloperca rogaea*), BOLD:ACC0647 (*Cephalopholis sonnerati*), BOLD:ACC0344 (*Epinephelus areolatus*), and BOLD:ADL8508 (*Plectropomus maculatus*). Given that it is rare in groupers that a BIN is restricted to only one location and unless there is a hotspot of diversity in the Andaman Islands, such results remain doubtful and call for further investigation.

Now, when polyphyletic species are composed of BINs with members from different geographic origin that do not match any geographic pattern, it is probable that these BINs flag sister species. This is the case for BINs highly associated with the name *E. amblycephalus* and that correspond to three sister species: *E. amblycephalus*, *E. stictus*, and the recently described species *E. craigi* (Figs. 3 and 4e). This is also true for the two BINs associated with the species name *E. bruneus*, since one of these corresponds to the COI sequence of the species *E. moara* that is still not recognized as valid in Eschmeyer's Catalog of Fishes (Fricke et al. 2019), despite arguments provided by Liu et al. (2013).

Lastly, in all remaining multi-BIN species, a phylogeographic structure has been revealed, with BIN geographic distributions that match biogeographic units. This suggests that the presence of more than one BIN in a species mirrors a complex evolutionary history. Several studies have already stressed phylogeographic structures in groupers such as *Cephalopholis argus*, *Epinephelus areolatus*, *E. polyphkadion*, *E. merra*, *Plectropomus areolatus*, and

P. leopardus (Gaither et al. 2011; DiBattista et al. 2013; Borsa et al. 2016; Ma et al. 2018). If we exclude *Plectropomus areolatus* that was not reviewed in this study due its absence in Vietnam, three of five of these species are multi BIN species. Most of these studies interpret the genetic structure of these species as a result of paleogeographic changes that directly impact the phylogeographic structure of groupers (Gaither et al. 2011; DiBattista et al. 2013; Borsa et al. 2016). A number of important biogeographic barriers in the Indo-Pacific have shaped the present-day genetic structure, such as the mid Indian Barrier or the Indo/Pacific Ocean divide. But Ma et al. (2018) also noticed that reproductive behavior is an important factor that can modulate the strength of a biogeographic barrier by either limiting or increasing population connectivity. According to Ma et al. (2018) discrete reproduction in small groups of *Plectropomus leopardus* individuals may have favored a stronger genetic structure of Pleistocene origin in the West Indo-Pacific than *Plectropomus areolatus* and *Epinephelus polyphkadion*, which breed in large numbers on a few spawning grounds. Secondary contact and genetic connectivity may be stronger for species presenting such behavior, explaining why some genetic breaks in the West Indian Pacific are not observed.

To conclude, the association of several BINs to a species cannot be interpreted straightforwardly. If, in a number of cases, misidentification and hybridization artificially increase the apparent genetic diversity of a species, the presence of several BINs can also flag putative cryptic species or a strong phylogeographic structure. More barcoding studies focusing on fish families are needed to clarify the association between a species and BINs and, thereby, improve the validity and reliability of the species identification engine provided by BOLD. In any case, beyond species identification, once clarified for multi-BIN species, it would certainly be possible to use the BINs not only to identify a specimen but also to track its biogeographic origin.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed by the authors.

Sampling and field studies All necessary permits for sampling and observational field studies have been obtained by the authors from the competent authorities and are mentioned in the acknowledgements, if applicable.

Data availability All data generated or analyzed during this study are included in this published article [and its supplementary information files]. DNA barcodes generated during the current study are available in the project file SERV: Epinephelidae of Vietnam on BOLD systems website (<http://boldsystems.org>).

Author contribution JDD conceived and designed research. JDD, MHP, TTVY, DHH, and QVV conducted experiments. JDD analyzed data and wrote the manuscript. All authors read and approved the manuscript.

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