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Aristotle's scientific contributions to the classification, nomenclature and distribution of marine organisms

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Abstract

The biological works of the Greek philosopher Aristotle include a significant amount of information on marine animals. This study is an overview of Aristotle's scientific contribution to the knowledge of marine biodiversity and specifically to taxonomic classification, nomenclature and distribution of marine species. Our results show that Aristotle's approach looks remarkably familiar to present day marine biologists since: (i) although not directly aiming at it, he gave a taxonomic classification of marine animals, which includes physical groups ranked on three levels at least; (ii) most of Aristotle's marine "major groups" correspond to taxa of the order rank in Linnaeus's classification and to taxa of the class rank in the current classification; (iii) a positive correlation was found between the number of taxa per group identified in Aristotle's writings and those described by Linnaeus; (iv) Aristotle's classification system exhibits similarities with the current one regarding the way taxa are distributed to higher categories; (v) a considerable number of Aristotle's marine animal names have been used for the creation of the scientific names currently in use; (vi) he was the first to give an account of Mediterranean marine fauna, focusing on the Aegean Sea and adjacent areas. In view of the above, we suggest that the foundations of marine taxonomy as laid down by Aristotle are still echoing today.

Keywords: Aegean Sea, Ancient Greece, history of marine biology, marine biodiversity, philosophy of biology.

Introduction

The Greek philosopher Aristotle (see BOX 1 for a short biography) is known as a universal scientist with a wide range of interests. While medicine, mathematics and astronomy had already been developed by pre-Socratic philosophers, Aristotle first defined the scientific method and laid the foundations of several scientific disciplines (see Lloyd, 1970; Shields, 2012).

Biology attracted his attention more than any other science (*epistēmē*) and biological writings constitute over 25% of the surviving Aristotelian corpus (Gotthelf & Lennox, 1987). Aristotle was the first to systematically observe and describe biological diversity (Ross, 1977; Leroi, 2014). A great part of his biological works is devoted to the study of marine animals. His interest in marine biology can be linked to his close relationship with the sea; the place where he was born and raised (Macedonian coast) along with his stay for several years on the eastern coast of the Aegean Sea (Assos in Asia Minor and Lesbos Island) probably aroused his interest in the study of the marine environment. He was familiar with the great variety of fish and marine invertebrates harvested and exploited by the coastal Aegean communities, as demonstrated by archaeological records (Mylona, 2008). Aristotle carried out most of his marine research during his stay on Lesbos Island, more specifically in Kalloni Bay, which is frequently mentioned in his biological writings as *Pyrraiōn Evripos* (the Strait of *Pyrra*), *Pyrra* being a town on the eastern coast of the Bay (Thompson D'Arcy, 1913). There, with the help of local fishermen, he had the opportunity to study existing marine life; he also had access to material for his anatomical work and was able to observe, first hand, aspects of the biology and behaviour of marine animals. Consequently, it has been assumed that the bulk of his biological work was done during his stay in Lesbos Island (Lee, 1948). However, Solmsen (1978) suggested that his biological studies continued during his subsequent stay for 6 years in Macedonia, while educating Alexander the Great, and completed during the 13 years of teaching at the Lyceum in Athens.

Aristotle also developed the first scientific classification of animals based on his interpretation of their interrelationships. The taxonomical component of his biology was questioned by some classicists who considered that classification had not been a theoretical task for Aristotle as it had been for the 18th-19th century taxonomists, and that he presented a variety of orderings of animals according to different points of view (see Pellegrin, 1986). In contrast, his classification was recognized and praised by the early taxonomists and evolutionists. Thus, Charles Darwin admired his work as a taxonomist and compared him to Carl Linnaeus (Gotthelf, 1999), while Cuvier (1841) commented that Aristotle's "… genius for

classifying was the most extraordinary ever produced by nature…" Based on these appraisals, an evaluation of Aristotle's contribution to taxonomy by modern biologists showed that a fairly consistent classification exists in his zoological works (Fürst von Lieven & Humar, 2008).

Being the first written documents on zoology and marine biodiversity, Aristotle's works formed the basis for the subsequent few authors (e.g. Pliny the Elder) who wrote on these subjects until the middle of the 16th century. Aristotle's knowledge of animals was passed on to the early modern taxonomists of the 16th-18th centuries, including Linnaeus (Linnaeus, 1758-1759) and Cuvier (Cuvier & Valenciennes, 1828), through his original writings in Greek or in Latin translations, or through Pliny's *Natural History* (Leroi, 2014).

BOX 1. Aristotle was born in 384 BC. Up to the age of sixteen he lived in Stagira, a small town in Macedonia, Northern Greece. He joined Plato's Academy in Athens where he stayed and was instructed by Plato himself for the next twenty years. After Plato's death, he left Athens and spent five years in Asia Minor and on Lesbos Island. In 342 BC, he returned to his homeland, invited by Philip of Macedon to become a tutor of his 13-year-old son Alexander (later "the Great"). He returned to Athens again, and established his own philosophical school, the 'Lyceum', and for the next 13 years taught and wrote the greatest part of his treatise on philosophy and science. Increasingly, he immersed himself in empirical studies, combining theory with investigations, thereby shifting away from Platonism. After a long and fruitful life and career, he died in Chalkis, on the Island of Euboea, in 323 BC. In recognition of his important contribution to philosophy and science, UNESCO declared year 2016 (the year of his 2400th birth anniversary) "Aristotle Anniversary Year".

Aristotle's contribution to the knowledge of marine animals has been the subject of older studies (Thompson D'Arcy, 1947) and has recently attracted the interest of marine scientists who worked on the identification of marine taxa described in his biological works (e.g. Scharfenberg, 2001; Tipton, 2006; Voultsiadou & Vafidis, 2007; Ganias *et al*., 2017). Aiming to explore the roots of marine biological study, these works provide baseline information for comparisons between ancient and current conditions. Their results can also provide input to other scientists, including historians, archaeologists and philosophers.

Taking into account the long discussion on Aristotle's taxonomy, the opposing views among scholars and scientists and the interesting outcomes of recent research on his marine invertebrates and fish, we considered it worthy to evaluate his contribution to the study of marine biodiversity from the marine biologist's perspective. For this purpose, we compiled a complete classification of marine species according to Aristotle and compared it for the first time, and as far as possible, with Linnaeus's and current classification, using multivariate analysis. Moreover, we examined his work on marine animal names and the extent to which it contributed to the current marine species nomenclature. Finally, we drafted a general report on marine species distributions in his works.

Methodology

For the purposes of this study, Aristotle's biological works [*History of Animals* (*HA*), *Parts of Animals* (*PA*), *Movement of Animals* (*MA*), *Progression of Animals* (*IA)* and *Generation of Animals* (*GA*)] were studied, from the LOEB classical Library, Harvard University (Peck, 1942, 1961, 1965, 1970; Forster, 1961; Balme, 1991) translations, and the standard editions of Greek classical text therein. The catalogue of Aristotle's marine animal names along with the recent taxa corresponding to them (see Table S1) was compiled mostly by extracting the relevant identifications from the publications on Aristotle's invertebrates and fishes of Voultsiadou & Vafidis (2007), Voultsiadou *et al*. (2010) and Ganias *et al*. (2017); a few fresh water fish species and a crustacean are also included in the list. Marine tetrapods were added to this list, by analyzing information from the original writings mentioned above, thus covering all marine animal diversity recorded by Aristotle. The updated taxonomy of the animal species occurring in Aristotle's books was accomplished using the World Register of Marine Species (WoRMS Editorial Board, 2017). For the purposes of the statistical analysis, we took into account only Aristotle's names that correspond to distinct current species (not to higher taxa), even if it was not possible to identify all of them to species level.

In order to evaluate Aristotle's classification of marine organisms and estimate to what extent his concept of taxonomy remains today, we compared the classification of the 181 taxa mentioned in his biological works with the current classification of the same taxa. We based this comparison of the two classification schemes on the taxa relatedness and used the Average Taxonomic Distinctness ($\Delta+$), and Variation in Taxonomic Distinctness ($\Lambda+$) indices. Average Taxonomic Distinctness is defined by Clarke & Warwick (1998) as:

$$\Delta^+ = [\sum\sum_{i<j} \omega_{ij}] / [s(s-1)/2]$$

where ω_{ij} is the taxonomic path length between species i and j, and s is the number of species.

Variation in Taxonomic Distinctness is defined by Clarke & Warwick (2001) as:

$$\Lambda^+ = [\{\sum\sum_{i<j} \omega_{ij}^2\} / \{s(s-1)/2\}] - [\Delta^+]^2.$$

The two indices calculate the average degree to which the species in a classification are taxonomically related to one another, i.e., the taxonomical breadth of the classification, and the evenness of taxa distribution across the taxonomic tree, respectively. To our knowledge, this is attempted for the first time.

To make the comparisons possible, we constructed two types of matrices for each of the classification systems: (a) an aggregation matrix with all species and their higher classification and, (b) a species by higher taxa matrix where the distribution of the species in the higher taxa was coded as 1/0 (presence/absence), following Warwick & Somerfield (2008). We used the 6 primary taxonomic levels (i.e. species, genus, family, order, class and phylum) for the aggregation matrix of WoRMS and only four that are available in Aristotle's classification system. A number of assumptions were made in order to fill in the gaps in Aristotle's classification system. For those taxa, which were not identified to species level, we assumed that (a) all their intermediate ranks were unique, and (b) Aristotle did not assign them to any intermediate level of his classification system. This is the most parsimonious assumption to run the entire exercise without the need of heavy modelling and the consequent dependence of the results on the process.

Next, both Δ^+ and Λ^+ values were calculated from the distribution of the species to higher taxonomic categories in both systems (Clarke & Warwick, 2001) and were compared by means of a two-tailed Mann-Whitney test (Mann & Whitney, 1947). Assuming that (a) the two classification systems are independent in that they were developed in different time frames and under different theoretical frameworks, and (b) the Taxonomic Distinctness values represent the taxa interrelations in the two classification systems, we tested the hypothesis that the distributions of these values calculated from the two systems are not different; or, simply, that the two classification systems do not differ in species relatedness measures.

Since taxa in Aristotle's taxonomic ranks correspond to different levels of the current classification system (e.g. rank 3 includes taxa at the phylum, class and order levels, e.g. Porifera, Malacostraca and Cetacea, respectively), we made all possible comparisons between Δ^+ and Λ^+ results for all taxa comparing ranks 2 and 3 with those from different levels of the current classification system (i.e. family, order, class, and phylum). Aristotle's rank 4 is composed only by two taxa (*anhaima* = bloodless and *enhaima* = blooded animals), a division which is not comparable to any category of our current classification system. In addition, it is not possible to calculate the Δ^+ and Λ^+ values for the taxa composing the first level (species and rank 1, respectively) simply because there isn't any category below to calculate the distribution of the taxa composing that category to species or rank 1 level.

All the above analyses were performed using the PRIMER v6 Package (Clarke & Gorley, 2006) and the Social Science Statistics website.

Aristotle, the "marine Linnaeus" avant la lettre: his classification of marine animals

In his endeavour to bring a degree of order to animal diversity, Aristotle gave an account of the rules to be followed in order to classify animals in his work *Parts of Animals* (*PA*642-644). Some of his ideas were: (i) a simple dichotomous division of animal *genē* (genera = groups or taxa) should be avoided since it is arbitrary; (ii) animal *genē* should be defined on the basis of multiple characters rather than a single one without, however, defining these characters; (iii) animal *genē* are physical groups that take a certain name (like birds or fish), while other groupings (like terrestrial and aquatic) are anonymous (i.e. those based on non-taxonomic characters); (iv) animals that differ by analogy are put in different *genē* (e.g. a bird that has feathers and a fish that has scales), while those that differ by excess and defect or by the more and the less can be grouped together (e.g. a bird with short wings and another with long ones). According to Lloyd (1961), his rejection of the usefulness of dichotomy in his biological works represents an important development in his thoughts on the classification of animals since it contrasts sharply with the acceptance of that method in his previous works.

Even though his intention was not to give a comprehensive classification of animals and he did not define any categories or ranks to assign his animal groups, a hierarchical grouping of marine animals is noticeable in his works with many of his groupings being 'monophyletic', as Fürst von Lieven & Humar (2008) suggest through a cladistic analysis of Aristotle's animal groups, based on characters derived from his *History of Animals*.

Aristotle divided animals into *anhaima* (bloodless animals - the invertebrates) and *enhaima* (blooded animals - the vertebrates) and he defined several *megista genē* (major genera – the modern higher taxa). His classification of marine animals is presented in Figure 1, which clearly shows that his major groups are comparable, to some degree, both to the classification presented by Linnaeus (Fig. 2) and the current taxonomic groups. Actually, Aristotle's major groups mostly correspond to Linnaeus' taxa of the order rank, with the exception of Ichthyes that correspond to the class Pisces, and to the class rank of the modern classification (his *malakia, malakostraka, ichthyes* and *kētodē* are the modern Cephalopoda, Malacostraca, Pisces and Cetacea, respectively). Although a thorough comparison of Aristotle's classification with that of Linnaeus is not possible, since Linnaeus never worked in the same biogeographic sector in which Aristotle did (Aegean Sea), a few issues can be pointed out: (i) Aristotle classified both bony and cartilaginous fish in one group called *Ichthyes*, while Linnaeus classified cartilaginous fish in the class Amphibia, along with turtles, frogs and snakes and kept the class Pisces only for the bony fish; (ii) Aristotle kept *entoma* (insects) and *malakostraka* (crustaceans) as two different groups; Linnaeus on the other hand placed the current crustaceans in the order Aptera of his class Insecta; (iii) Aristotle classified echinoderms and ascidians along with gastropods and bivalves in *ostrakoderma* while Linnaeus classified these groups along with sea anemones, polychaetes and cephalopods in the order Mollusca;

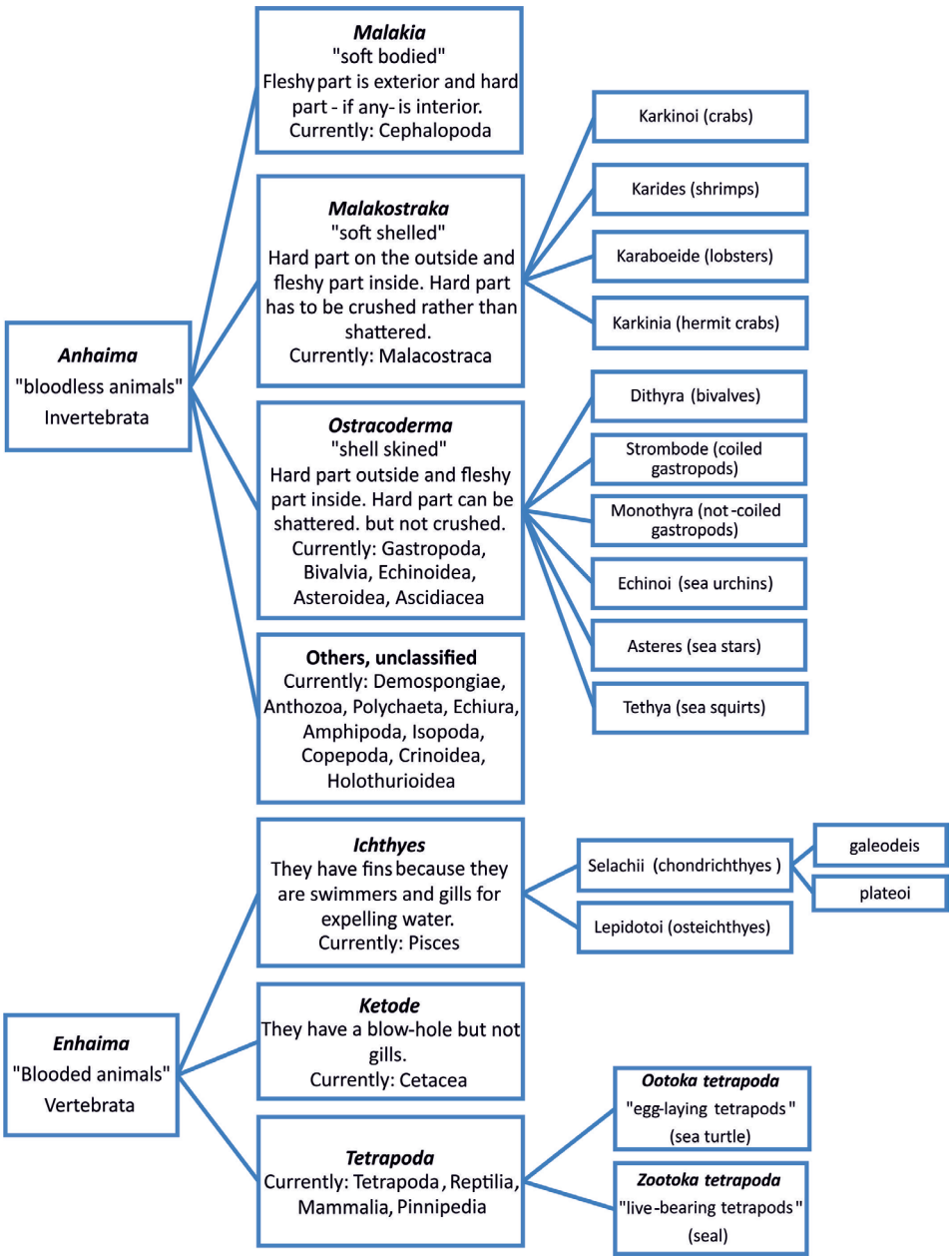

Fig. 1*:* Schematic representation of Aristotle's marine animal taxonomic classification including the diagnostic characters for each group. Bold italics indicate Aristotle's names Latinized and the English translation of these names are inside quotation marks" The general morphological characters and the corresponding current taxa are given for each animal group.

(iv) Aristotle correctly included the nautilus and the paper nautilus (*Argonauta argo* Linnaeus, 1758) in his *malakia* (current cephalopods) while Linnaeus placed them with gastropods in the order Testacea.

Beyond their differences in the number of ranks and the breadth of the groups, the two classification schemes both have a typical hierarchical structure. Probably, observations of this kind made previous researchers suggest that Linnaeus "made Aristotle's method of classification work" (Balme, 1970) and that "he went further than Aristotle but following the same path in the process of animal classification" (Pellegrin, 1986).

Compared to the modern classification, Aristotle's grouping of marine animals presents several differences. Fürst von Lieven & Humar (2008) suggest that, despite these differences, the cladogram reconstructing Aristotle's system of animal groups is very close to a modern phylogenetic tree. Besides the absence of a taxon equivalent to modern Mollusca in Aristotle and the absence of an equivalent to the Aristotelian *ostracoderma* in contemporary classification highlighted by these authors, one can find several "errors", as for example the placement of (i) ascidians and echinoids in *ostracoderma* (*PA*680a5) along with bivalves and gastropods, because of their hard body cover, and (ii) the angler fish in *selachia* along with rays and skates (*HA*749a23), probably because of its flattened body form, although Aristotle knew that it was oviparous and had a bony skeleton. However, when

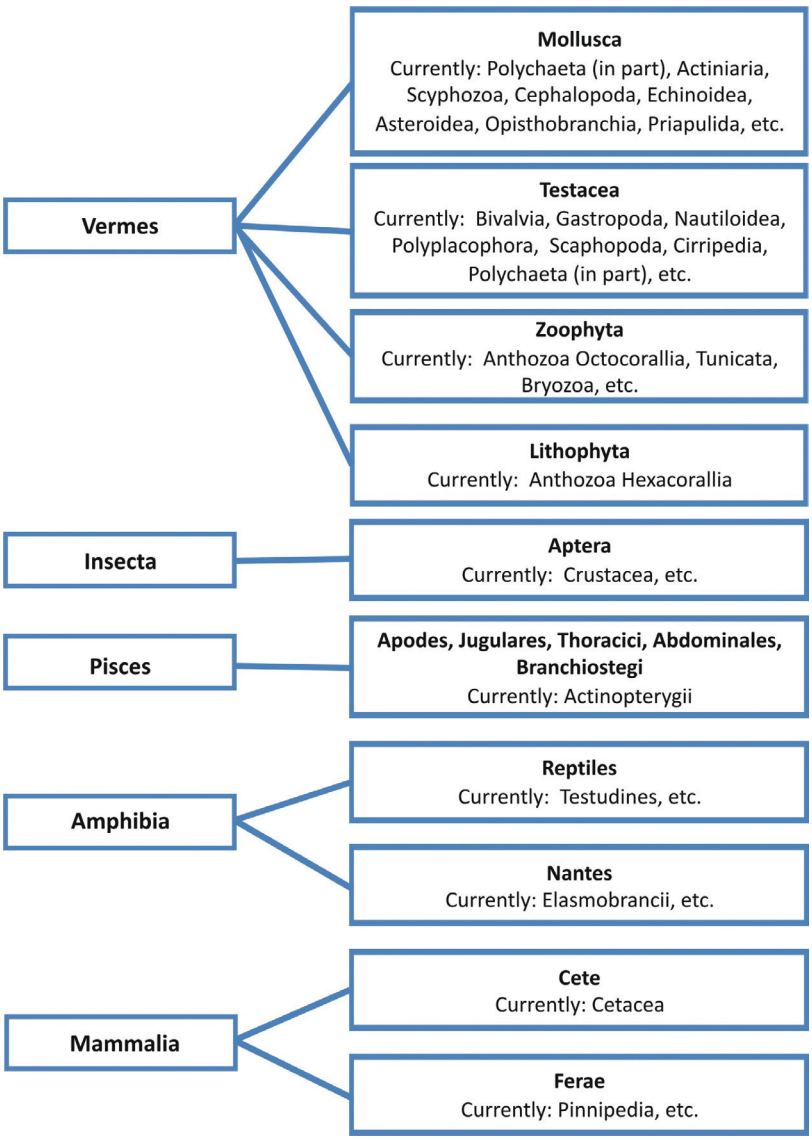

Fig. 2: Schematic representation of Linnaeus's classification of marine animals, at class and order rank, as presented in the 10th Edition of his *Systema Naturae* (Linnaeus, 1758-1759).

we take into account the huge challenges Aristotle must have faced when developing his pioneering work in marine taxonomy more than two millennia ago, one can only admire him, as Charles Darwin did after a limited encounter with Aristotle's writings, two months before his death (Gotthelf, 1999).

Besides his well-defined major groups, shown in Figure 1, Aristotle defined several *eidē* (species) as dualizing (*epamphoterizonta*), i.e. combining traits of two different groups. Thus, he considered sea anemones (*PA*681b1) and ascidians as having both plant and animal traits. He also described sponges as resembling plants but reacting to stimuli like animals (*HA*487b10, 588b21) while, much later, Linnaeus (1758-1759) classified sponges among algae (Algae, Cryptogamia) along with lichens. Moreover, while he classified *karkinia* (hermit crabs) in *malakostraka*, he noted that in a way they are intermediate between *malakostraka* and *ostracoderma*, since they look like the former but live in a shell like the latter (*HA*529b20). Some animals were characterized intermediate by Aristotle, though not between two different groups but according to their mode of life; the seal, for instance, is partly terrestrial and partly marine, since it breaths air and gives birth on land but feeds in the sea (*HA*566b27).

In his biological works, one can find more than 1,400 records of marine animal names, which were identified as 200 taxa of various taxonomic categories and 181 taxa of the species category (not all of them identified to species level) as can be seen in Table S1. From the data of Table S1, the number of taxa per group of marine animals identified from Aristotle's writings were estimated and presented in Table 1, along with those defined by Linnaeus (1758-1759). According to these data, a strong positive correlation was found between the number of taxa per group described by Aristotle and those described by Linnaeus (Spearman's rho = 0.75, $P < 0.05$). As shown in Table S1, around 61% of the marine animals identified

to species level in Aristotle's works, have been first described by Linnaeus.

The extent of Aristotle's interest in marine animals ranges from simply mentioning them to describing their morphology and anatomy in detail. Many times, throughout his biological writings, he refers to the *Anatomai* (the Anatomies - a separate book thought to contain his drawings, which is not extant) for a better understanding of his descriptions. Characteristic examples of marine animal groups with particular interest for Aristotle and consequently with exhaustive descriptions and specific reference to their diversity are (i) the cephalopods, for which he gives a detailed comparison of *sēpia* (cuttlefish), *polypous* (octopuses), *teuthos* and *teuthis* (squids) and distinguishes the anatomy of males and females (*HA*524-525); (ii) the Macrura Reptantia [*astakos* = *Hommarus gammarus* (Linnaeus, 1758) and *karabos* = *Palinurus elephas* (Fabricius, 1787)], which he also describes in a comparative manner (*HA*525-526); (iii) the bath sponges, for which he explains the nature and morphology, and names the four species harvested in the Mediterranean (*HA*548b); (iv) the sea urchins, that are given a thorough description of general body structure and anatomy (*HA*530b). Some of these descriptions have been examined thoroughly in the light of modern biology (Scharfenberg, 2001; Voultsiadou, 2007; Voultsiadou & Chintiroglou, 2008).

But, are the foundations of marine taxonomy as laid down by Aristotle still echoing today? An answer to this question was given by the results of the statistical analysis performed on the basis of the two taxonomic measures Δ^+ and Λ^+. The results of the Mann-Whitney U test showed that the comparisons of both the values Δ^+ and Λ^+ from rank 2 against order and family levels, and rank 3 against class and order levels, do not offer any evidence to reject the null hypothesis that the two systems of classification (Aristotle's and contemporary) do not differ in terms of the interrelationships of their own taxa, whereas the comparisons of rank 2 with class level and rank 3 with phylum level, do offer such evidence (Table 2).

These results suggest that, at least partially, the two classification systems present significant similarities both in terms of the breath of their taxonomic trees and the distribution of their taxa to the higher categories. The compelling interpretation of this result is that part of Aristotle's concept of taxonomy is indeed still echoing in our currently used system.

Aristotle's contribution to marine animal nomenclature

Records of animal names, mostly terrestrial, appear occasionally in the extant written documents of the classical literature prior to Aristotle's time. One can find some in the epics of Homer and Hesiod, the fables of Aesop, Aeschylus' tragedies, Aristophanes' comedies, Plato's philosophy, Herodotus' history and Hippocrates' medicine. However, a considerable percentage of the names that appear in Aristotle's writings are not found in earlier written documents (see Voultsiadou & Vafidis, 2007; Ganias *et al.*, 2017). This does not necessarily mean that Aristotle invented all these names, but rather that he was the first to assemble the existing names in a biological treatise and created new ones where needed.

Table 1. Summary table showing the numbers of marine taxa identified from Aristotle's works, marine taxa identified by Linnaeus (with indication of currently valid species in brackets), currently accepted marine species occurring in Greek waters and currently accepted marine species occurring in the Mediterranean Sea IHO area, according to Coll *et al*. (2010). Information on the number of taxa identified by Linnaeus is based on the World Register of Marine Species (WoRMS Editorial Board, 2017). Information regarding Greek marine waters is based on the preliminary and validated species checklists of the Greek Taxon Information System (GTIS) initiative of the LifeWatchGreece Research Infrastructure (Bailly *et al*., 2016). Marine quadrupeds in this context are limited to Cetacea, Pinnipedia and Reptilia.

	Taxa identified by Aristotle	Taxa identified by Linnaeus	Species in Greek waters	Species in the Mediterranean Sea
Porifera	5	53 (10)	215	681
Cnidaria	4	237 (80)	86	757
Polychaeta	1	132 (50)	849	1,122
Echiura	1	0 (0)	1	6
Mollusca	28	1832 (596)	812	2,113
Crustacea	21	164 (99)	813	2,239
Echinodermata	9	127 (31)	91	154
Ascidiacea	1	25 (5)	75	229
Pisces	105	1150 (292)	510	650
Marine quadrupeds	6	40 (19)	16	28
TOTAL	181	3,760 (1,182)	3,468	7,979

Table 2. Results of the two-tailed Mann-Whitney U Test for different taxonomic ranks of Aristotle's and the current classification systems (* significance at the 0.05 level, ** significance at the 0.01 level).

	Taxonomic distinctness (AvTD or Δ+)		Variation in AvTD (VarTD or Λ+)	
Combinations	Z-Score	p-value	Z-Score	p-value
Rank 3 vs. Phylum	-3.41954	**0.00062****	-2.45117	**0.01428***
Rank 3 vs. Class	1.46806	0.14156	0.91074	0.36282
Rank 3 vs. Order	-1.23204	0.2187	-1.14004	0.25428
Rank 2 vs. Class	-2.40296	**0.0164***	-2.9613	**0.00308****
Rank 2 vs. Order	-0.1616	0.87288	0.49667	0.61708
Rank 2 vs. Family	-1.35952	0.17384	0.13354	0.89656

Many animal names used by Aristotle – such as *polypous*, *sēpia*, *karabos*, *astakos*, *xiphias* – will have been the vernacular names at the time, while other names had already been used to describe certain groups of animals in the works of earlier authors, e.g. *anhaima* and *enhaima* in Empedocles's *Testimonia*. Several names, however, were probably invented by Aristotle in order to describe the observed animal diversity; such names are: *kētodē* (cetaceans), *dithyra* (bivalves), *monothyra* (univalves) and *malakostraka* (soft-shelled).

For many of the early taxonomists of the 16th-18th centuries who had chosen the Greek language to develop the scientific terminology in their field of expertise, Aristotle's works were a rich source of inspiration for zoological names. Linnaeus (1758-1759), in his *Systema Naturae,* while establishing the binomial nomenclature and the names of higher taxa, used a variety of Greek names, mostly based on Aristotle. Those names were Latinized from Aristotle's Greek names, and include: *Atherina, Asterias, Delphinus, Echinus, Muraena, Ostrea, Pinna, Perca, Phocoena, Sepia, Solen, Spongia, Trigla* and *Xiphias*. Moreover, *Brissus* (Gray), *Carcinus* (Leach), *Pinnotheres* (Latreille), *Scyllarus* (Fabricius), and *Spatangus* (Gray) are examples of Latinized Aristotelian names given to invertebrate genera by 19th century taxonomists (see WoRMS Editorial Board, 2017). Probably due to insufficient understanding of Aristotle's descriptions, some names have been wrongly used for taxa other than those described by him; *Lepas,* the name given by Linnaeus to a genus of barnacles is a notable example; Aristotle used this name for the limpet currently known as *Patella caerulea* Linnaeus, 1758.

Aside from zoological nomenclature, Aristotle's writings also served as a source of terms pertaining to marine biology. A characteristic example is 'Aristotle's lantern', which has been used since the 18th century for the jaw apparatus of echinoids. After a recent review of Aristotle's description (Voultsiadou & Chintiroglou, 2008), along with a study of archaeological findings from the area and the period he lived in, and other contemporary texts, it was proposed that the term should be correctly used for the test of the sea urchin since the whole animal resembles an ancient lantern (lamp holder) and the jaw apparatus resembles the lamp inside it.

The identification of animals behind Aristotle's names is not always easy (Leroi, 2014) and several past attempts resulted in misidentifications (see Ganias *et al*., 2017, for detailed comments). The correct assignment of classical names and Aristotle's descriptions to current taxa depends on the amount of information provided by him, which in some cases is adequate and in others insufficient. The fact that many of Aristotle's names provide clues for identifying his taxa is very helpful when these are not easily recognizable from his descriptions. As can be seen from the following examples, the Greek words usually denote some of the animal's characters: (i) *pinnotheres* (*pinna* + *tērō* = guard) was used by Aristotle to name the crab "guarding the fan mussel" thereby referring to *Pinnotheres pisum* (Linnaeus, 1767), a parasitic crab living inside bivalves (such as *Pinna*); (ii) *porphyra,* was used to name the gastropods that produced the reddish-purple colour (*porfyreos* meaning purple-coloured), comprising the three different species, all known as sources of purple dye: *Bolinus brandaris* (Linnaeus, 1758), *Hexaplex trunculus* (Linnaeus, 1758) and *Stramonita haemastoma* (Linnaeus, 1767) (see Alfaro & Mylona, 2014).

The fact that almost all Aristotle's marine animals have an Aegean distribution (see next section) and that many of his names are still used in Modern Greek as common names for the same animal taxa, e.g. *spongos* (Dictyoceratida), *dithyra* (Bivalvia), *pinna* (*Pinna nobilis* Linnaeus, 1758), *solen* (Solenoidea), *astakos* (*H. gammarus*), *echinos* (Echinoidea), *ichthyes* (Pisces), *selachia* (Elasmobranchii), *xiphias* (*Xiphias gladius* Linnaeus, 1758), *porhyra* (Muricidae) facilitates identification. Finally, assistance in the identification of names not well-documented by Aristotle can sometimes be obtained from information on animal properties found in the works of other classical authors, subsequent to Aristotle, including Dioscorides, Xenocrates, Athenaeus and Galen, who wrote mostly about the uses of marine animals for dietary and medicinal purposes.

Thus, Aristotle clearly lives on in marine nomenclature, not only by leaving behind a tremendous source of

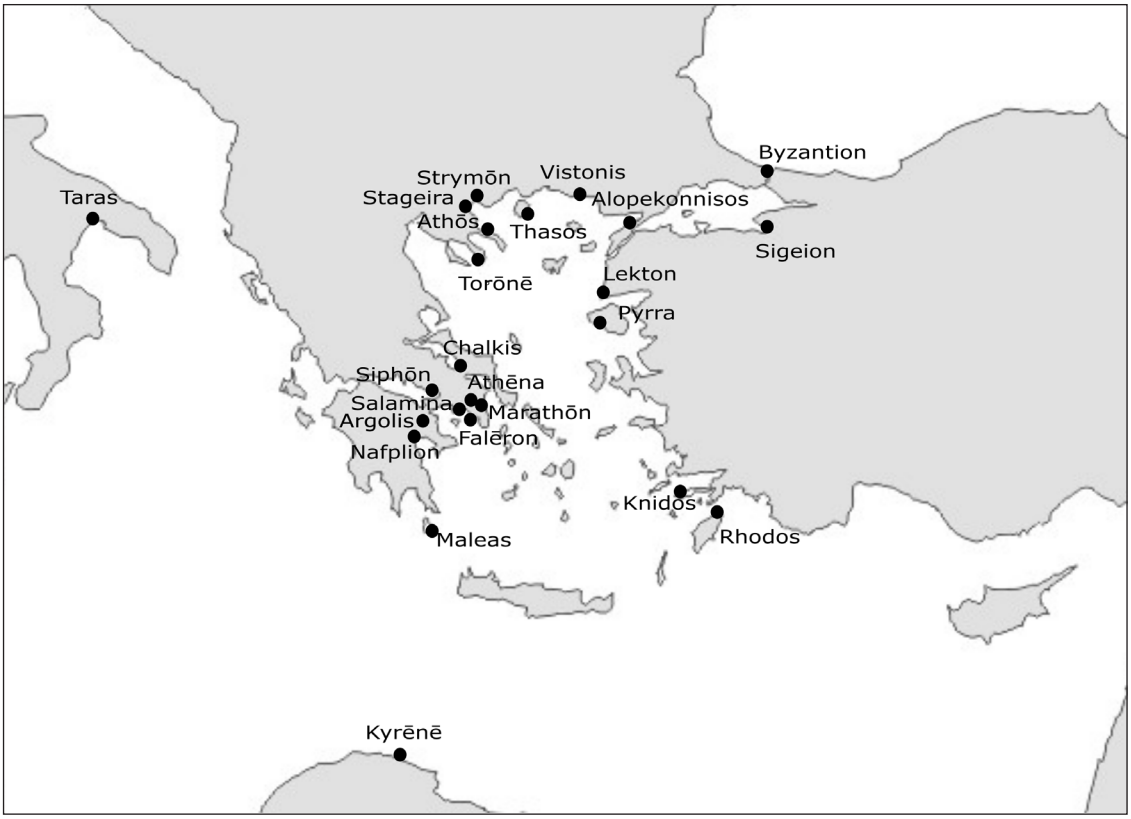

Fig. 3: Coastal locations from which marine animals are reported by Aristotle in his biological works. Aristotle's birth place (Stageira, Macedonia) is also included.

information and inspiration for scientists, but also in the taxa named by him. Moreover, according to the WoRMS database, marine taxonomists have described one genus and three species with a reference to his name: *Aristotelopanope* Števčić, 2011 (Crustacea, Brachyura), *Bogmarus aristotelis* Risso, 1820 (Pisces), *Hemiasterella aristoteliana* Voultsiadou-Koukoura & van Soest, 1991 (Porifera) and *Phalacrocorax aristotelis* (Linnaeus, 1761) (Aves).

Marine species distributions according to Aristotle

Aristotle's works provide a first organized account of Mediterranean marine fauna. Almost all of the 181 species he mentions were found in the Mediterranean Sea. An exception is probably the "octopus inside a shell", likely referring to a *Nautilus* species, of which he might have been informed about by scientists that followed Alexander the Great in his campaigns to Asia. Obviously, Aristotle focuses his interest on the marine fauna of the Aegean Sea. A synopsis of coastal locations from which marine animals are reported in his biological works is presented in Figure 3.

Besides the Aegean and adjacent localities, he was also familiar with several other Mediterranean areas. In his multifaceted work *Meteorologica (Meteor*354a), in which he studied physical, chemical and geological oceanography among other aspects, he demonstrated a good knowledge of Mediterranean geography (Fig. 4). He called the Mediterranean "the sea inside the Pillars of Hercules". He mentioned the Aegean Sea (*Aegaeos*), the Black Sea (*Pontos*), the Sea of Azov (*Maeotis*), the Red Sea (*Erythra*), the Sea of Sicily (*Sikelikos*), the Tyrrhenian Sea (*Tyrrēnikos*) and the Sea of Sardinia (*Sardonikos*). For all the above Mediterranean basins and peripheral seas, he described their bathymetry and water circulation patterns, and named the main rivers flowing into them: the Danube (*Istros*) and Nile (*Neilos*), "the two greatest rivers that flow into our sea", the Don (*Tanais*), Guadalquivir (*Tartēsos*), Rhone (*Rodanos*) and the rivers of the "Hellenic land" (*Hellenikos topos*), corresponding to Modern Greece, i.e. *Acheloos, Strymon, Nestos* and *Evros*. Moreover, in his biological works, the Aegean, Black Sea, Sea of Marmara (*Propontis*), Adriatic (*Adria*) and Red Sea are mentioned when discussing fish migrations and the distribution of exploited invertebrates. Figure 4 clearly shows that Aristotle's world covered three of the marine provinces recognized today (Spalding *et al*., 2007): the Mediterranean Sea, the Black Sea and the Red Sea. Lee (1948) estimated that most place-names appearing in Aristotle's biological works correspond to present day localities in Greece (36%) and Asia Minor (including Lesbos Island) (35%), while the rest are in Europe (14%), Asia (9%) and Africa (6%).

Although he described a small number of taxa compared to the number of species known today from the Aegean and Mediterranean Sea (Table 1), and no correlation

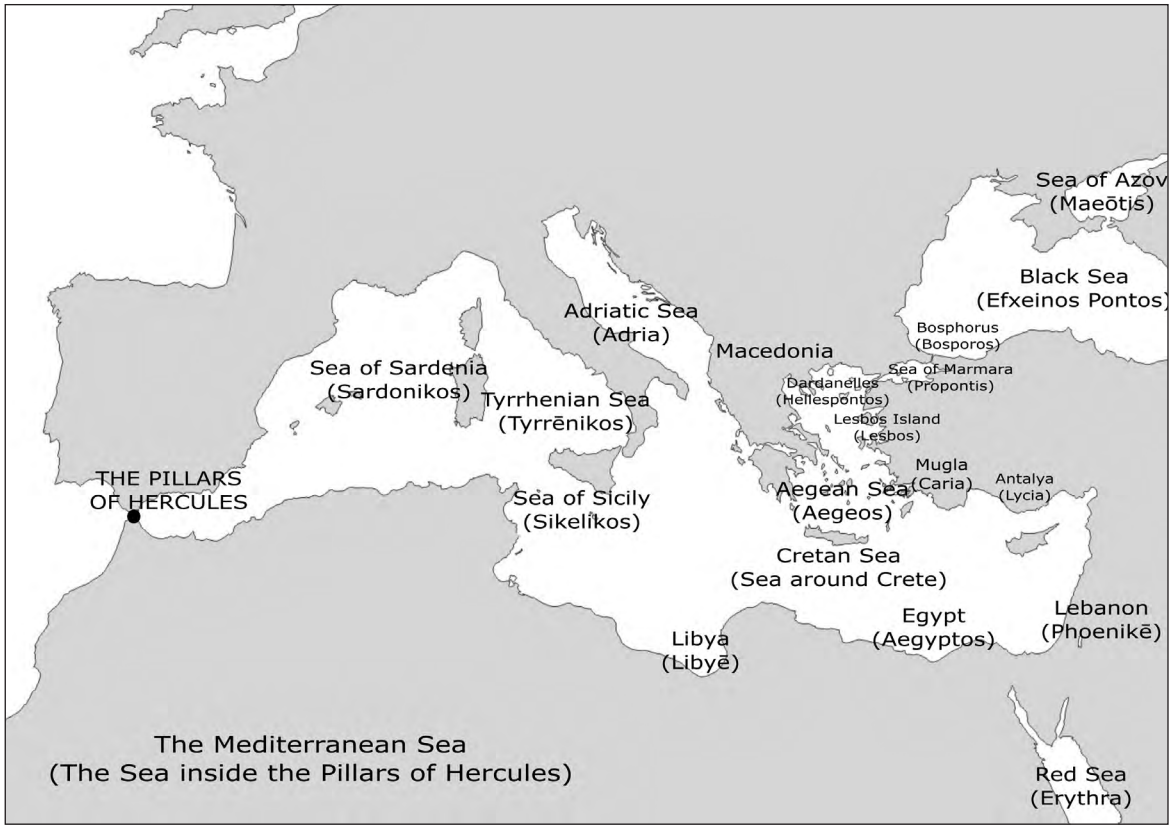

Fig. 4: Geography of the Mediterranean Sea according to Aristotle based on his *Meteorologica* and biological works.

was found between his numbers of species and the recent ones, we can safely state that Aristotle had relatively balanced knowledge of the marine fauna in his area of study, as Voultsiadou & Vafidis (2007) suggested, with two exceptions: the fish to which he paid special attention and polychaetes, which he almost ignored. As Ganias *et al*. (2017) noticed, he mostly reported fishes because of their importance to humans or because he was fascinated by their peculiar life history. The group of polychaetes, on the other hand, had neither of the above qualities plus the fact that they are inconspicuous to free divers.

Aristotle provides information on the distribution of several marine animals, largely those of interest to humans. For example, he notes that (i) the bath sponges, which were harvested and used widely, grew larger and more abundant in certain places on the coast of Asia Minor (see Voultsiadou, 2007); (ii) the scallops had vanished from Kalloni Bay as a result of the fishing method (see Voultsiadou *et al*., 2010); (iii) in the Black Sea, the only big marine animals were the *phocoena* (*HA*566b9) identified as the Black Sea harbour porpoise *Phocoena phocoena relicta* Abel, 1905 and a small dolphin. Aristotle was indeed correct about the cetaceans, and this knowledge is currently expanded, with at least two dolphin species inhabiting this marine area: the Black Sea bottlenose dolphin *Tursiops truncatus ponticus* Barabash-Nikiforov, 1940 and the Black Sea common dolphin *Delphinus delphis ponticus* Barabasch-Nikiforov, 1935.

Ganias *et al*. (2017) gave an account of Aristotle's knowledge on fish migrations from the Aegean to the Black Sea and vice versa for purposes of reproduction and feeding. Aristotle claimed that there was a connection between the river Danube and the Adriatic Sea through which some small fish moved from the Black Sea to the Adriatic (*HA*598b16). He also commented on annual fish migrations in and out of Kalloni Bay (*HA*621b12). He was aware of fish that spend part of their life cycle entering estuaries and rivers (*HA*569a7), such as the grey mullet (*Mugil cephalus* Linnaeus, 1758). And although he knew that adult eels migrate from the marshes and the rivers to the sea (*HA*569a8), the fact that he had never seen the eel *Anguilla anguilla* (Linnaeus, 1758) spawning led him to postulate that eels were formed from mud (*HA*570a), by "spontaneous generation" (*automatos genesis*), i.e. the generation of living things from non-living matter. More than 2,400 years later, the eel migration routes from Europe to the Sargasso Sea still largely remain a mystery. Recently, the migration route of this critically endangered species was documented using modern day acoustic telemetry (Huisman *et al*., 2016).

Aristotle also discusses differences in the occurrence and growth of marine animals from place to place. In one place, he says, an animal may be totally absent, in another it may be small, short-lived, or may not thrive (*HA*543b24). He notes that cephalopods, bivalves and gastropods, which are rarely found in the Black Sea, thrive and grow very large in the Red Sea (*HA*606a10).

Concluding remarks

Aristotle did not identify his inquiry on living organisms as 'biology' or 'zoology', since he approached the study of animals as part of the general study of nature; nevertheless, one can detect in his biological works the roots of different disciplines of biology, including contemporary marine biology and zoological classification. His biological works have been studied by classicists as part of his philosophy and they have tried to understand his ideas and methodology (Lloyd, 1961; Balme, 1987; Furth, 1987). Some scholars suggested that taxonomy was not a major and theoretical task in his biological works (see Pellegrin, 1986); these scholars mainly invoke that Aristotle's animal classification was not clearly taxonomical since he made several attempts to order animal diversity under different criteria, such as the mode of life or reproduction.

Studying Aristotle's biological works from their point of view, biologists have seen them as natural science rather than as philosophy; and this enabled them to notice points that philosophers and philologists have missed (Leroi, 2014). Thus, Thompson D'Arcy (1913) noted: "He was a very great naturalist. When he treats of natural history his language is our language and his methods and problems are well-nigh identical with our own" and "… it is at least certain that biology was in his hands a true and comprehensive science". More importantly, Ernst Mayr, the great evolutionary biologist of the 20th century, called him "the father of biological classification" (Mayr & Aschlock, 1991).

The modern taxonomist can easily notice that Aristotle presented a taxonomic classification of animals into "physical groups that take a certain name" (*PA*642b15), such as *ichthyes*, according to their similarities and differences in characteristic traits; on the other hand, the division of animals into "anonymous" groups according to oviparity-viviparity (see Ross, 1977) or marine/terrestrial mode of life, was not a taxonomical classification, but merely a distinction based on non-taxonomic characters; and it is true that Aristotle seems fully aware that many of these distinctions are not differences between groups of animals (Lloyd, 1961). Fürst von Lieven & Humar (2008), examining a set of characters from *History of animals* described in his works, have shown that Aristotle's classification consists largely of non-overlapping ('monophyletic') groups, and only few names referred to overlapping groupings.

Our study of Aristotle's classification regarding marine organisms, in comparison with Linnaeus's and contemporary classification, suggests that the way Aristotle approached the study of what we now know as biological classification looks remarkably familiar to present day marine biologists and that his concept of taxonomy is still echoing in our currently used system. Aristotle's knowledge of marine organisms and their classification looks outstanding, particularly when one considers that he was the first to introduce such a system, and that there was a complete lack of basic research equipment, such as microscopes and scuba gear, at the time. In his days, Aristotle already recognized the importance of being able to distinguish between species and to inventorise them and, although Linnaeus is seen as the 'official' start of modern taxonomy, many traces of Aristotle's work are still visible in current day taxonomy. Besides his contribution to the classification and distribution of marine organisms, Aristotle provides significant information on the traits (ecological, biological, and distributional) of marine organisms, which is worth analysing. An overview of fish traits with characteristic examples has been given by Ganias *et al*. (2017), while a detailed analysis of all marine animals described by Aristotle is the subject of an ongoing study.

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