Diatom diversity and distribution in Madeira Island streams (Portugal)

Catarina Ritter‡, Pedro M. Raposeiro‡, Vítor Gonçalves‡
‡ CIBIO, Research Center in Biodiversity and Genetic Resources, InBIO Associate Laboratory / Faculty of Sciences Pbr>and Technology, University of the Azores, Ponta Delgada, Portugal

Corresponding author: Catarina Ritter (catarinaritter@hotmail.com)
Academic editor: Saúl Blanco
Received: 19 Oct 2020 | Accepted: 11 Nov 2020 | Published: 16 Dec 2020
Citation: Ritter C, Raposeiro PM, Gonçalves V (2020) Diatom diversity and distribution in Madeira Island streams (Portugal). Biodiversity Data Journal 8: e59813. https://doi.org/10.3897/BDJ.8.e59813

Abstract

Background

Here, we present the data obtained from the samples collected in a field campaign during the spring of 2015 which aims for a better understanding of the diversity and distribution patterns of freshwater diatoms in Madeira Island. Following European and Portuguese standards and recommendations for routine diatom sampling and analysis, we collected samples in 40 sites, distributed in 27 permanent streams and identified the diatom species present, using general diatom floras and studies in Portuguese freshwater diatoms.

New information

Little is known about the diversity and distribution of freshwater diatom assemblages from Madeira Archipelago. This study reports a survey in 40 sites in Madeira Island distributed in 27 permanent streams. A total of 965 diatom (Bacillariophyta) occurrences were recorded, belonging to 130 different taxa from 44 genera and 27 families. The families with the highest number of occurrences were Bacillariaceae (176), Achnanthidiaceae (135) and Naviculaceae (133). The two diatom endemisms, described previously in Madeira Island (Lange-Bertalot 1993), Nitzschia macaronesica Lange-Bertalot and Navicula madeirensis Lange-Bertalot, were only observed in a small number of sites, located mostly at
Laurissilva forest. Sixty species are new records, not only to Madeira Island, but also to the Madeira Archipelago.

Keywords
Bacillariophyta, oceanic islands, freshwater systems, new records, diatom occurrences

Introduction
Diatoms (Bacillariophyta) are microscopic algae and one of the most abundant and diverse group of aquatic, pigmented single-celled photosynthetic eukaryotes, which can be found in almost every type of aquatic environment around the globe (Kociolek 2007, Pla et al. 2016). These microalgae are characterised by an outer silica wall (frustule) that makes them easy to collect and preserve for later identification. Benthic diatoms, in particular, are important contributors to primary production in streams and are widely used as indicators for monitoring the ecological status of aquatic systems and also for past environmental and climatic reconstructions (Battarbee et al. 2006), since many species have distinct ecological optima and narrow tolerance (Cohen 2003). Diatom communities inhabiting streams have been studied in several regions of the globe (e.g. Tison et al. 2005, Grenier et al. 2006, Mora et al. 2017, Falasco et al. 2016, Liu et al. 2019), including insular streams (Delgado et al. 2012, Delgado et al. 2013, Kopalová et al. 2011, Kopalová and van de Vijver 2013, Gonçalves et al. 2015, Vasselon et al. 2017).

Despite their great importance, current knowledge about the freshwater diatoms on insular streams of Madeira Archipelago is limited in comparison with freshwater macroinvertebrates (Hughes et al. 1998, Hughes and Furse 2001, Hughes 2006), bryophytes (Sérgio and Fontinha 1994, Sérgio et al. 2006, Sim-Sim et al. 2008, Sim-Sim et al. 2014, Sim-Sim et al. 2011, Boch et al. 2019) and hyphomycetes communities (Raposeiro et al. 2020). Although diatoms from the Madeira Archipelago have been a matter of study for more than 150 years (Grunow 1867, De-Toni 1891, De-Toni 1892, Zimmermann 1909, Zimmermann 1911, Schodduyn 1927, Mölder 1947, Lange-Bertalot 1993, Kaufmann et al. 2015, Gonçalves et al. 2016), including the description of two regional endemisms, little is known about the regional overall diversity of these microalgae in Madeira Island. The importance of insular freshwater studies of microalgal diversity is centred around the concept that these ecosystems tend to be less complex, providing much potential for testing ideas about biogeographic theory and species distribution limits (Flower 2005).

Here, we provide a detailed dataset that contains freshwater diatom occurrences collected during a field campaign on Madeira Island, increasing the knowledge on the epilithic diatom inhabiting permanent streams in Madeira Island. Our purpose is to release this valuable dataset, since no similar datasets have been previously published for Madeira Archipelago and it constitutes a relevant tool of comparison for aquatic ecologists, for example, biogeographic patterns, climate change or other studies on oceanic islands.
Project description

Title: Diatom diversity and distribution in Madeira Island streams (Portugal)

Personnel: Collections were undertaken and occurrence data recorded during the spring of 2015 in Madeira Island. The collectors were Pedro Raposeiro and Vitor Gonçalves. Identifications were made by Catarina Ritter and supervised by Vitor Gonçalves.

Study area description: The Madeira Archipelago is an oceanic archipelago located in the North Atlantic between latitudes 32°24' and 33°07'N and longitudes 16°16' and 17°16'W (Fig. 1). Madeira Island is the highest (Pico Ruivo - 1861 m) and largest island (~ 740 km²) of the archipelago and about 90% of its area is higher than 500 m above sea level (Ribeiro 1985). Madeira Island presents a high diversity of habitat types, including the largest surviving area of Laurissilva forest in Macaronesia, classified as a UNESCO World Natural Heritage site (IUCN 1999). Due to its oceanic condition, Madeira Island presents a mild temperate oceanic climate strongly influenced by winds from the NE and the Canary Islands current, presenting a relative humidity between 55-75% and annual rainfall between 500 and 1,000 mm (AEMET & IM 2012). An important aspect of the climate in Madeira Island is the persistent nebulous covering of fog, which normally exists in high altitude resulting in an important source of groundwater recharge (Prada et al. 2005). Under this mild temperate oceanic climate, groundwater hydrology is essential for surface water and for the persistence and functioning of the insular aquatic ecosystems as a high number of the permanent streams are fed by springs.

Figure 1. Geographical location of the study stream sites. a. Madeira Archipelago in the Atlantic Ocean highlighted by a red square; b. Madeira Island in the Madeira Archipelago; c. Studied stream sites.
Madeira Island comprises approximately 126 catchments and 200 streams presenting a typical radial drainage pattern common in oceanic islands (Marques 1994). According to Prada et al. 2005, the hydrographic network present in the Island is characterised by deep narrow valleys with a typical U-transverse profile as these are still in a young phase. Most of the streams have a torrential character with high flow rates (Hughes 2006).

**Sampling methods**

**Study extent:** Epilithic freshwater diatoms (Bacillariophyta Karsten 1928) from 40 sites (MAD01 – MAD40) from 27 permanent streams in Madeira Island.

**Sampling description:** In the spring of 2015, epilithic biofilm samples were collected in 40 sites (MAD01 – MAD40) from 27 permanent streams in Madeira Island (Table 1). The sampling sites ranged in altitudes (low, medium and high) and land-uses (natural, agricultural and urban) (Figs 2, 3, 4). For diatom analysis, samples were prepared following the European (Kelly et al. 1998, European Committee for Standardization 2003, European Committee for Standardization 2004) and national recommendations (INAG 2008). Epilithic diatoms were taken from stones with a toothbrush in each sampling site (Fig. 5). Immediately after collection, diatom samples were fixed with formalin at 4% final concentration. Permanent slides were prepared with Naphrax® and at least 400 valves per sample were counted and identified at the lowest taxonomic level possible under oil-immersion phase contrast light microscopy using a Leica DM2500 (Leica Microsystems GmbH, Wetzlar, Germany).

| Sampling code | Stream                  | Municipality          | Sampling date | Latitude(ºN) / Longitude(ºW) | Altitude(m) |
|---------------|-------------------------|-----------------------|---------------|------------------------------|-------------|
| MAD01         | Ribeira dos Socorridos  | Câmara de Lobos       | 28/04/2015    | 32.66319, -16.9606           | 85          |
| MAD02         | Ribeira Brava           | Ribeira Brava         | 28/04/2015    | 32.73395, -17.021            | 409         |
| MAD03         | Ribeira da Vargem       | São Vicente           | 28/04/2015    | 32.76807, -17.0305           | 450         |
| MAD04         | Ribeira de São Vicente  | São Vicente           | 28/04/2015    | 32.77415, -17.0245           | 325         |
| MAD05         | Ribeira Grande          | São Vicente           | 28/04/2015    | 32.77599, -17.0244           | 311         |
| MAD06         | Ribeira Grande          | São Vicente           | 28/04/2015    | 32.28433, -16.7232           | 60          |
| MAD07         | Ribeira Brava           | São Vicente           | 28/04/2015    | 32.75216, -17.0244           | 903         |
| MAD08         | Ribeira Brava           | São Vicente           | 28/04/2015    | 32.74842, -17.0257           | 833         |
| MAD09         | Ribeira dos Socorridos  | Câmara de Lobos       | 29/04/2015    | 32.74522, -16.9591           | 826         |
| Sampling code | Stream                  | Municipality          | Sampling date | Latitude(°N) / Longitude(°W) | Altitude(m) |
|---------------|-------------------------|-----------------------|---------------|------------------------------|-------------|
| MAD10         | Ribeira da Gomeira       | Câmara de Lobos       | 29/04/2015    | 32.74572, -16.9646           | 725         |
| MAD11         | Corgo da Ribeira de Anélis | Câmara de Lobos       | 29/04/2015    | 32.74059, -16.9652           | 780         |
| MAD12         | Ribeira do Cidrão        | Câmara de Lobos       | 29/04/2015    | 32.72749, -16.9653           | 597         |
| MAD13         | Ribeira do Machico       | Machico               | 29/04/2015    | 32.71876, -16.7642           | 10          |
| MAD14         | Ribeira do Juncal        | Machico               | 29/04/2015    | 32.77081, -16.8289           | 36          |
| MAD15         | Ribeira do Juncal        | Machico               | 29/04/2015    | 32.76142, -16.8376           | 187         |
| MAD16         | Ribeira do Faial         | Machico               | 29/04/2015    | 32.74741, -16.8313           | 560         |
| MAD17         | Ribeira do Machico       | Machico               | 29/04/2015    | 32.73962, -16.8347           | 624         |
| MAD18         | Ribeira Primeira         | Machico               | 29/04/2015    | 32.73101, -16.8388           | 791         |
| MAD19         | Ribeira do Machico       | Machico               | 29/04/2015    | 32.73715, -16.8493           | 877         |
| MAD20         | Ribeira de Santa Cruz    | Santa Cruz            | 29/04/2015    | 32.68695, -16.792            | 7           |
| MAD21         | Ribeira da Janela         | Porto Moniz           | 30/04/2015    | 32.85522, -17.1537           | 81          |
| MAD22         | Ribeira do Alecrim       | Porto Moniz           | 30/04/2015    | 32.75164, -17.1121           | 1391        |
| MAD23         | Ribeira da Janela         | Porto Moniz           | 30/04/2015    | 32.7603, -17.1241            | 1089        |
| MAD24         | Ribeira da Janela         | Porto Moniz           | 30/04/2015    | 32.76077, -17.1283           | 1041        |
| MAD25         | Ribeira dos Cedros       | Porto Moniz           | 30/04/2015    | 32.76582, -17.1256           | 899         |
| MAD26         | Ribeira da Janela         | Porto Moniz           | 30/04/2015    | 32.76503, -17.1324           | 1003        |
| MAD27         | Ribeira da Janela         | Porto Moniz           | 30/04/2015    | 32.76191, -17.1252           | 1271        |
| MAD28         | Ribeira do Alecrim       | Porto Moniz           | 30/04/2015    | 32.7535, -17.129             | 1182        |
| MAD29         | Ribeira Frio             | Santana               | 01/05/2015    | 32.72254, -16.8897           | 846         |
| MAD30         | Córrego do Arrochete     | Santana               | 01/05/2015    | 32.73768, -16.8864           | 637         |
| MAD31         | Ribeira da Metade        | Santana               | 01/05/2015    | 32.74293, -16.9064           | 686         |
| MAD32         | Ribeira das Lajes         | Santana               | 01/05/2015    | 32.73838, -16.9057           | 23          |
| MAD33         | Ribeira de São Roque do Faial | Santana               | 01/05/2015    | 32.78725, -16.8497           | 42          |
| MAD34         | Ribeira Seca             | Santana               | 01/05/2015    | 32.78758, -16.8505           | 103         |
| MAD35         | Ribeira de São Jorge     | Santana               | 01/05/2015    | 32.81442, -16.9044           | 121         |
| MAD36         | Ribeira dos Arcos        | Santana               | 01/05/2015    | 32.81342, -16.904            | 517         |
| Sampling code | Stream                          | Municipality | Sampling date | Latitude(°N) / Longitude(°W) | Altitude(m) |
|---------------|--------------------------------|--------------|---------------|-----------------------------|-------------|
| MAD37         | Ribeira de São Jorge           | Santana      | 01/05/2015    | 32.82849, -16.8978          | 21          |
| MAD38         | Ribeira de Santa Luzia         | Funchal      | 02/05/2015    | 32.67818, -16.9182         | 25          |
| MAD39         | Ribeira da Fonte do Bugio      | Calheta      | 02/05/2015    | 32.72153, -17.1784         | 22          |
| MAD40         | Ribeira da Ponta do Sol        | Ponta do Sol | 02/05/2015    | 32.6803, -17.1052          | 85          |

**Figure 2.** Sampling site representing the natural land-use. Located at Ribeira Primeira, Santo António da Serra, Machico (MAD18).

**Figure 3.** Sampling site representing the agricultural land-use. Located at Ribeira de São Jorge, Santana (MAD37).
Figure 4. Sampling site representing an urban land-use. Located at Ribeira da Janela, Porto Moniz (MAD21).

Figure 5. Collecting epilithic diatoms from stones with a toothbrush at each sampling site.
Quality control: Diatom morphometric features were determined by photomicrography (Leica DFC495) with the aid of image analysis software (LAS version 3.8.0). Diatom identification was based on reference diatom floras (e.g. Krammer and Lange-Bertalot 1986, Krammer and Lange-Bertalot 1988, Krammer and Lange-Bertalot 1991, Krammer and Lange-Bertalot 2000, Krammer and Lange-Bertalot 2002, Lange-Bertalot et al. 2017), as well as on recent bibliographic sources, including the series “Diatoms of Europe”, “Bibliotheca Diatomologica”, relevant taxonomic papers (e.g. Trobajo et al. 2013, Wetzel et al. 2015) and studies in Portuguese freshwater diatoms (Novais et al. 2014). Nomenclatural and taxonomic status used here follows Algaebase (Guiry and Guiry 2020).

Step description: The data have been published as a Darwin Core Archive (DwC-A), which is a standardised format for sharing biodiversity data as a set of one or more data tables. The core data table contains 965 occurrences with 130 records (Ritter et al. 2020).

Geographic coverage

Description: Madeira Island, Madeira Archipelago, Macaronesia, Portugal.

Coordinates: 32.6228N and 32.8815N Latitude; -17.2739W and -16.6487W Longitude.

Taxonomic coverage

Description: All diatoms were identified to genus or species level. In total, 130 taxa were identified belonging to five subclasses, 17 orders, 27 families and 44 genera distributed in the subphylums Coscinodiscophytina and Bacillariophytina.

Taxa included:

| Rank       | Scientific Name   | Common Name |
|------------|-------------------|-------------|
| phylum     | Bacillariophyta   | Diatom      |

Usage licence

Usage licence: Open Data Commons Attribution License

IP rights notes: This work is licensed under a Creative Commons Attribution (CC-BY) 4.0 License.

Data resources

Data package title: Diatom distribution in Madeira Island streams (Portugal)

Resource link: [http://ipt.gbif.pt/ipt/resource?r=occmad&v=1.2](http://ipt.gbif.pt/ipt/resource?r=occmad&v=1.2)
Alternative identifiers:  https://www.gbif.org/dataset/296407fd-6661-4ac8-afa0-f480d5e1d4de

Number of data sets:  1

Data set name:  Diatom distribution in Madeira Island streams (Portugal)

Data format:  Darwin Core Archive

Data format version:  1.2

Description:  This paper presents data from freshwater diatoms surveys developed in Madeira Island in 2015. The dataset has been published as a Darwin Core Archive (DwC-A), which is a standardised format for sharing biodiversity data as a set of one or more data tables. The core data table contains 40 events (eventID), 965 occurrences (occurrenceID) with 130 taxa (taxonID). The number of records in the data table is illustrated in the IPT link. This IPT archives the data and thus serves as the data repository. The data and resource metadata are available for downloading in the downloads section.

| Column label           | Column description                                                                 |
|------------------------|-----------------------------------------------------------------------------------|
| scientificNameAuthorship | The authorship information for the scientificName.                                  |
| type                   | The nature of the resource.                                                        |
| basisofRecord          | The specific nature of the data record.                                            |
| occurrenceID           | Identifier of the record, coded as a global unique identifier.                     |
| eventID                | Identifier of the event, unique for the dataset.                                   |
| eventDate              | Time interval when the event occurred.                                             |
| continent              | Continent of the sampling site.                                                    |
| waterBody              | Water body of the sampling site.                                                   |
| islandGroup            | Island group of the sampling site.                                                 |
| island                 | Island from the Island Group of the sampling site.                                 |
| country                | Country of the sampling site.                                                      |
| countryCode            | Code of the country where the event occurred.                                      |
| municipality           | Name of the municipality where the event occurred.                                 |
| locality               | Name of the locality where the event occurred.                                     |
| decimalLatitude        | The geographic latitude of the sampling site.                                      |
| decimalLongitude       | The geographic longitude of the sampling site.                                     |
| geodeticDatum          | The spatial reference system upon which the geographic coordinates are based.      |
taxonID | The identifier for the set of taxon information (data associated with the Taxon class). Specific identifier to the dataset.
scientificName | The name with authorship applied on the first identification of the specimen.
acceptedNameUsage | The specimen accepted name, with authorship.
knight | Kingdom name.
phylum | Phylum name.
class | Class name.
order | Order name.
family | Family name.
genus | Genus name.
specificEpithet | The name of the first or species epithet of the scientificName.
infraspecificEpithet | The name of the lowest or terminal infraspecific epithet of the scientificName, excluding any rank designation.
taxonRank | The taxonomic rank of the most specific name in the scientificName.
coordinateUncertaintyInMetres | The indicator for the accuracy of the coordinate location in metres, described as the radius of a circle around the stated point location.

### Additional information

### Analysis

This study presents 965 diatom (Bacillariophyta) occurrences in 40 sites in Madeira Island, belonging to 130 different taxa from 44 genera, 27 families, 4 suborders, 17 orders, 5 subclasses, 3 classes and 2 subphyllums (Table 2).

| Orders          | Families | Genera | Total taxa | Total species | New records | Madeira endemisms |
|-----------------|----------|--------|------------|---------------|-------------|-------------------|
| Aulacoseirales  | 1        | 1      | 2          | 1             | 1           | 1                 |
| Bacillariales   | 1        | 2      | 22         | 21            | 10          | 1                 |
| Cocconeidales   | 2        | 6      | 18         | 16            | 9           |                   |
| Cymbellales     | 3        | 7      | 18         | 18            | 8           |                   |
| Eunotiales      | 1        | 1      | 4          | 3             | 3           |                   |
| Eupodiscales    | 1        | 1      | 1          | 1             | 1           |                   |
| Fragilariales   | 2        | 3      | 14         | 14            | 9           |                   |
| Orders            | Families | Genera | Total taxa | Total species | New records | Madeira endemisms |
|-------------------|----------|--------|------------|---------------|-------------|-------------------|
| Licmophorales     | 1        | 1      | 1          | 1             |             |                   |
| Mastogloiales     | 1        | 2      | 3          | 2             | 3           |                   |
| Melosirales       | 2        | 2      | 2          | 2             |             |                   |
| Naviculales       | 7        | 12     | 2          | 31            | 13          | 1                 |
| Rhopalodiales     | 1        | 1      | 31         | 2             |             |                   |
| Stephanodiscales  | 1        | 1      | 2          | 2             | 2           |                   |
| Surirellales      | 1        | 1      | 1          | 1             | 1           |                   |
| Tabellariales     | 1        | 2      | 3          | 3             |             |                   |
| Thalassiophysales | 1        | 1      | 4          | 3             | 1           |                   |

The subphylum Coscinodiscophytina, represented by one class, two orders and three families, accounted for 1.5% of the total occurrences, while the subphylum Bacillariophytina registered 98.4% of the total occurrences. With two classes and four subclasses, most occurrences (815) were registered in the Bacillariophycidae subclass.

The families with the highest number of occurrences were Bacillariaceae (176), Achnanthidiaceae (135) and Naviculaceae (133). However, the families with the highest number of taxa were Bacillariaceae (23), Naviculaceae (15), Achnanthidiaceae (15) and Rhoicospheniaceae (10). The families with lower occurrences (< 5) were Surirellaceae (1), Diploneidaceae (2), Aulacoseiraceae (2), Eupodiscaceae (2) and Stephanodiscaceae (2). However, the families with the smallest number of diatom taxa were Eupodiscaceae (1), Naviculales incertaesedis (1), Surirellaceae (1) and Ulnariaceae (1).

The genera with the highest number of occurrences were *Nitzschia* (174), *Navicula* (130), *Planothidium* (73), *Cocconeis* (54), *Sellaphora* (51), *Fragilaria* (51) and *Gomphonema* (50). The other 37 genera had less than 50 occurrences. The genera with the highest number of taxa were *Nitzschia* (22) and *Navicula* (13).

*Achnanthidium minutissimum* (Kützing) Czarnecki and *Planothidium lanceolatum* (Brébisson ex Kützing) Lange-Bertalot were the most frequent species occurring in 38 from 40 sites (MAD20 and MAD13 were the exceptions). *Nitzschia soratensis* E.A.Morales & M.L.Vis (37 sites), *Cocconeis placentula* var. *euglypta* (Ehrenberg) Grunow (36 sites), *Amphora pediculus* (Kützing) Grunow ex A.Schmidt (34 sites), *Navicula reichardtiana* Lange-Bertalot (33 sites) and *Ulnaria ulna* (Nitzsch) Compère (31 sites) were amongst the most ubiquitous diatoms.

A total of 45 diatom taxa occurring at only one sampling site were considered rare. These include benthic species, such as *Achnanthes minuscula* Hustedt, *Achnanthidium pyrenaicum* (Hustedt) H.Kobayasi, *Adlafia minuscula* (Grunow) Lange-Bertalot, *Adlafia multnomahii* E.A.Morales & M.Lee, *Caloneis silicula* (Ehrenberg) Cleve, *Encyonema amanianum* Kramer, *Eunotia arcus* Ehrenberg, *Eunotia paludosa* Grunow, *Frustulia...
vulgaris (Thwaites) De Toni, *Gomphonema augur* Ehrenberg, *Luticola mutica* (Kützing)
D.G.Mann, *Nitzschia brevissima* Grunow, *Nitzschia filiformis* (W.Smith) Van Heurck,
*Planothidium daui* (Foged) Lange-Bertalot, *Rhopalodia gibba* (Ehrenberg) Otto Müller,
amongst others; planktonic species, such as *Aulacoseira granulata* (Ehrenberg) Simonsen;
tychoplanktonic species, such as *Fragilaria capucina* Desmazières, *Pseudoaestuosa* *elliptica* (Schumann) Edlund, *Mores* & Spaulding, *Pseudoaestuosa* *robusta* (Fusey)
D.M.Williams & Round, *Pseudoaestuosa subconstricta* (Grunow) Kulikovskiy & Genkal,
*Staurosirella lapponica* (Grunow) D.M.Williams & Round, *Stephanodiscus minutulus* (Kützing) Cleve & Möller, *Stephanodiscus parvus* Stoermer & Håkansson; and aerophilic
species, such as *Diploneis elliptica* (Kützing) Cleve, *Diploneis praeterrxima* Lange-Bertalot
& A.Fuhrmann, *Humidophila brekkaensis* (Petersen) R.L.Lowe, Kociolek, J.R.Johansen,
Van de Vijver, Lange-Bertalot & Kopalová and *Orthoseira roeseana* (Rabenhurst) Pfitzer.

Another 32 diatom taxa were considered occasional, occurring in two to five sampling
sites. These included benthic species, such as *Achnanthidium gracillimum* (F.Meister)
Lange-Bertalot, *Amphora inariensis* Krammer, *Craticula molestiformis* (Hustedt) Mayama,
*Eunotia implicata* Nörpel, Lange-Bertalot & Alles, *Gomphonema acuminatum* Ehrenberg,
*Gomphosphenia lingulatiformis* (Lange-Bertalot & E.Reichardt) Lange-Bertalot, *Grunowia solgensis* (A.Cleve) Aboal, *Hippodonta capitata* (Ehrenberg) Lange-Bertalot, Metzeltin & Rotary,
*Laticola goeppertiana* (Bleisch) D.G.Mann ex J.Rarick, S.Wu, S.S.Lee & Edlund, *Navicula madeirensis* Lange-Bertalot, *Navicula recens* (Lange-Bertalot) Lange-
Bertalot, *Nitzschia recta* Hantzsch ex Rabenhurst, *Planothidium amphibium* C.E.Wetzel,
L.Ector & L.Pfister, *Platezza oblongella* (Østrup) C.E.Wetzel, Lange-Bertalot & Ector,
*Pleurosira laevis* (Ehrenberg) Compère, *Psammothidium hustedtii* (Krasske) S.Mayama,
planktonic species, such as *Fragilaria gracilis* Østrup and the tychoplanktonic species
*Staurosirella pinnata* (Ehrenberg) D.M.Williams & Round and *Tabellaria flocculosa* (Roth)
Kützing.

The mean number of taxa per sample was 24.1 ± 1.1 SE taxa. MAD40, MAD14, MAD26
and MAD23 were the samples with the highest number of taxa, 49, 38, 34 and 32,
respectively. The samples with the lowest number of taxa were MAD20, MAD19 and
MAD09 with 11, 14 and 15 taxa, respectively.

The two diatom endemisms, described previously in Madeira Island (Lange-Bertalot,
1993), *Nitzschia macaronesica* Lange-Bertalot and *Navicula madeirensis* Lange-Bertalot,
were only observed in a small number of sites. *Nitzschia macaronesica* was present in 10
sites: Ribeira do Cidrão (MAD12), Ribeira do Juncal (MAD14), Corgo da Ribeira dos Aneis
(MAD16), Ribeira da Janela (MAD23, MAD24 and MAD26), Ribeira dos Cedros (MAD25),
Ribeira da Metade (MAD31), Ribeira das Lages (MAD32) and Ribeira de São Jorge
(MAD37). This endemism appeared in sites with a richer diatom community (mean number
of taxa of 28.9 ± 1.5 SE), located mostly at high altitude and was associated with *Navicula
cryptocephala, Navicula reichardtiana, Nitzschia soratensis* and *Ulnaria ulna*, apart from
the ubiquitous *Achnanthidium minutissimum, Amphiara pediculus, Cocconeis placentula
var. euglypta* and *Planothidium lanceolatum*. 

12 Ritter C et al
Navicula madeirensis occurred only in four sites from different permanent streams: Ribeira do Faial (MAD16), Ribeira do Machico (MAD19), Ribeira do Alecrim (MAD28) and Ribeira da Fonte do Bugio (MAD39). These four sites were distributed in low (1), medium (1) and high (2) altitudes and they have a mean number of taxa below average (23.5 ± 2.9 SE). Navicula madeirensis occurred in association with Planorothidium frequentissimum (Lange-Bertalot) Lange-Bertalot, Rhoicosphenia abbreviata (C.Agardh) Lange-Bertalot and Karayevia clevei (Grunow) Round & Bukhtiyarova, apart from the ubiquitous Achnanthisidium minutissimum, Amphora pediculus, Cocconeis placentula var. euglypta and Planorothidium lanceolatum.

In this survey, 60 records were new, not only to Madeira Island, but also to the Madeira Archipelago (Table 3). These include 55 species, two varieties and three genera (sp.).

| Class                  | Order       | Family          | First records for Madeira Archipelago | Sampling sites |
|------------------------|-------------|-----------------|---------------------------------------|----------------|
| Bacillariophyceae      | Bacillariales | Bacillariaceae  | Nitzschia acidoclinata                 | MAD40          |
|                        |             |                 | Lange-Bertalot 1976                    |                |
|                        |             |                 | Nitzschia alpinobacillum               | MAD40          |
|                        |             |                 | Lange-Bertalot 1993                    |                |
|                        |             |                 | Nitzschia clausii                      | MAD25          |
|                        |             |                 | Hantzsch 1860                          |                |
|                        |             |                 | Nitzschia dealpina                     | MAD28          |
|                        |             |                 | Lange-Bertalot & Hoffmann 1993         |                |
|                        |             |                 | Nitzschia filiformis                   | MAD14          |
|                        |             |                 | (W.Smith) Van Heurck 1896              |                |
|                        |             |                 | Nitzschia filiformis var. conferta     | MAD14          |
|                        |             |                 | (P.G.Richter) Lange-Bertalot 1987      |                |
|                        |             |                 | Nitzschia fonticola                    | MAD06; MAD11;  |
|                        |             |                 | (Grunow) Grunow 1881                   | MAD12; MAD13;  |
|                        |             |                 |                                        | MAD14; MAD14;  |
|                        |             |                 |                                        | MAD31; MAD34;  |
|                        |             |                 |                                        | MAD36; MAD37;  |
|                        |             |                 |                                        | MAD40          |
| Class               | Order               | Family            | First records for Madeira Archipelago | Sampling sites |
|---------------------|---------------------|-------------------|----------------------------------------|----------------|
|                     |                     | Cocconeidales     | Nitzschia perminuta Grunow 1881         | MAD11; MAD12; MAD14; MAD16; MAD25; MAD34; MAD37; MAD38 |
|                     |                     |                   | Nitzschia pusilla Grunow 1862           | MAD08; MAD09; MAD11; MAD21; MAD38 |
|                     |                     |                   | Nitzschia recta Hantzsch ex Rabenhorst 1862 | MAD25; MAD26 |
|                     |                     |                   | Nitzschia tubicola Grunow 1880          | MAD39 |
|                     |                     |                   | Achnanthidium gracillimum (F.Meister) Lange-Bertalot 2004 | MAD22 |
|                     |                     |                   | Achnanthidium jackii Rabenhorst 1861    | MAD30 |
|                     |                     |                   | Achnanthidium saprophilum (H.Kobayashi & Mayama) Round & Bukhtyiarova 1996 | MAD32 |
|                     |                     |                   | Achnanthidium straubianum (Lange-Bertalot) Lange-Bertalot 1999 | MAD01; MAD33; MAD36 |
|                     |                     |                   | Planothidium amphibium C.E.Wetzel, L.Ector & L.Pfister 2014 | MAD09; MAD10; MAD12; MAD21 |
|                     |                     |                   | Planothidium daui (Foged) Lange-Bertalot 1999 | MAD19 |
|                     |                     |                   | Planothidium dubium (Grunow) Round & Bukhtyiarova 1996 | MAD40 |
| Class            | Order              | Family                      | First records for Madeira Archipelago | Sampling sites     |
|------------------|--------------------|-----------------------------|---------------------------------------|--------------------|
|                  |                    | Adlafia bryophila           |                                       | MAD14, MAD15, MAD21, MAD22, MAD23, MAD36 |
|                  |                    | (J.B.Petersen) Lange-Bertalot 1998 |                                       |                    |
|                  |                    | Adlafia minuscula           |                                       | MAD21              |
|                  |                    | (Grunow) Lange-Bertalot 1999 |                                       |                    |
|                  |                    | Adlafia multnomahii         |                                       | MAD14              |
|                  |                    | E.A.Morales & M.Lee 2005    |                                       |                    |
| Cymbellales      | Anomoeoneidaceae   | Encyonema amanianum         |                                       | MAD23              |
|                  |                    | Krammer 1997               |                                       |                    |
|                  | Gomphonemataceae   | Gomphonema augur            |                                       | MAD40              |
|                  |                    | Ehrenberg 1841             |                                       |                    |
|                  |                    | Gomphonema clavatulum      |                                       | MAD07, MAD08, MAD11, MAD14, MAD15, MAD21, MAD23, MAD25, MAD26, MAD27, MAD31 |
|                  |                    | E.Reichardt 1999           |                                       |                    |
|                  | Rhoicospheniaceae  | Gomphonema minutum         |                                       | MAD23, MAD40       |
|                  |                    | (C.Agardh) C.Agardh 1831    |                                       |                    |
|                  | Eunotiales         | Gomphosphenia lingulatiformis (Lange-Bertalot & E.Reichardt) Lange-Bertalot 1991 | MAD14; MAD15; MAD39 |
|                  | Eunotiaceae        | Eunotia arcus              |                                       | MAD22              |
|                  |                    | Ehrenberg 1837             |                                       |                    |
|                  |                    | Eunotia sp.                |                                       | MAD08; MAD18; MAD19; MAD24; MAD27 |
| Class         | Order          | Family          | First records for Madeira Archipelago | Sampling sites   |
|--------------|----------------|-----------------|--------------------------------------|------------------|
|              | Fragilariales  | Fragiliariaceae | *Eunotia paludosa* Grunow 1862        | MAD31            |
|              |                |                 | *Fragilaria microvaucheriae* C.E.Wetzel & Ector 2015 | MAD26; MAD35; MAD36; MAD37; MAD40 |
|              |                |                 | *Fragilaria pectinalis* (O.F.Müller) Lyngbye 1819 | MAD03; MAD21; MAD23; MAD26; MAD36; MAD40 |
|              |                |                 | *Fragilaria perminuta* (Grunow) Lange-Bertalot 2000 | MAD16; MAD25     |
|              |                |                 | *Fragilaria recapitellata* Lange-Bertalot & Metzeltin 2009 | MAD06; MAD12; MAD31; MAD32; MAD34; MAD38 |
|              |                |                 | *Fragilaria rumpens* (Kützing) G.W.F.Carlson 1913 | MAD05; MAD20; MAD22; MAD23; MAD28; MAD30; MAD35 |
| Staurosiaceae|                | Pseudostaurosira elliptica (Schumann) Edlund, Morales & Spaulding 2006 |                     | MAD08            |
|              |                | Pseudostaurosira robusta (Fusey) D.M.Williams & Round 1988 |                     | MAD30            |
|              |                | Pseudostaurosira subconstricta (Grunow) Kulikovsky & Genkal 2011 |                     | MAD26            |
|              |                | Staurosirella lapponica (Grunow) D.M.Williams & Round 1987 |                     | MAD23            |
| Mastogloiales|                | Achnanthaceae   | *Achnanthes brevipes* var. brevipes Agardh 1824 | MAD40            |
| Class          | Order           | Family                  | First records for Madeira Archipelago | Sampling sites |
|---------------|-----------------|-------------------------|---------------------------------------|----------------|
| Naviculales   | Diadesmidaceae  | *Humidophila brekkaensis* (Petersen) R.L. Lowe, Kociolek, J.R. Johansen, Van de Vijver, Lange-Bertalot & Kopalová 2014 | MAD27              |                |
|               |                 | *Diploneis praetermissa* Lange-Bertalot & A.Fuhrmann 2016 | MAD19              |                |
| Naviculaceae  |                 | *Caloneis silicula* (Ehrenberg) Cleve 1894 | MAD34              |                |
|               |                 | *Hippodonta capitata* (Ehrenberg) Lange-Bertalot, Metzeltin & Witkowski 1996 | MAD02; MAD14      |                |
|               |                 | *Navicula angusta* Grunow 1860 | MAD13; MAD14; MAD40 |                |
|               |                 | *Navicula cryptotenelloides* Lange-Bertalot 1993 | MAD40              |                |
|               |                 | *Navicula recens* (Lange-Bertalot) Lange-Bertalot 1985 | MAD26; MAD29      |                |
|               |                 | *Navicula rostellata* Kützing 1844 | MAD28; MAD29; MAD40 |                |
|               |                 | *Navicula tantula* Hustedt 1943 | MAD07; MAD08; MAD14; MAD25; MAD26; MAD27; MAD28; MAD33; MAD34; MAD37; MAD39 |                |
|               |                 | *Navicula tenelloides* Hustedt 1937 | MAD14; MAD25; MAD27; MAD34 |                |
| Class                      | Order                      | Family              | First records for Madeira Archipelago | Sampling sites |
|----------------------------|----------------------------|---------------------|---------------------------------------|---------------|
|                            |                            | Sellaphoraceae      | Sellaphora atomoides (Grunow) Wetzel & Van de Vijver 2015 | MADO2; MADO4; MADO7; MADO8; MADO12; MADO13; MADO15; MADO16; MADO17; MADO18; MADO21; MADO22; MADO23; MADO29; MADO30; MADO33; MADO34; MADO36; MADO38; MADO39; MADO40 |
|                            |                            | Stauroneidaceae     | Craticula molestiformis (Hustedt) Mayama 1999 | MADO11; MADO12; MADO30 |
|                            |                            |                     | Fistulifera saprophila (Lange-Bertalot & Bonik) Lange-Bertalot 1997 | MADO01; MADO02; MADO04; MADO09; MADO10; MADO12; MADO13; MADO14; MADO15; MADO16; MADO17; MADO18; MADO20; MADO21; MADO33; MADO34; MADO35; MADO38; MADO40 |
|                            |                            | Surirellales        | Surirella terricola Lange-Bertalot & E.Alles 1996 | MADO40 |
|                            |                            | Thalassiophysales   | Catenulaceae                       | AMPHORA sp. | MADO31 |
|                            |                            | Coscinodiscophyceae | Aulacoseirales                    | AULACOSEIRA sp. | MADO04 |
|                            |                            | Mediophyceae        | Stephanodisccales                 | Stephanodiscus minutulus (Kützing) Cleve & Möller 1882 | MADO14 |
|                            |                            |                     |                                       | Stephanodiscus parvus Stoermer & Håkansson 1984 | MADO40 |

**Discussion**

The diatom diversity (130 taxa belonging to 44 genera) displayed by Madeira Island in the 27 permanent streams in this study is due to the habitat complexity (including water quality, habitat structure and climate), as well as large scale-effects stemming from the Islands’
isolation and geographical location as was found on other oceanic islands (Flower 2005, Gonçalves et al. 2015).

Diatom diversity from Madeira Island is relatively low when compared to other oceanic islands and continental regions (e.g. Herlory et al. 2013, Gonçalves et al. 2015, Jyrkänkallio-Mikkola et al. 2018). This kind of comparison is difficult to make since it depends on the sampling efforts: the number of samples analysed, the timing of the samplings, the number of surveys carried out, the physical and chemical composition of the waters, the number of substrates sampled and the taxonomic effort with which the diatom valves were analysed (Morales et al. 2009, Veselá and Johansen 2009).

Nonetheless, when comparing archipelagos in the Macaronesia Region, 201 diatom taxa were recorded in 316 samples from 14 permanent Azorean streams (Gonçalves et al. 2015). However, the number of diatom taxa recorded per sample was higher in Madeira Island (24.1 ± 1.1 SE) than in the Azores (20.9 ± 2.7 SE). Additionally, it is worth mentioning that this study is focused on the main island from the Madeira Archipelago which does not represent the different microhabitats present in all the other islands.

Comparisons to other regions in the world reveal how diatom diversity in Madeira Island is “poor”. For instance, in a tropic region (Sub-Saharan Africa), the number of diatom taxa identified in 67 sites in Kenya was significantly greater (297 taxa) than the number of taxa recorded in Madeira Island (Jyrkänkallio-Mikkola et al. 2018).

The low diversity of freshwater biota has already been reported to the Madeira Archipelago (Hughes and Malmqvist 2005), as well as other oceanic islands in the world (Brasher et al. 2004, Flower 2005, Delgado et al. 2012).

This insular oceanic ecosystem should offer some degree of isolation from continental floras, but the special conditions that promote speciation on islands are not present, for example, extreme water quality or geological age and activity (Flower 2005). It is therefore unsurprising that the great majority of taxa had a cosmopolitan distribution (e.g. Achnanthidium minutissimum, Planthtidium lanceolatum, Nitzschia soratensis, Cocconeis placentula var. euglypta) (Flower 2005, Gonçalves et al. 2015). This indicates a lack of isolation mechanisms operating in the Island, but the diatom taxa present are nevertheless clearly attributable to different biogeographical regions.

The Macaronesia Region should register more endemisms for many groups as do other regions (e.g. Antarctic Region, Van de Vijver et al. 2011, Van De Vijver et al. 2004, Kopalová et al. 2009, Kopalová et al. 2011), but due to the lack of research in this Region as stated before, only a few have been found. This might be one of the reasons why we had some taxonomic challenges. Diatoms are extremely diverse and there are many species that have not been described yet, thus the species delimitation is still controversial (Licea et al. 2016). For some diatom groups, it was difficult to distinguish closely-related species because of their wide morphological variation or because many taxa frequently differed in detail from published descriptions. We took a conservative attitude for these taxonomic differences and disregarded small differences in morphometric data.
Considering the significant differences between the islands of Madeira Archipelago, such as geological ages, volcanic composition, climate patterns and distribution, land uses, types of forest and orography, we expect higher diatom species richness and exclusive taxa from these islands (Porto Santo, Desertas, Selvagens). Furthermore, increasing the sampling effort in Madeira Island, for instance, by sampling other streams and/or other sites in the Laurissilva forest, may result in the identification of other diatom taxa. Additionally, higher time replication and larger datasets are required to better understand distribution patterns and large-scale spatial patterns of species dispersal. According to Smucker and Vis (2011), there is a significant under-estimation of diatom diversity when exclusively collecting epilithic habitats for documenting species distribution and for conservation purposes. Taking this into consideration, different methods to obtain the greater number of diatom taxa for each site are encouraged, for instance, by following two distinct sampling techniques (transects located in riffles and from microhabitats) (Falasco et al. 2016).

The factors controlling taxa richness, as well as the regional endemic taxa, remain unclear as there is no convincing link with the simplified habitat features recorded during the study and more research is needed. Relationships are probably multivariate in nature and include site history, unmeasured micro-habitat availability and climate (Flower 2005, Pajunen et al. 2016).

The results of this study provide baseline knowledge on the current distribution of freshwater diatoms on Madeira Island streams, revealing a distinct, but taxonomically simple diatom flora, typical from oceanic island ecosystems (Flower 2005, Gonçalves et al. 2015). In order to better understand the complexity of these streams, depth studies on the temporal and spatial distribution patterns, population dynamics, species’ interactions, guilds and traits are essential for improving knowledge and the development of future effective monitoring and conservation programmes and measures for local stakeholders.

Acknowledgements

This work was funded by national funds through FCT – Foundation for Science and Technology under the PTDC/CTA-AMB/28511/2017 and DL57/2016/ ICETA/EEC2018/25. The field surveys comply with the current laws of Portugal. Thanks are also extended to the reviewers for their very useful comments on earlier versions of this manuscript.

Author contributions

CR, PMR, VG conceived the study and PMR and VG carried out the sampling campaign in Madeira Island. CR prepared and identified the epilithic diatoms and VG supervised. CR wrote the paper with inputs from all authors. All authors agree with the final version of the paper.
References

• AEMET & IM (2012) Atlas climático de los archipiélagos de Canarias, Madeira y Azores. Agencia Estatal de Meteorología

• Battarbee R, Jones V, Flower RJ, Cameron N, Bennion H, Carvalho L, Juggins S (2006) Diatoms. In: Smol J, Birks HJ, Last W (Eds) Tracking environmental change using lake sediments. Vol. 3. Terrestrial, algal, and siliceous indicators. Springer Netherlands, 47 pp. [ISBN 1-4020-0681-0]. https://doi.org/10.1007/0-306-47668-1_8

• Boch S, Martins A, Ruas S, Fontinha S, Carvalho P, Reis F, Bergamini A, Sim-Sim M (2019) Bryophyte and macrolichen diversity show contrasting elevation relationships and are negatively affected by disturbances in laurel forests of Madeira island. Journal of Vegetation Science 30: 1122-1133. https://doi.org/10.1111/jvs.12802

• Brasher AD, Wolff R, Luton C (2004) Associations among land-use, habitat characteristics, and invertebrate community structure in nine streams on the island of Oahu, Hawaii. U.S. Geological Survey Water-Resources Investigations Report 03-4256, Denver: 47.

• Cohen AS (2003) Paleolimnology: The History and Evolution of Lake Systems. Oxford University Press [ISBN 9780195133530] https://doi.org/10.1093/oso/9780195133530.001.0001

• Delgado C, Pardo I, García L (2012) Diatom communities as indicators of ecological status in Mediterranean temporary streams (Balearic Islands, Spain). Ecological Indicators 15: 131-139. https://doi.org/10.1016/j.ecolind.2011.09.037

• Delgado C, Ector L, Novais HM, Blanco S, Hoffmann L, Pardo I (2013) Epilithic diatoms of springs and spring-fed streams in Majorca Island (Spain) with the description of a new diatom species Cymbopleura margalefii sp. nov. Fottea 13 (2): 87-104. https://doi.org/10.5507/fot.2013.009

• De-Toni JB (1891) Sylloge Algarum omnium hucusque cognitarum. Vol. II. Bacillarieae Sectio I. Rhaphideae. Padova [Padua]

• De-Toni JB (1892) Sylloge Algarum omnium hucusque cognitarum. Vol. II. Bacillarieae Sectio II. Pseudorhaphideae. Padova [Padua]

• European Committee for Standardization E (2003) Water quality – Guidance standard for the routine sampling and pre-treatment of benthic diatoms from rivers. EN 13946:2003.

• European Committee for Standardization E (2004) Water quality – Guidance standard for the identification, enumeration and interpretation of benthic diatom samples from running water. EN 14407:2004.

• Falasco E, Piano E, Bona F (2016) Diatom flora in Mediterranean streams: flow intermittency threatens endangered species. Biodiversity and Conservation 25 (14): 2965-2986. https://doi.org/10.1007/s10531-016-1213-8

• Flower RJ (2005) A taxonomic and ecological study of diatoms from freshwater habitats in the Falkland Islands, South Atlantic. Diatom Research 20 (1): 23-96. https://doi.org/10.1080/0269249X.2005.9705620

• Gonçalves V, Marques HS, Raposeiro PM (2015) Diatom assemblages and their associated environmental drivers in isolated oceanic island streams (Azores archipelago as case study). Hydrobiologia 751 (1): 89-103. https://doi.org/10.1007/s10750-015-2174-8
• Gonçalves V, Marques H, Teixeira D, Raposeiro P (2016) Freshwater diatoms from Desertas Islands (Madeira, Portugal). Arquipelago. Life and Marine Sciences, Supplement 9. 2nd International Conference on Island Evolution, Ecology and Conservation: Island Biology 2016, Angra do Herismo, Azores.

• Grenier M, Campeau S, Lavoie I, Park YS, Lek S (2006) Diatom reference communities in Québec (Canada) streams based on Kohonen self-organizing maps and multivariate analyses. Canadian Journal of Fisheries and Aquatic Sciences 63 (9): 2087-2106. https://doi.org/10.1139/f06-101

• Grunow A (1867) Reise seiner Majestät Fregatte Novara um die Erde. Botanischer Theil I. Band. Algen. Kaiserlich-Königliche Hof- und Staatsdruckerei, Wien

• Guiry MD, Guiry GM (2020) AlgaeBase. World-wide electronic publication, National University of Ireland, Galway. URL: https://www.algaebase.org; searched on 13 October 2020

• Herlory O, Bonzom J, Gilbin R, Frelon S, Fayolle S, Delmas F, Coste M (2013) Use of diatom assemblages as biomonitor of the impact of treated uranium mining effluent discharge on a stream: case study of the Ritord watershed (Center-West France). Ecotoxicology 22 (8): 1186-1199. https://doi.org/10.1007/s10646-013-1106-5

• Hughes S, Furse M (2001) Development of a biotic score for the assessment of the ecological quality of the rivers and streams of Madeira. Arquipélagos, Life and Marine Sciences. Supplement 2: 19-32.

• Hughes SJ, Furse MT, Blackburn JH, Langton PH (1998) A checklist of Madeiran freshwater macroinvertebrates. Boletim do Museu Municipal do Funchal 50 284: 5-41.

• Hughes SJ, Malmqvist B (2005) Atlantic Island freshwater ecosystems: challenges and considerations following the EU Water Framework Directive. Hydrobiologia 544 (1): 289-297. https://doi.org/10.1007/s10750-005-1695-y

• Hughes SJ (2006) Temporal and spatial distribution patterns of larval Trichoptera in Madeiran streams. Hydrobiologia 553 (1): 27-41. https://doi.org/10.1007/s10750-005-0627-1

• INAG (2008) Manual para a avaliação biológica da qualidade da água em sistemas fluviais segundo a Directiva Quadro da Água: Protocolo de amostragem e análise para o fitobentos – diatomáceas. Ministério do Ambiente, Ordenamento do Território e do Desenvolvimento Regional. Instituto da Água, I.P. 63 pp.

• IUCN W (1999) IUCN guidelines for the prevention of biodiversity loss due to biological invasion. Species 31: 28-42.

• Jyrkänkallio-Mikkola J, Siljander M, Heikinheimo V, Pellikka P, Soininen J (2018) Tropical stream diatom communities – The importance of headwater streams for regional diversity. Ecological Indicators 95: 183-193. https://doi.org/10.1016/j.ecolind.2018.07.030

• Kaufmann M, Santos F, Maranhão M (2015) Checklist of nanno- and microphytoplankton off Madeira Island (Northeast Atlantic) with some historical notes. Nova Hedwigia 101: 205-232. https://doi.org/10.1127/nova_hedwigia/2015/0265

• Kelly MG, Cazaubon A, Coring E, Dell'Uomo A, Ector L, Goldsmith B, Guasch H, Hürlimann J, Jarlman A, Kawecka B, Kwandrans J, Laugaste R, Lindstrom EA, Leitao M, Marvan P, Padisák J, Pipp E, Prygiel J, Rott E, Sabater S, van Dam H, Vizinet J (1998) Recommendations for the routine sampling of diatoms for water quality assessments in Europe. Journal of Applied Phycology 10 (2): 215. https://doi.org/10.1023/A:1008033201227
• Kociolek P (2007) Diatoms: Unique eukaryotic extremophiles providing insights into planetary change. Proceedings of SPIE - The International Society for Optical Engineering 6694: 1-15. https://doi.org/10.1117/12.731445
• Kopalová K, Elster J, Nedbalová L, Van de Vijver B (2009) Three new terrestrial diatom species from seepage areas on James Ross Island (Antarctic Peninsula Region). Diatom Research 24 (1): 113-122. https://doi.org/10.1080/0269249X.2009.9705786
• Kopalová K, Nedbalová L, De Haan M, Van De Vijver B (2011) Description of five new species of the diatom genus Luticola (Bacillariophyta, Diadesmidaceae) found in lakes of James Ross Island (Maritime Antarctic Region). Phytotaxa 27: 44-60. https://doi.org/10.11646/phytotaxa.27.1.5
• Kopalová K, van de Vijver B (2013) Structure and ecology of freshwater benthic diatom communities from Byers Peninsula, Livingston Island, South Shetland Islands. Antarctic Science 25 (2): 239-253. https://doi.org/10.1017/S0954102012000764
• Krammer K, Lange-Bertalot H (1986) Bacillariophyceae, Teil 1: Naviculaceae. 1. Gustav Fischer Verlag, Stuttgart, Jena
• Krammer K, Lange-Bertalot H (1988) Bacillariophyceae, Teil 2: Epithemiaceae, Bacillariaceae, Surirellaceae. 2. Gustav Fischer Verlag, Stuttgart, Jena, 595 pp.
• Krammer K, Lange-Bertalot H (1991) Bacillariophyceae, Teil 4: Achnanthaceae, Kritische Erganzungen zu Navicula (Lineolate) und Gomphonema. 4. Gustav Fischer Verlag, Stuttgart, Jena
• Krammer K, Lange-Bertalot H (2000) Bacillariophyceae, part 5: English and French Translation of the Keys. Gustav Fisher Verlag, Stuttgart, Jena
• Krammer K, Lange-Bertalot H (2002) Bacillariophyceae. Teil 3: Centraceae, Fragariaceae, and Eunotiaceae. 3. Gustav Fischer Verlag, Stuttgart, Jena
• Lange-Bertalot AH (1993) 85 neue Taxa und über 100 weitere neu definierte Taxa ergänzend zur Süsswasserflora von Mitteleuropa. Vol. 2/1-4. Bibliotheca Diamotologia 27: 1-164.
• Lange-Bertalot H, Hofmann G, Werum M, Cantonati M (2017) Freshwater Benthic diatoms of Central Europe. Over 800 common species used in ecological assessment. English edition with updated taxonomy and added species. English edition with updated taxonomy and added species. Koeltz Botanical Books [ISBN 978-3-946583-06-6]
• Licea S, Ji M, Luna R (2016) Checklist of diatoms (Bacillariophyceae) from the Southern Gulf of Mexico: Data-base (1979-2010) and new records. Journal of Biodiversity & Endangered Species 4: 1-7.
• Liu L, He X, Fu J, Yang Y, Mi W, Shi J, Wu Z (2019) Benthic diatom communities in the main stream of three gorges reservoir area and Its relationship with environmental factors. Huan jing ke xue= Huanjing kexue / [bian ji, Zhongguo ke xue yuan huan jing ke xue wei yuan hui "Huan jing ke xue" bian ji wei yuan hui.] 40: 3577-3587. https://doi.org/10.13227/j.hjkx.201901017
• Marques Z (1994) Avaliação dos recursos hídricos superficiais da Ilha da Madeira (Fase1). Laboratório Nacional de Engenharia Civil, Funchal.
• Mölder K (1947) Beiträge zur Kenntnis der Diatomeenflora auf den Azoren. Societas Scientiarum Fennica. Commentationes Biologicae 8: 1-11.
• Mora D, Carmona J, Jahn R, Zimmermann J, Abarca N (2017) Epilithic diatom communities of selected streams from the Lerma-Chapala Basin, Central Mexico, with the description of two new species. PhytoKeys 88 https://doi.org/10.3897/phytokeys.88.14612
• Morales E, Siver P, Trainor F (2009) Identification of diatoms (Bacillariophyceae) during ecological assessments: Comparison between light microscopy and scanning electron microscopy techniques. Proceedings of the Academy of Natural Sciences of Philadelphia 151: 95-103. https://doi.org/10.1635/0097-3157(2001)151[0095:IODBDE]2.0.CO;2
• Novais MH, Blanco S, Morais M, Hoffmann L, Ector L (2014) Catalogue of continental diatoms from Portugal, including the Archipelagos of Azores and Madeira: updated nomenclature, distribution and bibliography. Königstein: Koeltz Scientific Books https://doi.org/10.13140/RG.2.1.1034.9604
• Pajunen V, Luoto M, Soininen J (2016) Climate is an important driver for stream diatom distributions. Global Ecology and Biogeography 25 (2): 198-206. https://doi.org/10.1111/geb.12399
• Pla S, Hamilton P, Ballesteros E, Gavriló M, Friedlander A, Sala E (2016) The structure and diversity of freshwater diatom assemblages from Franz Josef Land Archipelago: A northern outpost for freshwater diatoms. PeerJ 4 https://doi.org/10.7717/peerj.1705
• Prada SN, da Silva MO, Cruz JV (2005) Groundwater behaviour in Madeira, volcanic island (Portugal). Hydrogeology Journal 13 (5): 800-812. https://doi.org/10.1007/s10040-005-0448-3
• Raposeiro PM, Faustino H, Ferreira V, Gonçalves V (2020) Aquatic Hyphomycetes from streams on Madeira Island (Portugal). Biodiversity Data Journal 8: e53690. https://doi.org/10.3897/BDJ.8.e53690
• Ribeiro O (1985) A ilha da Madeira até meados do século XX: estudo geográfico. Instituto de Cultura e Língua Portuguesa, Ministério da Educação
• Ritter C, Raposeiro P, Gonçalves V (2020) Diatom distribution in Madeira Island streams (Portugal). Occurrence dataset. Universidade dos Açores via GBIF.org. URL: https://doi.org/10.15468/bmhccu
• Schodduyn R (1927) Contribution pour l'hydrobiologie des îles de Funchal et Porto Santo. Brotéria, Série Botânica 23: 67-72.
• Sérgio C, Fontinha S (1994) Natural and semi-natural bryophyte flora of the coastal dry zones of Madeira Island. Boletim do Museu Municipal do Funchal 46 (254): 95-144.
• Sérgio C, Sim-Sim M, Carvalho M (2006) Annotated catalogue of Madeiran bryophytes. Boletim do Museu Municipal do Funchal 10.
• Sim-Sim M, Luís L, García C (2008) New data on the status of threatened bryophytes of Madeira Island. Journal of Bryology 30 https://doi.org/10.1179/174328208X322260
• Sim-Sim M, Bergamini A, Luís L, Fontinha S, Martins S, Lobo C, Stech M (2011) Epiphytic bryophyte diversity on Madeira Island: Effects of tree species on bryophyte species richness and composition. The Bryologist 114: 142-154. https://doi.org/10.1639/007-2745-114.1.142
• Sim-Sim M, Ruas S, Fontinha S, Hedenäs L, Sérgio C, Lobo C (2014) Bryophyte conservation on a North Atlantic hotspot: Threatened bryophytes in Madeira and Selvagens Archipelagos (Portugal). Systematics and Biodiversity 12 https://doi.org/10.1080/14772000.2014.918063
• Smucker N, Vis M (2011) Diatom biomonitoring of streams: Reliability of reference sites and the response of metrics to environmental variations across temporal scales. Ecological Indicators 11 (6): 1647-1657. https://doi.org/10.1016/j.ecolind.2011.04.011
• Tison J, Park YS, Coste M, Wasson JG, Ector L, Rimet F, Delmas F (2005) Typology of diatom communities and the influence of hydro-ecoregions: A study on the French
• Trobajo R, Rovira L, Ector L, Wetzel C, Kelly M, Mann D (2013) Morphology and identity of some ecologically important small Nitzschia species. Diatom Research 28 (1): 37-59. https://doi.org/10.1080/0269249X.2012.734531

• Van de Vijver B, Zidarova R, Sterken M, Verleyen E, de Haan M, Vyverman W, Hinz F, Sabbe K (2011) Revision of the genus Navicula s.s. (Bacillariophyceae) in inland waters of the Sub-Antarctic and Antarctic with the description of five new species. Phycologia 50 (3): 281-297. https://doi.org/10.2216/10-49.1

• Van De Vijver B, Gremmen N, Beyens L, Le Cohu R (2004) Pinnularia sofi Van de Vijver and Le Cohu spec. nov., a new spine-bearing, chain-forming Pinnularia species from the sub-antarctic region. Diatom Research 19 (1): 103-114. https://doi.org/10.1080/0269249X.2004.9705610

• Vasselon V, Rimet F, Tapolczai K, Bouchez A (2017) Assessing ecological status with diatoms DNA metabarcoding: Scaling-up on a WFD monitoring network (Mayotte island, France). Ecological Indicators 82: 1-12. https://doi.org/10.1016/j.ecolind.2017.06.024

• Veselá J, Johansen J (2009) The diatom flora of ephemeral headwater streams in the Elbsandsteingebirge region of the Czech Republic. Diatom Research 24 (2): 443-477. https://doi.org/10.1080/0269249X.2009.9705813

• Wetzel EC, Ector L, Van de Vijver B, Compère P, Mann GD (2015) Morphology, typification and critical analysis of some ecologically important small naviculoid species (Bacillariophyta). Fottea 15 (2): 203-234. https://doi.org/10.5507/fot.2015.020

• Zimmermann C (1909) Beitrag zur Kenntnis der Diatomaceen-Flora der Inseln Madeira und Porto Santo. Broteria. Revista de Sciencias Naturaes do Collegio de San Fiel: Serie Botanica 8: 114-127.

• Zimmermann C (1911) Beitrag zur Kenntnis der Diatomaceen-Flora der Inseln Madeira und Porto Santo [II]. Broteria. Revista de Sciencias Naturaes do Collegio de San Fiel: Serie Botanica 9: 103-120.