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Azorean freshwater invertebrates: Status, threats and biogeographic notes

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ABSTRACT

Azorean freshwater invertebrates: Status, threats and biogeographic notes

This paper presents an updated catalogue of the freshwater invertebrates of the Azores archipelago and reviews the published records to account for the current taxonomic status and changes in the nomenclature of the listed taxa.
The number of freshwater invertebrate species that has been recorded in the Azores has risen sharply throughout the 20th century to 241 species based on field collections and the identification by several generations of local and foreign researchers. The freshwater fauna has been described as the following: (i) being "disharmonic", i.e., lacking taxa commonly found in continental freshwater systems such as the Plecoptera, and (ii) possessing a relatively high degree of endemism in selected groups. As expected, most recorded invertebrates are primarily of Palaearctic origin. However, endemic species make up 11 % of the freshwater invertebrate fauna, which emphasises the unique character of Azorean freshwater habitats, the importance of conservation measures and the need to continue the study of these systems.

Key words: Azores, invertebrates, insular, freshwater systems, catalogue.

RESUMEN

Invertebrados acuáticos de las Azores: Estado, amenazas y notas biogeográficas

Este artículo presenta un catalogo actualizado de los invertebrados acuáticos presentes en el Archipiélago de las Azores. La revisión de los registros publicados de estos animales dulceacuícolas se ha realizado teniendo en cuenta el estado taxonómico actual y los cambios en las nomenclaturas de las taxones listados. De todas las maneras la lista no pretende ser un catalogo definitivo, dado que nuevos registros continúan apareciendo, en particular, aquellos que pertenecen a habitats poco estudiados, como es el caso de los sistemas acuáticos dulceacuícolas de las Azores.
El número de registros de especies de invertebrados de agua dulce en Azores ha sufrido un incremento importante a lo largo del siglo XX alcanzando 241 especies, que refleja los esfuerzos realizados en la recolección e identificación por parte de varias generaciones de investigadores. La fauna acuática es inarmónica faltando taxones comunes que si existen en los sistemas dulceacuícolas continentales, tal es el caso de los Plecoptera, y abundam los endemismos en otros grupos. La mayoría de invertebrados catalogados son primordialmente de origen Paleártico. Sin embargo, el porcentaje de especies endémicas es de 11 % lo que enfatiza el carácter único de estas especies de Las Azores, la importancia de su conservación y la necesidad de proseguir con un trabajo continuado.

Palabras clave: *Azores, invertebrados, insular, sistemas dulceacuícolas, catálogo.*

INTRODUCTION

The presence of freshwater invertebrates in oceanic islands has always raised questions concerning dispersal, colonization and evolution; even their absence is proclaimed as evidence about the mechanisms governing those processes (e.g. Bass, 2003; Covich, 2006).

During the latter part of the nineteenth century, several naturalists visited the Azores. Guerne published the first works on the Azorean freshwater fauna (Guerne, 1887a,b,c; 1888a,b) following visits to six islands (Corvo, Flores, Faial, Pico, Graciosa and São Miguel) between 1887 and 1889. In the same year Barrois published several papers, including the first records of water mites (Barrois, 1888a) and additions for Ostracods, Cladocera, Branchiopods (Barrois, 1888b) and Rotifers (Barrois, 1888c).

Chopard and Méquignon (1930) made collections on the Azores subsequently publishing several papers that included the first records of Odonata (Navás, 1933) and several additions to the Coleopterous fauna (Méquignon, 1942a, b). Collections made in 1938 by Frey, Stora and Cedercreutz provided additions to the Azorean Diptera (Frey, 1945; Stora, 1945; Cedercreutz, 1941). Subsequently, Freeman (1959), Marcus & Marcus (1959), Sciacchitano (1961, 1964a,b), Carlsson, (1963), Nielsen (1963), Nybom (1965) reported more findings based on Brinck and Dahl's findings following the Lund University Expedition to Madeira and the Azores in 1957. Svensson (1970, 1977) published on the Coleptera (Dytiscidae and Gyrinidae) while Backhuys (1975), contributed to the Azorean freshwater fauna in his revision of the Azorean land and fresh-water malacofauna. The local naturalist Dalberto Pombo has performed several collections on different islands with a specific concentration on Santa Maria. Defaye & Dussart (1991) recorded several species of Copepoda after studying material that was collected during the Biaçores expedition in 1971 by Monod. On his trip to São Miguel, Pico, Terceira and Flores, Green (1992) studied and published on zooplankton diversity. Medeiros *et al.* (1996) studied zooplankton diversity again in a commissioned work for the Azorean Government.

Murray *et al.*, (2004) provided several new additions and a checklist of chironomids. Borges *et al.*, (2005), published the first list of Azorean terrestrial fauna e flora, later updating and expanding upon this first publication (Borges *et al.*, 2010).

The implementation of the Water Frame Directive [European Parliament & The Council of the European (2000); WFD] has increased emphasis on the importance of regional freshwater studies and the characterization of biological elements. Studies have confirmed the presence of species described in past publications and found new records for the Archipelago (e.g. Malhão *et al.*, 2007; Raposeiro *et al.*, 2007; Gonçalves *et al.*, 2008; Raposeiro & Costa, 2009; Raposeiro *et al.*, 2009a,b). The literature has clearly shown that some groups have been better characterised than others. It is, however, unclear if the relative proportion of available publications for each group reflects its relative species richness. There can be little doubt, for example, that some groups are poorly known because of their small size, complicated taxonomy (e.g., Acari, Oligochaeta) or sampling difficulty (e.g. deep lakes, wetlands).

The current study presents an updated catalogue of the Azorean freshwater invertebrate fauna. An extensive review of all published records was performed and accounted for the current taxonomic status and any changes in the nomenclature. This list provided an updated inventory, which will require regular updates as new records continue to appear, especially from poorly studied habitats such as the freshwater bodies. The list is an useful resource for research and management and provides information on species distribution within the archipelago that will benefit conservation measures and future research on biogeographical and macroecological hypotheses using island systems.

METHODS

Study Area

The archipelago of the Azores is comprised of nine islands and several islets that can be divided into three groups (Fig. 1). São Miguel and Corvo

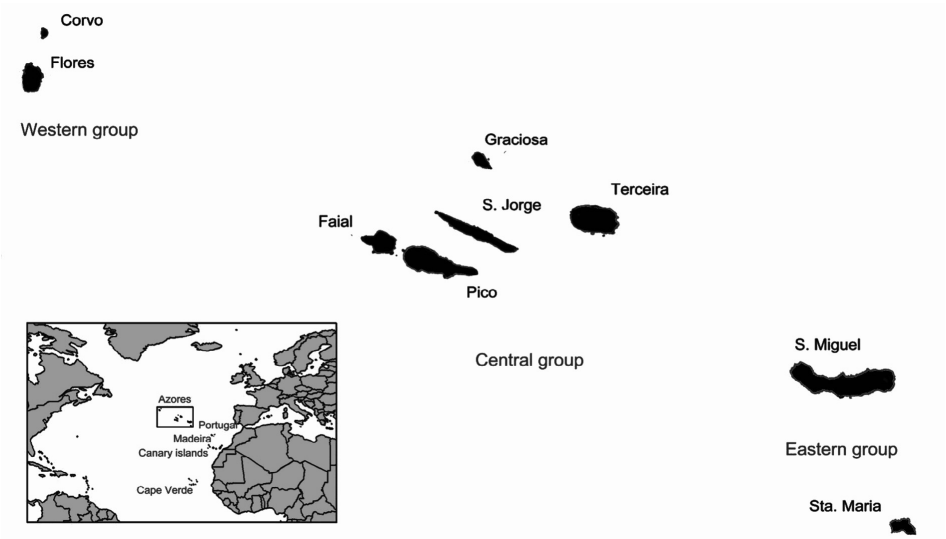

Figure 1. The location of the Azorean archipelago in the North Atlantic Ocean and the nine islands of the Azores. *Localización del Archipiélago de las Azores en el Océano Atlántico Norte y de las nueve islas de Las Azores.*

are the largest and smallest islands, respectively, with total areas of 745 km^2 and 17 km^2, respectively. The central group (Terceira, Faial, Graciosa, Pico and São Jorge) is situated 220 km from the western group (Flores and Corvo) and 136 km from the eastern group (São Miguel and Santa Maria). The archipelago spans 615 km and is located approximately 1300 km west of Portugal, 1600 km east of North America and 800 km northwest of Madeira. From a biogeographical perspective, the Azores archipelago is often grouped with the Cape Verdes, Canary Islands, Salvage Islands and Madeira in the Macaronesian region.

The Azorean climate is oceanic and temperate (Bettencourt, 1979). Wind patterns differ among the islands with south- and southwest-prevailing winds in the western and central groups and north- and northeastern-prevailing winds predominating in the eastern group (Porteiro, 2000). Geologically, the Azores archipelago forms a volcanic plateau that is 20–36 million years old. The youngest rocks are located on Pico island and are approximately 0.250 million years old, whereas the oldest rocks, which are located on the island of Santa Maria, emerged 8.12 million years ago (Borges & Brown, 1999; Quartau, 2007).

Azorean lotic systems are characteristically situated in small, short and steep catchments; the streams are short, steep and deeply incised. Permanent streams, fed by lakes or spring waters, exist only in Santa Maria, São Miguel, São Jorge, Faial and Flores islands (DROTRH/INAG, 2001). The Azores are particularly rich in lentic habitats with over 88 lakes (Porteiro, 2000), located on São Miguel, Terceira, Pico, Flores and Corvo. Lentic systems tend to be flooded volcanic craters and caldeiras (Azevedo, 1998; Nunes, 1999).

Checklist of the Azorean freshwater invertebrates

The taxonomic list was based on the published literature (Annex I) and some unpublished data, which was gathered during routine work that was performed for the regional government on the ecological quality of superficial waters over the last six years (eastern and western groups as well as in Faial and Pico in the central group). The nomenclature that was used for species was consistent with the recent list of European terrestrial species in Project FAUNA EUROPAEA (http://faunaeur.org).

All species of doubtful identification (e.g., misidentification, presence of species has never confirmed) were removed from the main list and were included in Annex III.

Codes describing species distribution across the nine Azorean islands were used as follows: COR – Corvo; FLO – Flores; FAI – Faial; PIC – Pico; GRA – Graciosa; SJG – São Jorge; TER – Terceira; SMG – São Miguel and SMR – Santa Maria. If no information was available on the island, the material was collected using the designation AZ for the Azorean archipelago. Zoogeographical comments are provided in the list using the following symbols: COS – Cosmopolitan or almost cosmopolitan; HOL – Holartic; PAL – Palaeartic; NEA – Neartic; ETH – Ethiopian; END – Endemic and MAC – Macaronesian.

RESULTS

A total of 241 species, belonging to 76 families and 164 genera, have been found in the bibliography and in unpublished data. Their name can be seen in the electronic version of this journal (www.limnetica.net/internet/index.html). The number of recorded species for each island is now 189 species for São Miguel, 111 species for Flores, 100 species for Terceira, 87 species for Faial, 83 species for Pico, 82 species for Santa Maria, 60 species for São Jorge and 29 species each for Graciosa and Corvo. A summary of the freshwater invertebrates groups found in the Azores and on each of the nine islands is given in Table 1. The Arthropoda represent the most diverse Azorean *Phylum,* comprising approximately 89.7 % of the taxa. The Diptera is the richest group (96 taxa) followed by Crustacea (92 taxa). The Hydracarina (*Sperchon brevirostris*) and Ephemeroptera (*Cloeon dipterum*) are represented by single species. The Chironomidae is the most diverse family with 43 species, 3 of which are endemic to Macaronesia. The highest number of endemic taxa occurs in the Diptera (16 taxa, 6.69 % of the species are endemic). The Empididae and Ephydridae both have 4 endemic species, followed by the Dolichopodidae with 3 endemic species; the single species of Simuliidae recorded from the Azores is also endemic.

The Azorean freshwater invertebrate fauna is predominantly Palaearctic (35 %) in origin (Fig. 2) with the majority of the taxa originating from Europe. Thirty percent of the taxa occur across several biogeographical regions. For example most of the Azorean Oligochaeta and zooplankton species have cosmopolitan distribution. Holartic taxa (20 %) are also well represented in Azores. Azorean endemic species comprise 11 % of the macroinvertebrate fauna; Macaronesian endemics comprise 3 % of the Azorean invertebrate fauna. Macaronesian endemics *Cardiocladius freyi*, *Dicranomyia michaeli*, *Dicranomyia vicina*, *Clogmia albipunctata, Hydroptila fortunata* occur in the Azores, Madeira and Canary Islands while *Diamesa alata* and *Microsepta freyi* are known from the Azores and Madeira.

Table 1. Diversity of the main groups for each island. *Diversidad de los grupos principales para cada isla.*

	Western			Central					Eastern	
Groups	AZ	COR	FLO	FAI	PIC	GRA	SJG	TER	SMG	SMR
Platyhelminthes	0	0	2	0	0	0	0	0	6	2
Mollusca	0	1	1	1	1	1	0	3	5	4
Annelida	0	0	2	6	1	2	0	2	13	4
Acari	0	0	1	1	0	0	1	1	1	1
Crustacea	0	3	31	18	28	5	3	19	64	19
Ephemeroptera	0	0	0	1	1	1	1	1	1	1
Odonata	0	4	4	4	4	2	4	4	4	4
Hemiptera	2	0	2	1	2	0	0	3	5	2
Coleoptera	0	2	8	5	6	2	4	6	8	10
Diptera	2	17	57	48	37	16	45	59	79	34
Trichoptera	1	2	3	2	3	0	2	2	3	1
Total	**5**	**29**	**111**	**87**	**83**	**29**	**60**	**100**	**189**	**82**

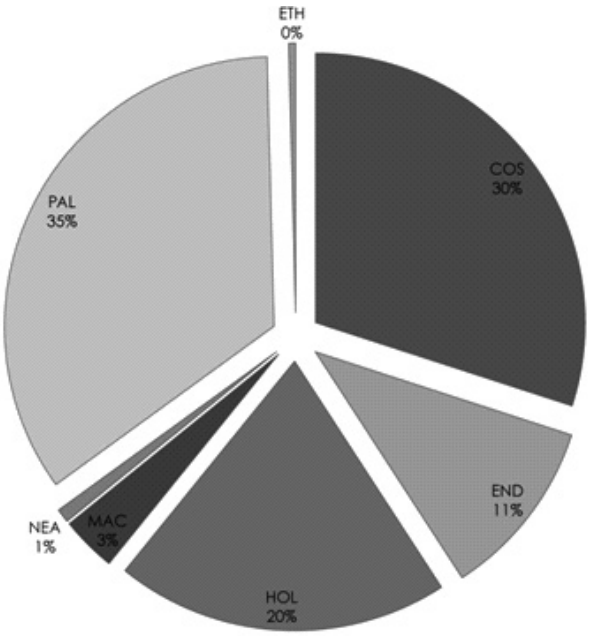

Figure 2. Biogeographic origin of Azorean freshwater invertebrates. Percentages of each origin are shown. PAL-Palaearctic; ETH-Ethiopian; COS-Cosmopolitan; END-Endemic; HOL-Holarctic; MAC-Macaronesian; NEA-Neartic. *Origen biogeográfico de los invertebrados acuáticos de Las Azores. Porcentajes para cada región biogeográfica considerada. PAL-Paleártico; ETH-Etíope; COS-Cosmopolita; END-Endémico; HOL-Holártico; MAC-Macaronésica; NEA-Neártica.*

DISCUSSION

The number of freshwater invertebrate species recorded from the Azores has risen sharply throughout the 20th century, and currently stands at 241 species. This increase is the result of increased sampling efforts and the identification of material by several generations of local and foreign researchers. For example, from the 1880's the 1960's, an average of 19 new records were added per decade. However, the number of new records has risen to an average of 24 per decade over the last 50 years. However, the knowledge of the actual diversity and complexity of the Azorean freshwater fauna is relatively incipient.

With the implementation of the WFD in 2000, studies characterizing Azorean freshwater ecosystems have increased. As a result the number of new records has increased by 11.98 % in the last decade. A summary of the freshwater invertebrates groups found in the Azores and on each of the nine islands is present in Table 1.

The quantity of freshwater available in the islands is vital for species diversity. For example, São Miguel, Flores and Terceira islands have several lakes, permanent streams, wetlands and peat bogs islands, providing a diverse array of freshwater habitats and favorable colonization conditions for colonizing species. In contrast, permanent streams are absent in Graciosa, Corvo and Pico. In addition, lakes are absent in Santa Maria, Graciosa and Faial. The low macroinvertebrate richness found in Azores archipelago is typical of truly oceanic islands. Their remoteness strongly limits the dispersal of colonisers and the evolution of trophically complex freshwater habitats (Covich, 2006; 2009). The Azorean freshwater fauna is "disharmonic", because it lacks the taxa that are common to continental freshwater systems such as the Plecoptera and with a relatively high degree of endemism in others groups such as Trichoptera and Coleoptera (Gonçalves *et al.*, 2008; Raposeiro & Costa, 2009; Raposeiro *et al.* 2009a). A reduced number of groups are present. Each group exhibits low levels of diversity (e.g., Ephemeroptera-*Cloeon dipterum*). Groups such as the Chironomidae and Trichoptera predominate, whereas others are poorly represented or absent. Similar to other Macaronesian islands, Plecoptera are absent from the Azores (Madeira-Hughes, 2006; Borges *et al.*, 2008; Canarias-Malmqvist *et al.*, 1993; Izquierdo *et al.*, 2001). The absence of key taxa such as stoneflies is caused by the low dispersal capacity of the adults and the highly specific ecological needs of the larvae (Fochetti & Tierno de Figueroa, 2008).

Numerous species are adapted for colonization of insular freshwater systems by using different mechanisms of active and passive dispersal (Bilton *et al.*, 2001; Covich, 2006; 2009). Passive dispersal via an external agent (e.g. strong winds storms; attachment to rafts of floating wood and pumice) usually results in long distance transoceanic dispersal (Thiel & Gutow, 2005; Covich, 2006; 2009). Dormant individuals (e.g. Zooplankton) and egg masses (e.g. Diptera and Gastropoda) can also be carried by other larger

organisms (e.g. Bilton *et al.*, 2001; Figuerola & Green, 2002; Green & Figuerola, 2005). In some Azorean species, like *Ischnura hastate* (Say) (Odonata: Coenagrionidae), a parthenogenetic species (Rivera *et al.*, 2005), a single individual can disperse and colonize available habitats.

Active dispersal, which involves the self-generated movement by individuals (swimming, crawling or flying), is more effective over shorter distances. This is important for "stepping stone" colonisation (Whittaker & Fernandez-Palacios, 2007) between islands. As result of these barriers and biogeographical "filters", the Azorean freshwater fauna is largely represented by insects with taxa that occupy a wide number of niches due to the relative absence of competitors for local resources. A similar situation pertains to Tenerife (Malmqvist *et al.*, 1993) and Madeira (Hughes, 2003).

The freshwater fauna of the Azores is impoverished when compared to other Macaronesian archipelagos (Madeira and the Canary islands). For example the percentage of endemic species in Azores (11 %) is lower than Madeira archipelago (25.5 % [Hughes, 2003]), and Canary Islands with (28 %) in Gran Canaria (Nilsson *et al.*, 1998) and 39 % in Tenerife (Malmqvist *et al.*, 1995).

The Madeira archipelago is three times smaller (810 km^2), older (Porto Santo-14 million years old) and closer to the mainland (800 km). The Canary Islands is three times larger (7447 km^2), older (Fuerteventura-20.6 million years old) and closer to the mainland (85 km). Given the isolation and geological youth of the Azores, the ancient freshwater colonisers had to travel over a significant distance from the Madeiran archipelago or, in most cases, from the European mainland (1200 km), over a relatively short geological period (Santa Maria-8.12 million years old).

The Coleoptera and Trichoptera have the highest levels of endemism for the region of Macaronesia (Table 2). The level of estimated endemism in the Azores (11 %) highlights the considerable conservation value of the invertebrate freshwater fauna. Extensive habitat destruction resulting from human intervention has affected the Azorean freshwater systems after the human colonisation of the islands. Contemporary legislation such as the Habitats Directive and the WFD encourage a proactive approach concerning the sustainable management and the protection of the natural environment and resources. As a consequence, Azorean authorities have established protected areas which are strategically important for maintaining freshwater biodiversity, as changes land use in the catchment strongly influence the ecological quality of freshwater systems (Cymbron *et al.*, 2005; Gonçalves *et al.*, 2008 Hughes *et al.*, 2007).

Table 2. Levels of endemicity (%) for selected freshwater insect orders in the Macaronesian region. Data from Gran Canaria (Nilson *et al.*, 1998), Tenerife (Malmqvist *et al.*, 1995) and Madeira (Hughes *et al.*, 1998; Hughes 2003) are shown. *Niveles de endemicidad (%) para órdenes de insectos acuáticos en distintas islas macaronésicas. Datos de Gran Canaria (Nilson* et al.*, 1998), Tenerife (Malmqvist* et al.*, 1995) y Madeira (Hughes* et al.*, 1998; Hughes 2003).*

Taxonomic group	Gran Canaria	Tenerife	Madeira	Azores
Ephemeroptera	40	33	0	0
Odonata	10	10	0	0
Hemiptera	13	17	0	0
Coleoptera	32	32	48	25
Trichoptera	30	64	67	33
Diptera	29	49	18	17

Like all insular systems, Azorean freshwater systems are potentially highly vulnerable to invasive species due to the low levels of diversity (and therefore competitors) and the relative availability of ecological niches. *Procambarus clarkii* and *Ferrisia fragilaris* (natives from America) have been introduced to Azorean freshwaters by aquarists. The existing conditions have allowed them to spread quickly from original site where they were introduced. Another example is the accidental introduction of *Lymnaea truncatula* in São Miguel via sheep imported from mainland Portugal. *Lymnaea truncatula* is an intermediate host for the trematode *Fasciola hepatica,* which causes fasciolosis. In Azores it is restricted to the eastern half of the island of São Miguel and to Santa Maria. More recently, Raposeiro *et al.*, 2009b reported the presence of *Branchiura sowerbyi* (Oligochaeta: Tubificidae) in Azores. The establishment and consequences of introduced species has been subject to discussion in many studies (e.g. Mooney & Hobbs 2000); however we are still not able to predict outcome of the introduction of particular species,

as well as the impact of invasions in general to specific ecosystem, although insular systems are historically highly vulnerable.

Long-term, in depth studies on the temporary-spatial distribution patterns, trophic complexity and patterns of voltinism of Azorean freshwater biological elements are essential for improving knowledge and the development of typologically appropriate monitoring and conservation programmes and measure for regional stakeholders. Such studies imply the active collaboration between politicians, scientists and the local population.

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