Multiple population structure of the giant eel Anguilla marmorata in Thua Thien Hue, Vietnam base on COI sequences

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Abstract

The giant mottled eel Anguilla marmorata is a species of great economic, ecological, and conservation values in the Southeast Asian region. The research aims to conservation and evaluation of the genetic diversity of A. marmorata populations living in Thua Thien Hue (TTH), Vietnam. The sequencing of the barcode region of the cytochrome c oxidase subunit 1 gene was carried out for 48 individuals of A. marmorata elvers, which were collected from five different ecosystem regions. The sequences were analyzed using various genetic, phylogenetic, and population analyses to assess their variability. A total of 20 polymorphic sites and 17 haplotypes were identified. Extremely low fixation (Fst = -0.073 – 0.003, < 0.05) was found for A. marmorata populations in the region. The populations showed signs of recent populations’ expansion, besides negative Tajima’s D test, Fu’s Fs, Fu and Li’s D* and F* test values. The genetic evolution of eel occurs in a randomized pattern over a large population, with the likelihood of rare alleles appearing in the population. In TTH (Viet Nam) territories, we indicated the five areas for conservation units with moderate eels’ populations’ diversity.

Introduction

In Viet Nam, there were 5 out of 19 species belong to the genus Anguilla (Watanabe et al. 2004; 2005). A. marmorata (Quoy & Gaimard, 1824) was identified to appear in the central high economic value (Huyen and Linh 2019). The species has a catadromous life-history strategy with distances from several hundred to thousands of kilometers when they were white grass eels from North ocean to South East Asian sea (Linh et al. 2010). During migration between oceans and freshwater during special stages of the life cycle, strong environmental changes have shaped not only their physiological characteristics (Wang et al. 2014) but also the genetic structure of eels (El-Nabi et al. 2017). Besides, upheaval conditions of river management, water containment, overfishing, and pollution may have influenced the movement of upstream eels (Wasserman et al. 2011) and downstream (Huyen and Phu 2015) led to the increase of population decline risk, on way back to oceans with mature and reproduction (Linh et al. 2010). Although in the world A. marmorata is ranked at LC level (least concern) (Pike et al. 2019), but it has been listed in the Viet Nam Red Data Book as VU (Vulnerable) lever since 2007 in Vietnam (Ministry of Science Technology and Environment 2007).

DNA barcoding provides an efficient method for species-level identifications (Hubert et al. 2008), to leading to the ecology and evolution of natural system was mentioned by (Kress et al. 2015), based on short, standardized gene regions. For animals, markers located on the mitochondrial genome, such as cytochrom b (cytb) gene, cytochrom c oxyase 1 (COI) gene, and D-loop region... often have been recommended using by scientists (Kress et al. 2015). In which, a short DNA sequence in the mitochondrial gene encoding COI with 600 base pairs (bp) has been accepted as a practical, standardized, species-level DNA barcode for animals (Kress et al. 2015). To assess the genetic diversity of the A. marmorata population has distributed in TTH, Vietnam regarding the distribution environment and examining the evolution and development of populations, identifying conservation units for A. marmorata in TTHue, we designed this study basing on the amplification and sequencing of polymerase chain reaction (PCR) for the COI subunit of A. marmorata collected in 5 different ecological regions.

Materials And Methods

Ethics statement

All animal protocols were approved by the Committee on the Ethics of Animal Experiments of Hue University, Vietnam (permit No. DHU2019-02-113), and were performed strictly with the Guide for fishing capture and animals of Institute of Biotechnology. Animals were fishing capture by fishermen and allowed the Provincial Department of Fisheries.

Collection of specimens

Wild adult specimens of A. marmorata were collected from 5 localities in TTH, Viet Nam, including Phong Dien (PD), Thao Long dam (DTL), Truoi dam (DTR), Nam Dong (ND), Bu Lu and Lang Co (PL) from October 2017 to October 2018 (Fig. 1). A. marmorata species were identified using the keys developed by Watanabe et al. (2004). Tissues from the adductor muscle were dissected from fresh specimens, preserved in 95% ethanol, and frozen at -80 °C until DNA extraction.

Genomic DNA isolation and amplification

Total genomic DNA was extracted by a description of (Kumar et al. 2007) with a modification for A. marmorata. The primer used to amplify the COI gene segment was designed based on the nucleotide sequence of the two gene bank codes: A. marmorata · AP007242.1 and A. marmorata · HQ141374.1. The nucleotide sequences of the primers are A. marFw-1: 5’-GACTAAGCTTACATCCG-3’ and A. marRv-1: 5’-GATGATATATGTGCGAGAAG-3’ (Huyen and Linh 2020). The PCR amplifications were performed in 35 μL reaction volumes: 1 μL DNA, 1 μL F-primer (10 mM), 1 μL R-primer (10 mM), 7 μL PCR buffer (10X), 0.5 μL dNTP (10 mM), 0.2 μL Enzyme Taq (5 U/ μL) and sterile distilled water addition to full volume 35 μL. PCR amplification was performed on the machine (MJ-Mini™ Persanol Thermal Cycle, Bio-Rad) according to the following thermal cycling: 95 °C/5 minutes; followed by 30 cycles: 95 °C / 45 seconds, 51 °C / 30 seconds, and 72 °C / 1 minute; The last is 72°C / 7 minutes. PCR product quality was checked by running electrophoresis on 1% agarose gel with buffers used as TAE 1X (Tris - acetate 40 mM + EDTA 1 mM) and stained with ethidium bromide fluorescent dye (EtBr 0, 5 µg / L) while washing the gel with distilled water for 10 minutes. The gel is observed by the Gel Documentation image analysis system.

Sequence alignment and molecular phylogenetic analysis

For all sequence analyses, COI genetic similarities were evaluated using the Basic Local Alignment Search Tool (BLAST) (http://www.ncbi.nlm.nih.gov/BLAST) to identify A. marmorata sequences. The raw DNA sequences were edited using BioEdit (Hall 1999) and the pairwise, as
well as multiple alignments of sequences, which was performed using ClustalW (Larkin et al. 2007) alignment editor. Multiple sequence alignment was also checked manually, and the consensus sequences were obtained. Molecular phylogenetic analyses were performed in MEGA X software (Kumar et al. 2018). Sequence data were subsequently analyzed for Neighbor Joining methods with bootstraps of 1000 replicates (Felsenstein 1985). Nucleotide composition analysis was carried out using BioEdit. Transition and transversions were equally weighted. The final consensus sequences were submitted to the National Center for Biotechnology Information (NCBI) database with accession number - MN067923 to MN067970. Standard genetic diversity indices, such as the number of haplotypes, polymorphic sites (S), haplotype numbers (h), haplotype diversity (Hd), nucleotide diversity (π), population mutation rates based on the number of segregation sites (θω) and mean the number of pairwise differences (θπ) was calculated with DnaSP 5.0 (Librado and Rozas 2009). Statistical analysis to distinguish DNA sequences evolving randomly (neutrality) with those evolving under a non-random process was done using Tajima's D (Tajima 1989); Fu's Fs tests; Fu & Li's Fs test and Fu & Li's D test (Tamura and Nei 1993). The Network version 5.0 software was implemented to estimate phylogenetic relationships among the unique haplotypes. Genetic differentiation, genetic distance, and migration rate among the populations were estimated by calculating the F statistic (Fst) between the populations and testing their significance with 1000 permutations.

Results

Genetic variation

Sequences of the 843 bp COI gene were determined in 48 specimens, 20 polymorphic sites, and 17 haplotypes were detected. 12 haplotypes were found in only one population, 2 (H1 and H9) were found equally between two populations, only 1 (H7) was found in three populations, and 2 (H4 and H5) were found in all five populations (Table 1 and Fig. 2). Haplotype positions were showed in Table 1.
| Haplotype | GenBank accession number | Nucleotide position beginning from 5' end |
|-----------|-------------------------|------------------------------------------|
| H1        | MN067923, MN067925, MN067938 | A C C T T C T G A A G T A T A C C A A |
| H2        | MN067924 | * * * * T C * * * A * * * * * * * |
| H3        | MN067926 | * * * * * C * A * A * * C * T * * * |
| H4        | MN067927, MN067928, MN067929, MN067932, MN067934, MN067937, MN067939, MN067943, MN067946, MN067947, MN067958, MN067959, MN067960, MN067963, MN067964, MN067966, MN067967, MN067970 | * * * * * C * * * * * * * * * * * * * |
| H5        | MN067931, MN067935, MN067940, MN067942, MN067950, MN067954, MN067962, MN067965 | * * * * * C * * * * G * * * * |
| H6        | MN067933 | * * * C C * * * * * G * * * * |
| H7        | MN067936, MN067945, MN067957 | * * * * * C * * A * * * * * * * |
| H8        | MN067941 | * * T * * * C A * * * * * * * * * * |
| H9        | MN067944, MN067969 | * * * * * C * * G * * * * * * * * |
| H10       | MN067948 | C * * * * * * G * * * * |
| H11       | MN067949 | * * * * * C * * * * G G * G * G * |
| H12       | MN067951 | C * * * * * C * * * * * * * * * * |
| H13       | MN067952 | C * * * * * C * * A * * * * * * * * |
| H14       | MN067953 | C T T * * * C A * * * * * * * * * * |
| H15       | MN067955 | * * * * * C * * * * * G * * * * |
| H16       | MN067961 | * * C C * * * * * * T * |
| H17       | MN067968 | * * * * * C * * * * * * * * * * |

Table 1: Variable position of 17 haplotypes of COI of A. marmorata in Thua Thien Hue, Vietnam
Haplotype diversity (h) and nucleotide diversity (π) based on COI genes for the 5 values are listed in Table 2. Haplotype diversity (h) and nucleotide diversity (π) values for the whole population in TTHue are 0.801 and 0.00196, respectively. Haplotype diversity of 5 populations in different eco-regions ranges from 0.7556 to 0.9000. In particular, the DTR population has the highest haplotype diversity value. The lowest belongs to DTL and PL. Nucleotide diversity values in these populations ranged from 0.00161 to 0.00242 with the highest in the PD population.

Concerning demographic estimators, methods of Tajima's D test, Fu's Fs, Fu, and Li's D* and F* test were used to test population neutrality (Tajima 1989), (Tamura and Nei 1993). The results in Table 2 show that all exposed exhibited significant negative values for all neutrality tests with p < 0.05. These indicators support standing 'expansion in these areas. The population of eel in TTH, evolved by a random selection expanded population, and rare alleles appear in the population with high frequency. Also, the value of Fu and Li's D* = -2.03402 (p < 0.05) indicated that in the study population, many individuals were showing a big difference compared to other individuals in the population. Besides, when considering the values of Tajima's D test, Fu's Fs, Fu and Li's D* and F* test in 5 individual populations according to the sampling area, the trend was similar but the value p > 0.05 except for Fu's Fs results for the COI gene in the PL. This shows that the difference in the individual eel is only significant when selected with large populations (14 individuals or more).

**Table 2.** Neutrality test results for COI data obtained for *A. marmorata* in TTH, Viet Nam

| Population | DTL | DTR | ND  | PD  | PL  | TTHue |
|------------|-----|-----|-----|-----|-----|-------|
| No. of sample | 10 | 5 | 9 | 14 | 10 | 48 |
| H | 5 | 4 | 6 | 9 | 5 | 17 (35.42%) |
| S | 7 | 4 | 6 | 9 | 6 | 20 |
| H<sub>d</sub> | 0.7556 ± 0.0168 | 0.9 ± 0.0259 | 0.88889 ± 0.00828 | 0.87912 ± 0.00621 | 0.75556 ± 0.01678 | 0.801 ± 0.00267 |
| Π | 0.00185 | 0.00190 | 0.00178 | 0.00242 | 0.00161 | 0.00196 |
| θ<sub>i</sub> | 2.47 | 1.92 | 2.21 | 2.83 | 2.12 | 4.51 |
| θ<sub>W</sub> | 1.56 | 1.60 | 1.50 | 2.04 | 1.36 | 1.65 |
| Tajima's D | -1.573* | -1.0938 | -1.3984 | -1.06599 | -1.4929 | -2.03402* |
| Fu's Fs | -1.181* | -1.405* | -2.978* | -4.742* | -1.507 | -12.228192* |
| Fu and Li's Fs | -1.818 | -1.0938 | -1.5509 | -1.07521 | -1.6893 | -2.93225* |
| Fu and Li's D | -1.634 | -1.0938 | -1.3904 | -0.8946 | -1.51 | -2.70391* |

**Abbreviations:** h haplotype numbers, S number of segregation sites, H<sub>d</sub> haplotype diversity, π nucleotide diversity, θ<sub>i</sub> Watterson's theta based on S, θ<sub>W</sub> theta based on π. *P < 0.05

**Population genetic structure**

Significant F<sub>ST</sub> values were observed in all pairwise comparisons between populations for the COI gene (p < 0.001; Table 3). Pairwise F<sub>ST</sub> values ranged from -0.073 to 0.048, indicating weak genetic differentiation between populations (F<sub>ST</sub> < 0.05). The biggest difference occurred in two populations DTL and PD (F<sub>ST</sub> = 0.04558), while Pairwise Nm value ranged from −0.01961 to 0.011456 (< 1) indicating extremely low gene flow among the populations.

**Table 3.** F<sub>ST</sub> value and gene flow among 5 populations of *A. marmorata* in Thua Thien Hue, Viet Nam

| Population | DTL | DTR | ND  | PD  | PL  |
|------------|-----|-----|-----|-----|-----|
| DTL | -- | 0.012 | -0.012 | -0.011 | 0.001 |
| DTR | -0.038* | -- | 0.003 | -0.012 | 0.011 |
| ND | -0.042* | -0.073* | -- | -0.020 | -0.011 |
| PD | 0.046* | -0.045* | 0.012* | -- | -0.010 |
| PL | 0.003* | -0.041* | -0.045* | 0.048* | -- |

Data allow the diagonal is F<sub>ST</sub>; Nm values are data above the diagonal.

* indicates the significance level of F<sub>ST</sub> value at p < 0.001.
Haplotype network analysis

The median-joining network (Figure 2) illustrates the polymorphic sites, including the number and frequency of the haplotypes for COI sequences. The COI network was radial-like with a high number of unique haplotypes closely related to 1 central haplotype (H4). Dominant haplotype H4 accounted for 27.87% (20/48) of all 48 specimens. This also indicated that H4 is an ancestral haplotype. H5 also showed the presence of all sub-populations in the study area with little correlation with other haplotypes, which indicated the specificity of it. The haplotypes tended to be dispersed in comparison to the central haplotype, revealing a tendency to generate discrepancies among independent individuals. The giant mottled eel A. marmorata populations in TTH are strongly correlated with each other, and there seems no separation of an individual population.

The evolutionary history was inferred using the Unweighted pair group method with arithmetic mean (UPGMA) (Sneath and Sokal 1973) in figure 3 with 1000 replicates of the bootstrap test (Felsenstein 1985). The sum of the branch length is 0.07028378. The tree is drawn to scale, with branch lengths in the same units as those of the evolutionary distances used to infer the phylogenetic tree. The evolutionary distances were computed using the Nei-Gojobori method (Nei and Gojobori 1986) in MEGA X (Kumar et al. 2018). The UPGMA tree showed that most of the haplotypes were weakly associated (less than 50% bootstrap support) or unresolved, the differences among which were possibly due to low nucleotide. Haplotypes of COI of A. marmorata in TT Hue were clustered into 2 obvious branches. H8 and H14 stand in the same independent branches with the remaining 14 haplotypes with bootstrap support of 56%. H5 and H15 together with H12 and H13 were grouped into 2 subgroups in branch 2 with the highest correlation (bootstrap> 60%). H4, H7, and H17 also form a group but have an extremely low bootstrap support rate of only 17%. The remaining haplotypes have a discrete distribution in the branch.

Discussion

A. marmorata with long life and long migration distance can have a strong population genetic structure. Genetic diversity within and between populations provides a potential genetic resource for future adaptation and can be vital for the fitness of a population (Xu et al. 2012). It is mainly explained by several historical and contemporary processes, such as genetic drift, effective migration, natural selection, fragmentation, and range expansion (Slatkin 1985). Earlier works have analyzed eel population genetics-based mainly on allozymes (Pantelouris et al. 1970, 1971) and demonstrated genetic differentiation between geographical locations. The genetic structure of A. marmorata was later re-assessed based on the region of the Cyt b, mitochondrial (mt) DNA, mitochondria control region (mtCR), COI and 16S rRNA genes. In which, COI gene barcode region exhibited a credible population-based diversity that exceeded that obtained with sequencing the mitochondrial Cytb gene, showing a percentage of haplotypes from the total sequences equaling 45% for COI, versus 15% for Cytb (El-Nabi et al. 2017). For the first time in Viet Nam, we could identify the level of genetic diversity of A. marmorata based on COI/basal.

Results of the COI gene in the region showed high levels of haplotype diversity (h = 0.7556–0.9000) and low levels of nucleotide diversity (π = 0.00161–0.00242). 17 haplotypes were identified in the 48 samples analyzed (35.42%). It is a similar trend with some other researchers on Anguilla species. For example, in A. marmorata, Fahmi et al. (2015) were found 44 haplotypes, h = 0.937 ± 0.013 and π = 0.861 ± 0.002 (%) in Indonesia based on analyzed the Cyt b gene (Fahmi et al. 2015) and 14 haplotypes, nucleotide diversity (π = 0.002) and haplotype diversity (h = 0.780) from mtCR sequences in Pohnpei and Kosrae (Donovan et al. 2012). And in other species, 129 haplotypes were identified with h = 0.92 –1.00 and π = 0.13–1.06% for 6 other species of tropical eels (A. inferior, A. nebulosi nebulosi, A. bicolor pacific, A. bicolor bicolor, A. celebesensis, A. borneensis) in Indonesia determined by Famil et al. (2015); And 44 segregating nucleotide sites, 33 haplotypes, haplotype diversity (h = 0.94), and nucleotide diversity (π = 0.008) were found when analyzed the COI of A. anguilla with 525 nucleotides in length by El-Nabi et al. (2017) base on DNA barcode technique.

Researchers often use Fst to assess gene flow, a higher Fst value indicates a lower level of gene flow (Nm) and higher genetic differentiation among populations (Hedrick 2005). Fst reflects the level of inbreeding within populations (Wright 1984) or the extent to which populations are differentiated (Hartl and Clark 2007). The presence of genetic structure is an outcome of limited gene flow and a high level of genetic drift within each reproductively isolated group. Fst values below 0.05 indicate negligible genetic differentiation, whereas values greater than 0.25 indicate high genetic differentiation within the analyzed population (Weir 1996). Fst values of A. marmorata in TT Hue, Viet Nam were significant but weak (Fst = -0.073–0.003; p< 0.05) and high Nm values were detected among the populations. This may be because primitive and highly conservative of the COI gene in the region showed high levels of haplotype diversity (h = 0.7556–0.9000) and low levels of nucleotide diversity (π = 0.00161–0.00242). 17 haplotypes were identified in the 48 samples analyzed (35.42%). A. marmorata was later re-assessed based on the region of the Cyt b, mitochondrial (mt) DNA, mitochondria control region (mtCR), COI and 16S rRNA genes. In which, COI gene barcode region exhibited a credible population-based diversity that exceeded that obtained with sequencing the mitochondrial Cytb gene, showing a percentage of haplotypes from the total sequences equaling 45% for COI, versus 15% for Cytb (El-Nabi et al. 2017). For the first time in Viet Nam, we could identify the level of genetic diversity of A. marmorata based on COI/basal.

Results of Fst analyses using UPGMA for all haplotypes show 2 similar branches one branch contains two types of haplotypes (COI) from two populations ND and PD and the other branch contains most of haplotypes from the remaining 5 populations. The ramification of the haplotypes has a low Bootstraps support value. This can be explained by several reasons. The first, Anguillid has a catadromous life-history strategy, spawning in remote tropical seas with larvae that are transported back by currents to their nursery grounds in freshwater or coastal areas (Arai 2016). Intense migration and long-lived habitats in the inland ecosystems, about six to 20 years or more in golden eel stage (Williamson and Boëtius 1993), have driven the formation of haplotypes independently of individual species. Secondly, A. marmorata, a catadromous eel, migrates upstream on nights, following the lunar cycle (Huyen et al. 2012). The dramatic changes of environmental between ocean and freshwater during migration shape their physiological features, e.g. visual sensitivity, olfactory ability, and salinity tolerance (Wang et al. 2014). This can also be proposed as a cause of the occurrence of rare genes and single haplotypes. This induces then isolation by time (IBT) of spawning groups. IBT causes a restriction in gene flow, taking place between early and late spawners (Hendry and Day 2005). And the last, based on analyzed three different phylogenetic trees of A. marmorata population in Thua Thien Hue, Vietnam, Huyen and Linh (2020) showed that there was the high genetic similarity of
individuals in eel populations in Thua Thien Hue and it was divided into two separate groups that are guided by the migration process and specific ecological (Huyen and Linh 2020).

**Declarations**

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**Authors' contributions**

Both authors discussed and designed the experiments. Kieu Thi Huyen conducted the main experiments and data analysis. All authors wrote, read, and approved the final manuscript.

**Availability of data and materials**

The datasets of COI sequences analyzed during the current study are available on the GenBank with accession number from MN067923 to MN067970. The data were simultaneously made available to ENA in Europe and the DNA Data Bank of Japan.

**Code availability** (software application or custom code)

Not applicable

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**Ethics approval and consent to participate**

All animals and samples applied to international, national, and regional and Institutional guidelines for animal care and rules in Vietnam.

**Consent for publication**

Not applicable

**Competing interests**

The authors report no conflict of interest.

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**Figures**

![Sample sites map of A. marmorata populations in TTH, Vietnam](image)

Figure 1

Illustrating sample sites map of *A. marmorata* populations in TTH, Vietnam
Figure 2
Median-joining network for COI haplotypes of A. marmorata in TTH, Viet Nam. On the connecting lines, red numbers present the variable sites between each haplotype pair. Different colors represent the different populations in the network (Yellor, Green, Blue, and Pink colors represented for DTL - Thao Long Dam, DTR - Truoi Dam, ND - Nam Dong and PD - Phong Dien respectively. PL - Phu Loc was indicated by red color).

Figure 3
The phylogenetic relationship of A. marmorata among the haplotypes was determined using COI. Figures before population codes, which are behind the haplotypes, indicate that the number of individuals from the population belongs to the haplotype. The scale bar is branch lengths in the same units as those of the evolutionary distances used to infer the phylogenetic tree.