Mapping endemic freshwater fish richness to identify high priority areas for conservation: an ecoregion approach

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Research Article

Keywords: Freshwater ecosystem, freshwater fish, richness mapping, conservation, Iran

Posted Date: January 19th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2495842/v1

Abstract

Freshwater ecosystems are among the most threatened ecosystems. Thus, knowing where these unique ecosystems' species richness reaches a peak can facilitate their conservation planning. By hosting 289 freshwater fishes, Iran is a major freshwater fish hotspot in the Middle East. Considering the accelerating rate of biodiversity loss, there is an urgent need to identify species rich areas and understanding of the mechanisms driving biodiversity distribution. In this study, we gathered distribution records of all endemic freshwater fishes of Iran (85 species) to develop their richness map and determine the most critical driver of their richness pattern with an ecoregion approach. We performed a generalized linear model (GLM) with quasi-Poisson distribution to identify contemporary and historical determinants of endemic freshwater fish richness. We also quantified endemic fish similarity among the 15 freshwater ecoregions of Iran. Results showed that endemic freshwater fish richness is highest in the Zagros Mountains and moderate level of richness was observed between Zagros and Alborz Mountains. High, moderate and low richness of endemic freshwater fish match with Upper Tigris & Euphrates, Namak, and Kavir & Lut Deserts ecoregions respectively. Precipitation and precipitation change velocity since the Last Glacial Maximum were the most important predictor of freshwater fish richness. Areas identified to have the highest species richness have high priority for the conservation of freshwater fish in Iran, therefore, should be considered in future protected areas development.

Introduction

Freshwater ecosystems (rivers, lakes and wetlands) support one-third of global vertebrates despite covering 1% of the Earth's surface (Gleick 1998; Balian et al. 2008; Strayer and Dudgeon 2010). They provide essential ecosystem services and benefits like drinking water, recreation and tourism, water for agriculture and energy, habitat for threatened species and climate regulation (Chopra 2005; Sun et al. 2017; Hanna et al. 2018; Kaval 2019; Vári et al. 2022). But climate change, land use change, habitat destruction, dam building, pollutions and invasive species are causing significant negative impacts on freshwater ecosystems worldwide (Chopra 2005; Dudgeon et al. 2006; Strayer and Dudgeon 2010; Boyero et al. 2012; Collen et al. 2014; Arthington et al. 2016; Cianfrani et al. 2018; WWF 2020). A key concern of conservation biology is to conserve freshwater ecosystems since they face multiple threats and remained among the least known and most threatened ecosystems in the world (WWF 2020; Vári et al. 2022; Maasri et al. 2022). Therefore, understanding freshwater species richness and spatial distribution are of outmost importance for identifying priority areas for their conservation. Despite species richness and drivers of invertebrates were extensively studied in freshwater ecosystems (Wiberg-Larsen et al. 2000; Hamada et al. 2002; Jacobsen 2004; Sickle et al. 2006; Downing and Leibold 2010; Miller et al., 2018) little is done on vertebrates of freshwater ecosystems (Uchida and Inoue 2010; Niu et al. 2012; Collen et al. 2014; Cianfrani et al. 2018).

With more than 18,000 species, freshwater fishes are among the most diverse taxonomic groups (Helfman et al. 2009; Hughes 2021). In fact, 51 percent of all 35,768 known fish species live in freshwater ecosystems (Hughes 2021). Due to their dispersal limitations and rapid decline in freshwater habitats, freshwater fishes are one of the most threatened groups of animals (Dudgeon et al., 2006; Dawson 2011; Arthington et al. 2016; Gozlan et al. 2019; Vári et al. 2022). They face threats such as river regulation, dam construction, land use change, hydropower development, habitat fragmentation, climate change, and invasive species (Dudgeon et al. 2006; Dawson 2011; Arthington et al. 2016; Szabolcs et al. 2022). A recent study has shown that one-third of freshwater fish are threatened with extinction (Hughes 2021). This group of species is less studied compared to terrestrial vertebrate groups like birds, mammals and reptiles (ISI Web of Science). Thus, knowing where their richness is highest and which environmental variables are influential in shaping their richness are essential to develop proper management plans for their conservation.

Iran hosts high species diversity and endemism due to its rich geological history, several phases of glacial and interglacial, sea level fluctuations, and presence of several major geographical barriers (Reviewed in Yousefi et al., 2022a). The country is home to 289 freshwater fishes belonging to 102 genera and 33 families (Jouladeh-Roudbar et al. 2020). Historical events like mountain uplifting and past climatic fluctuations are known as important drivers of freshwater fish distribution and speciation in Iran (Gholami et al. 2014; Esmaeili et al. 2014a, 2014b; Ghanavi et al. 2016; Schwarzer et al. 2017; Zareian et al. 2018b; Zarei et al. 2021). For instance, Schwarzer et al. (2017) suggested several scenarios to explain genetic divergence and phenotypic differentiation between geographical populations of *Iranocichla* in Iran due to past climatic fluctuations. Thus, historical factors might be the most important derivers of current distribution pattern of freshwater fishes in Iran.

The aims of this study are to create the first richness map of endemic freshwater fishes of Iran and explore the derivers of their richness pattern. This study also aimed to document the distribution and similarity of endemic freshwater fish within the freshwater ecoregions (Abell et al. 2008). Considering that freshwater fishes have low dispersal ability (less likely that responded to contemporary factors) and that previous studies have indicated that past climate change played an important role in shaping vertebrate distribution in Iran (reviewed in Yousefi et al. 2022), we speculated that past climate is the more influential factor in shaping freshwater fish richness. We are expecting to find a negative association between fish richness and past climate change (Tedesco et al. 2005; García-Andrade et al. 2021); on the other hand, areas with higher past climatic stability should host higher species diversity compared to regions with less climate stability (Jansson 2003; Sandel et al. 2011; Harrison and Noss 2017; Brown et al. 2020).

Materials And Methods

Endemic freshwater fish checklist and distribution records

To map endemic freshwater fish richness in Iran, we first prepared a checklist of endemic freshwater fishes for the country based on the available published checklists (Jouladeh-Roudbar et al., 2020). This checklist contains all valid endemic freshwater fishes of Iran until December 2022 (Table 1). In this study, distribution records of the endemic freshwater fish are based on our team long-term fieldworks and monitoring of freshwater fishes in Iran (Fig. 1) from 2005 to 2022 (Jouladeh-Roudbar et al. 2015, 2017, 2020). It is important to note that since we recorded each species geographic location with high accuracy, our data is not associated with the identification and spatial errors (Yousefi et al. 2020).

Environmental And Historical Predictors

Since the goal of this research is to disentangle the role of historical vs. contemporary variables in shaping the current richness pattern of endemic freshwater fish species in Iran, we selected variables related to the current climate (Fick and Hijmans 2017) and past climate (Pleistocene climate fluctuations) that are known to be important in shaping biodiversity distribution patterns in Iran (Hosseinzadeh et al. 2014; Kafash et al. 2020, 2021; Yousefi et al. 2022a, 2022b). For current climate, we took into account annual temperature and precipitation, which are freely accessible from WorldClim (Fick and Hijmans, 2017). To explore the role of Pleistocene climate fluctuations in shaping endemic freshwater fish richness we estimated changes in climate between the Last Interglacial (LGM ~ 130,000 BP) and the Last Glacial Maximum (LGM ~ 21,000 BP) today as well as the LGM and current climate (Sandel et al., 2011) in raster package (Hijmans, 2020). The LIG and LGM climate data were downloaded from PaleoClim which is a source of free, high-resolution paleoclimate data for biological modeling and GIS (Brown et al., 2018).

Table 1
Checklist of endemic freshwater fishes of Iran.

Order	Family	Species
Cypriniformes	Cyprinidae	*Barbus karunensis*
		Barbus miliaris
		Capoeta aculeata
		Capoeta alborzensis
		Capoeta anamisensis
		Capoeta buhsei
		Capoeta coadi
		Capoeta ferdowsii
		Capoeta gracilis
		Capoeta mandica
		Capoeta pyragyi
		Capoeta saadii
		Capoeta shajariani
		Carasobarbus sublimus
		Cyprinion tenuiradius
		Garra gymnothorax
		Garra hormuzensis
		Garra lorestanensis
		Garra mondica
		Garra nudiventris
		Garra persica
		Garra roseae
		Garra tashanensis
		Garra tiam
		Garra typhlops
	Gobionidae	*Romanogobio persus*
	Leuciscidae	*Acanthobrama persidis*

Order	Family	Species
		Acanthobrama urmianus
		Alburnoides damghani
		Alburnoides idignensis
		Alburnoides namaki
		Alburnoides nicolausi
		Alburnoides qanati
		Alburnoides samiii
		Alburnoides tabarestanensis
		Alburnus doriae
		Chondrostoma esmaeilii
		Chondrostoma orientale
		Squalius namak
	Cobitidae	*Cobitis avicennae*
		Cobitis faridpaki
		Cobitis linea
	Nemacheilidae	*Eidinemacheilus smithi*
		Oxynoemacheilus karunensis
		Oxynoemacheilus kiabii
		Oxynoemacheilus marunensis
		Oxynoemacheilus persa
		Oxynoemacheilus tongiorgii
		Paracobitis abrishamchianorum
		Paracobitis basharensis
		Paracobitis hircanica
		Paracobitis malapterura
		Paracobitis persa
		Paraschistura abdolii
		Paraschistura aredvii

Order	Family	Species
		Paraschistura delvarii
		Paraschistura hormuzensis
		Paraschistura ilamensis
		Paraschistura kermanensis
		Paraschistura makranensis
		Paraschistura naumanni
		Paraschistura nielseni
		Paraschistura susiani
		Sasanidus kermanshahensis
		Turcinoemacheilus bahaii
		Turcinoemacheilus hafezi
		Turcinoemacheilus saadii
Siluriformes	Bagridae	*Mystus cyrusi*
	Sisoridae	*Glyptothorax alidaeii*
		Glyptothorax galaxias
		Glyptothorax hosseinpanahii
		Glyptothorax shapuri
		Glyptothorax silviae
Gobiiformes	Gobiidae	*Ponticola hircaniaensis*
		Ponticola iranicus
		Ponticola patimari
Cichliformes	Cichlidae	*Iranocichla hormuzensis*
Cyprinodontiformes	Aphaniidae	*Aphaniops furcatus*
		Aphaniops ginaonis
		Aphaniops teimorii
		Esmaeilius isfahanensis
		Esmaeilius darabensis
		Esmaeilius persicus

Order	Family	Species
		Esmaeilius shirini
		Esmaeilius vladykovi

Richness Mapping And Statistical Analysis

We mapped the 85 endemic fish species with the outline method, Minimum Convex Polygons, in the adehabitatHR package (Calange 2011). Then we summed all created maps to produce an endemic freshwater fish richness map in the raster package (Hijmans 2015). We fitted a generalized linear model (GLM) with quasi-Poisson distribution to determine the relationship between endemic freshwater fish richness and the historical and contemporary variables. We computed the explained deviance for each variable separately and in combinations to identify the most crucial driver of endemic freshwater fish richness using the ‘ecospat.adj.D2.glm’ function in the R-package ‘ecospat’ (Di Cola et al. 2017) in R environment (R Core Team 2017).

The Similarity Of Endemic Fish Assemblages Among The Freshwater Ecoregions

In the present research, we quantified endemic freshwater fish distribution and similarity among the 15 freshwater ecoregions of Iran based on the presence records of the 85 endemic fish species (Table 1). In most cases of freshwater diversity mapping studies, fish species were analyzed based on watersheds (Oberdorff et al. 1995, 1997; Oberdorff et al. 2011; Tedesco et al. 2017; Qian et al. 2021; Miller and Román-Palacios 2021; Anas and Mandrak 2021; García-Andrade et al. 2021) but here we applied an ecoregion approach. To assess the similarity of endemic fish assemblages among the ecoregions (Kura - South Caspian Drainages, Lower Tigris & Euphrates, Upper Tigris & Euphrates, Caspian Marine, Orumiyeh, Caspian Highlands, Namak, Kavir & Lut Deserts, Turan Plain, Northern Hormuz Drainages, Middle Amu Darya, Esfahan, Upper Amu Darya, Baluchistan, Helmand – Sistan) (Fig. 2), we created a presence–absence matrix of all endemic fish species within the above-mentioned ecoregions. Then we used the Jaccard similarity index in the Past software (Hammer et al. 2001) to estimate the similarity of endemic freshwater fish assemblages among the ecoregions.

Results

Richness map

Until now, 85 endemic freshwater fishes were described from Iran. Family Nemacheilidae and Cyprinidae were the most diverse family each with 25 endemic species. *Capoeta*, with 11 species and *Garra* and *Paraschistura*, each with 10 species were the most spacious genera. A richness map was developed based on all 85 fish species distribution maps. Results showed that endemic freshwater fish richness is highest in the Zagros Mountains and moderate level of richness was observed between Zagros and Alborz Mountains. High, moderate and low richness of endemic freshwater fish match with Upper Tigris & Euphrates, Namak, and Kavir & Lut Deserts ecoregions, respectively. The Number of endemic freshwater fish ranges from 0 in central Iran to 13 in the Zagros Mountains (Fig. 3).

Variable Importance

Precipitation was identified as the most influential determinant of endemic freshwater fish richness, with a significant positive correlation ($p < .000$), meaning that areas with higher precipitation host more species. Precipitation explained the highest proportion of variance (37.5%) among all historical and contemporary variables. Precipitation change velocity since the LGM was the second most important predictor (24.5%) of endemic freshwater fish richness. The correlation of precipitation change velocity with richness was negative ($p < .000$), which means that areas, which experienced higher changes in precipitation host fewer species (Table 2).

Table 2
Results of generalized linear model with quasi-Poisson distribution to identify the most important drivers of lizard richness. The table shows estimates, associated z-values, p-values, the Akaike information criterion values (AIC) and explained deviance (D2) of variables.

Predictor	Slope	z value	p value	AIC	D2
Intercept	-0.0906	-1.656.			
Temperature	0.92310	0.709		3754	0.004
Precipitation	10.68488	8.219***	< .000	2717	0.375
Temperature change velocity (LGM)	4.19334	4.082***	< .000	3721	0.016
Precipitation change velocity (LGM)	-9.85701	-4.492***	< .000	3080	0.245
Temperature change velocity (LIG)	-1.56268	-1.184		3601	0.059
Precipitation change velocity (LIG)	-4.01509	-2.082*	< .05	3503	0.094
Full model				2303	0.526

Ecoregions Fish Similarity

Upper Tigris & Euphrates, followed by Northern Hormuz drainages were the most species rich ecoregions in Iran, with 53 and 14 species, respectively. No endemic species was recorded in the Middle Amu Darya and Upper Amu Darya ecoregions. According to the dendrogram of similarity of the 85 endemic freshwater fishes of Iran among the 15 ecoregions, Orumiyeh was the most unique ecoregion according to endemic fish presence. Kura - South Caspian Drainages and Caspian Highlands were the most similar ecoregions based on the distribution of endemic freshwater fishes. Upper Tigris and Euphrates and Helmand – Sistan were the most dissimilar ecoregions in the country (Table 3 and Fig. 4).

Table 3
Area and number of endemic freshwater fish species recorded in each freshwater ecoregion in Iran.

Ecoregions	Number of species
Kura - South Caspian Drainages	6
Lower Tigris & Euphrates	5
Upper Tigris & Euphrates	53
Caspian Marine	3
Orumiyeh	3
Caspian Highlands	5
Namak	9
Kavir & Lut Deserts	10
Turan Plain	4
Northern Hormuz Drainages	14
Esfahan	8
Baluchistan	6
Helmand – Sistan	1

Discussion

It is well demonstrated that the global distribution of biodiversity is spatially heterogeneous, but determining drivers of species richness is a real challenge, particularly for data poor regions of the world like the Middle East. Iran is a biodiversity rich country in the Middle East, and it is home to over 1317 vertebrate species (Yousefi et al. 2022a) of which many are endemic to the country (Kafash et al., 2020; Jouladeh-Roudbar et al., 2020). All of these make the country an ideal place for studying drivers of biodiversity distribution. This study is the first to map endemic freshwater fish richness and determine the drivers of their richness pattern in Iran, a rather neglected and biodiversity unknown country in the Middle East.

Our results showed that Upper Tigris & Euphrates harbours the highest number of endemic species; this makes the ecoregion a hotspot of freshwater biodiversity in Iran. This ecoregion geographically overlapped with the Zagros Mountains, which is known as an important biodiversity hotspot and centre of origin for terrestrial vertebrates of Iran, like reptiles and mammals (Anderson, 1999; Ahmadzadeh et al.

2013; Hosseinzadeh et al. 2014; Kafash et al. 2022, 2021; Malekoutian et al. 2020; Vaissi 2021; Yousefi et al., 2022b). Here we showed that not only the Zagros Mountains are a hotspot of terrestrial vertebrates but also they are a hotspot of freshwater vertebrates in Iran. Apart from being a hotspot of vertebrates, the Zagros Mountains served as important past climatic refugia for several groups of vertebrates (Perktaş et al. 2011; Ahmadzadeh et al. 2013; Farasat et al. 2016; Malekoutian et al. 2020; Vaissi 2021). All of these make the mountains a critical geographic unit for the conservation of biodiversity in Iran.

Although we initially expected past climate to be the most influential factor in shaping freshwater fish richness in Iran, we found that current precipitation was the most crucial variable in explaining endemic freshwater fish richness pattern. Considering that fish are aquatic species positive correlation of fish richness with precipitation can be justified that areas which receive higher precipitation can provide optimal environmental conditions for them (Bateman et al. 2010). Also, rainfall, floods and a decrease in water temperature trigger spawning and migration in fishes. Similar to our study, several studies of other taxonomic groups also detected a stronger correlation between precipitation with species richness. For instance, precipitation was identified as the most important predictor of bat richness in Iran (Kafash et al. 2021). Precipitation change velocity since the LGM was identified as the second most important predictor of endemic freshwater fish richness. This is in line with previous studies which documented the role of past climate change in different fish species as well as species richness pattern in Iran (Gholami et al. 2015; Schwarzer et al. 2017).

The impacts of past climate change are well documented on the distribution of biodiversity across the globe (Jansson 2003; Hewitt 2004; Sandel et al. 2011; Weigelt et al. 2016; Theodoridis et al. 2020). Generally, areas that experienced higher climate change host fewer species and climatically stable area harbour hotspots of species diversity and endemism (Jansson 2003; Hewitt 2004; Sandel et al. 2011; Harrison and Noss 2017; Brown et al. 2020). In line with this general pattern and our initial expectation, we found a strong negative correlation between endemic freshwater fish richness and precipitation change velocity. Meaning that areas which were climatically less stable since the LGM host fewer endemic freshwater fish species.

We estimated the similarity of freshwater ecoregions based on the endemic fish presence and absence. Estimated similarity among the ecoregions can be explained by past and current hydrological connectivity of the ecoregions (Filipe et al. 2009; Gholami et al. 2014; Esmaili et al. 2020) which facilitated dispersal and faunal exchange among the ecoregions. Orumiyeh ecoregion was the unique ecoregion because 80% of its assemblage cannot be found in other ecoregions, thus it should be prioritized for conservation. There are clear biogeographic affinities between Orumiyeh ecoregion and the Aras adjacent to the north, even though it might only be 0.5 million years old. During past, humid climatic periods, probably last time during the peak of the last glaciation, Urmia was a freshwater lake of a much bigger size allowing fishes to migrate from of tributary of the lake to another. Since Lake Orumiyeh dried out and became a salt lake (NGOI 2003).

Freshwater ecosystems are at greater risk of biodiversity losses compared to their surrounding terrestrial ecosystems (Turak et al. 2017; Albert et al. 2020). But they are poorly protected globally meaning that they are more vulnerable to human activities (Szabolcs et al. 2022). Like other parts of the world, the freshwater ecosystems of Iran are poorly protected (Darvishsefat 2008). This study contributed to the protection of freshwater biodiversity in freshwater fish by identifying areas with the highest freshwater fish richness. These areas should be included in the current protected areas of the country or considered for the selection of new protected areas to increase freshwater ecosystems legal protection. This is particularly important because protected areas of Iran were initially designed to protected large mammals like wild goat (*Capra aegagrus*), wild sheep (*Ovis orientalis* and *Ovis vignei*) and Persian gazelle (*Gazella subgutturosa*) thus other vertebrate groups especially freshwater fishes were completely ignored (Darvishsefat 2008).

The richness map created in this study is based on the current distribution records of endemic freshwater fishes of Iran. But there are several factors that can change the identified richness pattern in the country, like climate change, land use change, invasive species, habitat fragmentation through dam construction (Jouladeh-Roudbar et al. 2020; Makki et al. 2021). For instance, it is predicted that endemic freshwater fish of Iran will shift their distribution in response to climate change (Yousefi et al. 2020; Makki et al. 2021). Thus, this map can serve as a baseline to document the role of environmental changes and human activities in altering biodiversity distribution patterns in general and endemic freshwater fish richness pattern in particular.

Conclusions

Freshwater fishes were the subject of numerous diversity mapping studies at a different spatial scale and geographical regions (Hoeinghaus et al. 2007; Filipe et al. 2009; Bogotá-Gregory et al. 2020; Qian et al. 2021). But, freshwater fishes of Iran received no attention in this regard. Here, we presented the first richness map of all endemic freshwater fishes of Iran and showed that their richness is highest in the Zagros Mountains/ Upper Tigris & Euphrates ecoregion. This highlights that Zagros Mountains are an unquestionable biodiversity hotspot for all vertebrate groups in Iran. Advancing our knowledge on the spatial distribution of freshwater biodiversity in Iran, this study revealed that freshwater fish richness is shaped by current and past climate. Future studies should examine the richness pattern of all freshwater fishes of the country to find a better understanding of spatial distribution of biodiversity in general and freshwater species in particular in Iran.

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Declarations

Author Contributions Masoud Yousefi conceived and designed the study. Arash Jouladeh-Roudbar collected the data. Anooshe Kafash and Masoud Yousefi performed data analysis and visualisation. The first draft of the manuscript was written by Masoud Yousefi with contribution from Arash Jouladeh-Roudbar and Anooshe Kafash. All authors read and approved the final manuscript.

Conflict of interest The authors declare they have no financial or non-financial conflict of interest to disclose.

Figures

Figure 1

Photos of some surveyed habitats of endemic freshwater fishes of Iran. From top left Sivan River; Siyah gav Lake; Hari River, Beshar River; Kashaf River; Shadegan wetland; Loen cave. Photos by Arash Jouladeh-Roudbar.

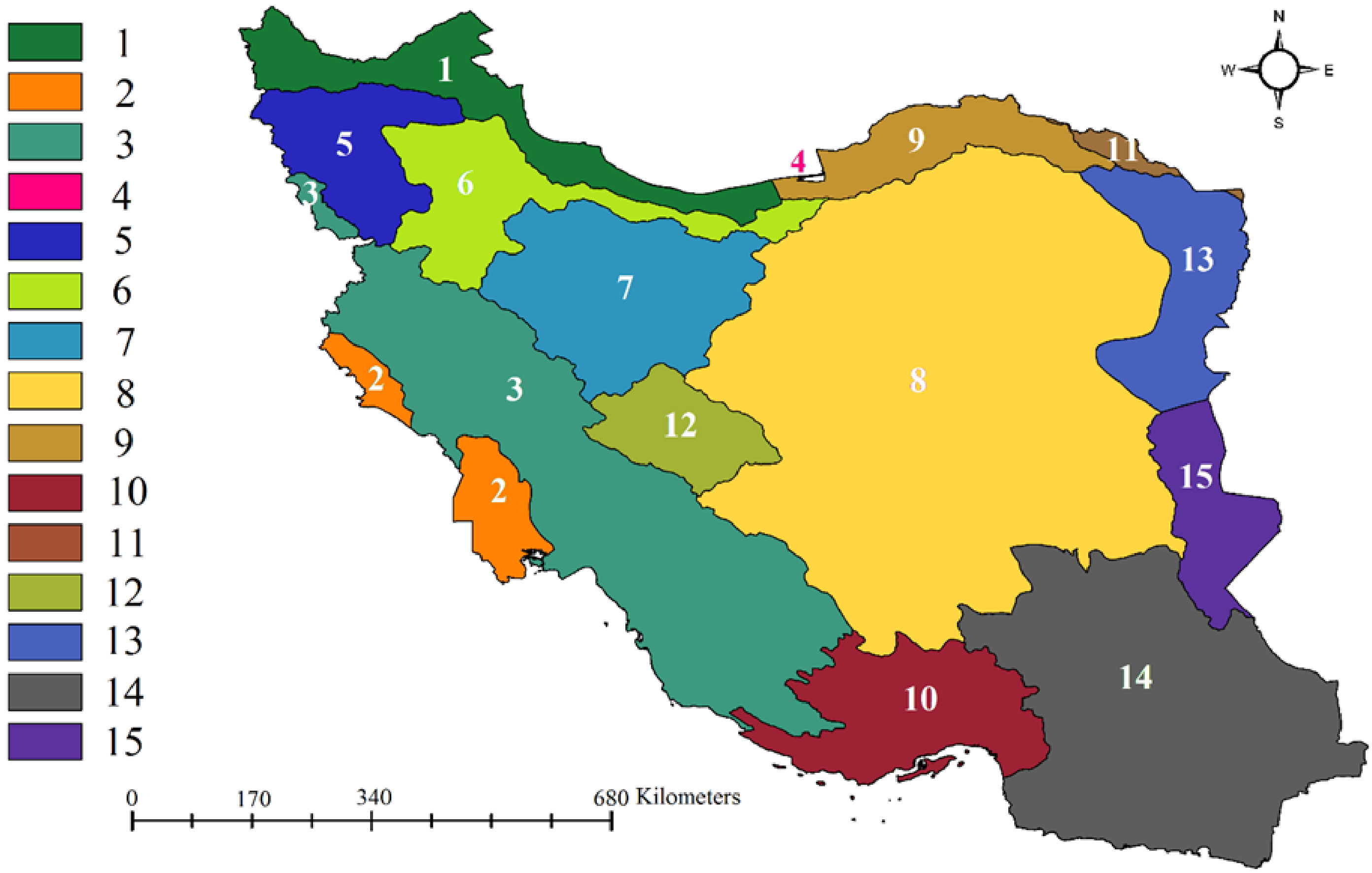

Figure 2

Freshwater ecoregions of Iran (Abell et al. 2008). 1. Kura - South Caspian Drainages, 2. Lower Tigris & Euphrates, 3. Upper Tigris & Euphrates, 4. Caspian Marine, 5. Orumiyeh, 6. Caspian Highlands, 7. Namak, 8. Kavir & Lut Deserts, 9. Turan Plain, 10. Northern Hormuz Drainages, 11. Middle Amu Darya, 12. Esfahan, 13. Upper Amu Darya, 14. Baluchistan, 15. Helmand – Sistan.

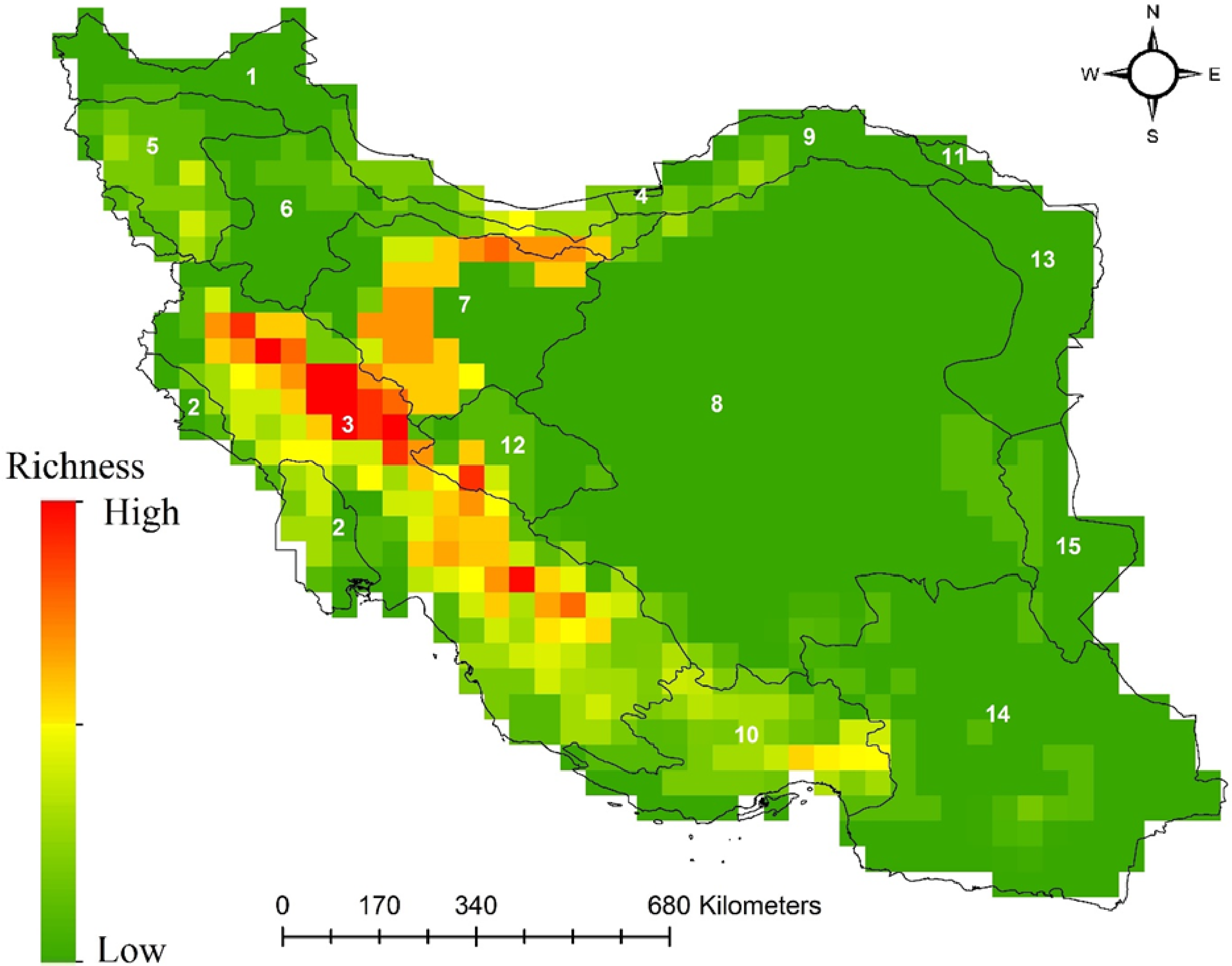

Figure 3

Richness map of 85 endemic freshwater fishes of Iran. Species richness range from 0 in Middle Amu Darya and Upper Amu Darya ecoregions to 13 in Upper Tigris & Euphrates. Polygons and numbers show Iran's freshwater ecoregions as follows: 1. Kura - South Caspian Drainages, 2. Lower Tigris & Euphrates, 3. Upper Tigris & Euphrates, 4. Caspian Marine, 5. Orumiyeh, 6. Caspian Highlands, 7. Namak, 8. Kavir & Lut Deserts, 9. Turan Plain, 10. Northern Hormuz Drainages, 11. Middle Amu Darya, 12. Esfahan, 13. Upper Amu Darya, 14. Baluchistan, 15. Helmand – Sistan.

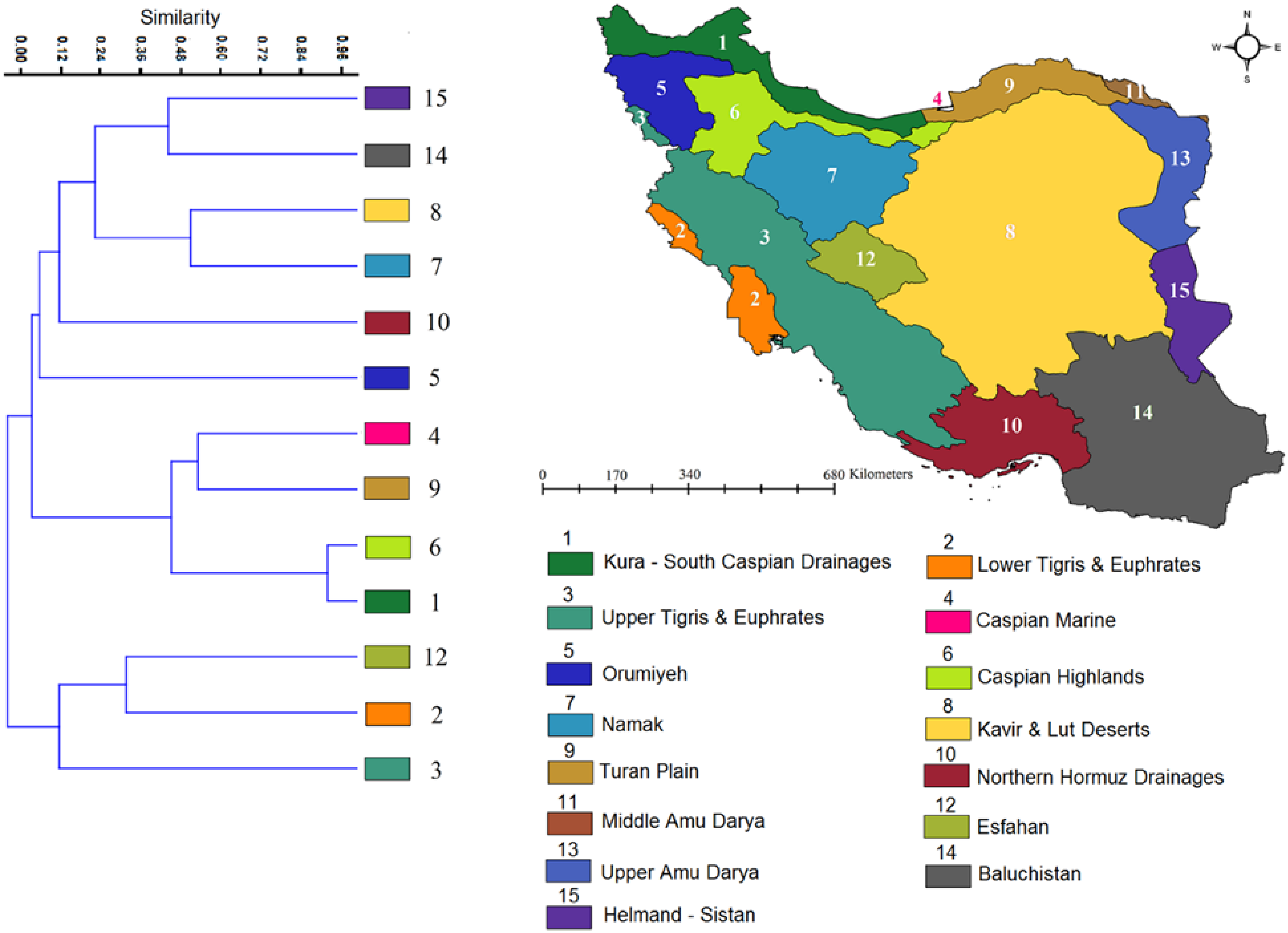

Figure 4

Dendrogram of the overall similarity for the 85 endemic freshwater fishes of Iran among the 15 ecoregions. Freshwater ecoregions of Iran (Abell et al., 2008). 1. Kura - South Caspian Drainages, 2. Lower Tigris & Euphrates, 3. Upper Tigris & Euphrates, 4. Caspian Marine, 5. Orumiyeh, 6. Caspian Highlands, 7. Namak, 8. Kavir & Lut Deserts, 9. Turan Plain, 10. Northern Hormuz Drainages, 11. Middle Amu Darya, 12. Esfahan, 13. Upper Amu Darya, 14. Baluchistan, 15. Helmand – Sistan.