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The species problem in evolution education

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ABSTRACT

An issue that might concern the species problem is the understanding and acceptance of evolution by students. The reason is that some of the modern concepts, which have been developed to define the species category, do not fit the evolutionary theory. In addition, some other concepts are simply criteria for the delimitation of species taxa. In particular, the biological and morphological species concepts, which are present in every textbook and are used almost exclusively in the teaching of evolution, can intensify students' essentialist perceptions. However, these perceptions could be effectively dealt with the development of the species problem and the nature of species taxa in the classroom, and also the treatment of species as one more level of organization of biological systems during teaching process. This approach is employed in a lesson with a view to contributing to the structure of a fully developed conceptual framework by the students in order to understand the evolution.

Keywords: species problem, evolution education, acceptance and understanding of evolution, essentialism

INTRODUCTION

The species problem has long history and has gone through various stages. Until Darwin's (1859) publication on "Origin of species", the species problem concerned the origin and geographical distribution of the species taxa (Coleman, 1962). Most naturalists of the time treated species taxa as real, distinct, and unchanging entities, appearing in a moment of creation and their diversity was finite (Mayr, 1982). Mostly they used various criteria, either morphological, reproductive, or both. Thus, scientists were able to identify and classify the species taxa. The rankings they created were artificial and arbitrary, and served specific practical purposes, related to the increasing number of specimens in their collections and in botanical gardens (Claridge et al., 1997; Winsor, 2006b). Those naturalists formed their theory about the classification of organisms in nature having been influenced by the way they had interpreted Plato and Aristotle and matched the theological doctrines of the time (Richards, 2010).

But after the publication of "Origin of species", species became controversial entities with unclear boundaries (Zachos, 2016). Thus, the modern species problem emerged, which is caused by

(a) the conceptual treatment of the term "species" (Ghiselin, 1974; Mayr, 1996),

(b) the view that species can represent the same units in taxonomy and evolution (Natham & Cracraft, 2020), and

(c) the construction of the science of Biology in branches (Richards, 2010).

If species taxa are the units of evolutionary change (Kluge, 1990) and speciation is one of the basic concepts of the evolutionary theory (Shtulman, 2006), then the treatment of species taxa in the classroom as units of classification in the teaching of the evolutionary concepts can intensify students' misunderstandings and especially those related to essentialist conceptions of living organisms. On the contrary, the adoption of a concept that best fits modern evolutionary theory and phylogenetics is expected to help students address to these essentialist concepts.

HISTORICAL REVIEW

Contemporary philosophers and biologists have agreed that the notions of defining species in the classification of the biological world, which were developed between the 16th and 19th centuries, are thought to had derived from Plato's and Aristotle's interpretations of the universal order of things, which included not only plants and animals, but anything that can be divided into species. According to the prevailing view–at least as far as non-biological classifications are concerned–these two philosophers considered all kinds of things in nature as distinct, naturally separate categories, which are defined by unchangeable, eternal, and essential properties (Hull, 1967; Richards, 2010; Wilkins, 2009).

In the 16th century the need for the classification of living organisms arose, due to the increasing numbers of plant specimens, which enriched the collections of botanists and naturalists, as well as botanical gardens (Winsor, 2006a, 2006b). At the same time, this classification required the existence of a background theory to support it, and so naturalists began to use a hierarchical system, which included species and genera consistent with both Aristotle's system and the theological doctrines of the time (Claridge et al., 1997; Mayr, 1982; Richards, 2010). Their classifications were used for practical purposes, easy to apply, learn, and memorize them (Winsor, 2006b). For this reason, they used features related to morphology and reproduction as criteria for recognizing the membership of a species, without defining the category of the species in a specific sense (Wilkins, 2009).

The naturalists of the time adopted the hierarchical system of classification of organisms and the binomial nomenclature of species, introduced by Linnaeus (Ereshefsky, 1997; Mayr, 1982), which fixed the categories species and genus and stabilized the names of the species (Richards, 2010). The latter was a field of misinterpretations and led to inability to communicate, due to the fact that each researcher constructed their own terms (Claridge et al., 1997; Ereshefsky, 1997; Larson, 1968; Richards, 2010).

At the same time, these naturalists believed that all species were created simultaneously, and they were endowed, for the moment of creation, with the special characteristics and properties that discriminate them from each other. These special features were conserved for each species by reproduction and infertility (Claridge et al., 1997; Coleman, 1962; Eigen, 1997; Hull, 1967). Thus, according to them, the variation within species was finite (Mayr, 1982) and the features of the initial pair of organisms are modified by use and uselessness without the occurrence of new characteristics in the next generations (Coleman, 1962; Kottler, 1978). As a consequence of that view, for the most of them, species was real, stable, immutable, and distinct entities.

At that time, there were also views, which argued that species change or transform over time, without, however, proposing some mechanism of selection or isolation. In particular, Lamarck believed that species are continuous, branching genealogies (Lamark, 1914 as referred to in Wilkins, 2009, p. 106) in which intermediate forms are missing because

(a) they exist in unexplored areas,

(b) they have become extinct from human intervention, or

(c) they are transformed into new species (Claridge et al., 1997; Mayr, 1982; Oxenham, 2015; Wilkins, 2009).

Thus, there was a different from the current problem regarding species, which concerned two components:

(a) their origin and

(b) their distribution (Coleman, 1962) and these were the ones that Darwin (1859) dealt with, with the arguments he presented in "Origin of species" (Coleman, 1962; Wilkins, 2009).

Darwin (1859), in "Origin of species", proposed that species appear by the means of natural selection, that is, they are not created, but evolved. His effort focused on separating the concept of species stability and their appearance with special creation phenomena, from the functional and taxonomic criteria used by naturalists for their classification. Thus, he needed only criteria that distinct the real taxonomic species to explain how they evolve and not any theoretical background concept for their classification (Mallet, 2010). Consequently, he avoided giving a specific definition of the term "species" and at the same time rejected the way in which his colleagues perceived the term, as appears mainly in his correspondence (Richards, 2010).

He considered that, in essence, there are not any dividing lines between species, subspecies, and varieties (Kampourakis, 2014; Kottler, 1978; Mallet, 2010; Richards, 2010). In his mature years he did not treat species as groups of individuals that were defined on the basis of certain characteristics by naturalists, who had considerable experience in the classification or had the appropriate scientific specialization, but species, were populations united by common origin, which can be distinguished by certain adaptations (Stamos, 2013) and were timeless entities (de Queiroz, 2011; Zachos, 2016). Darwin (1859) in "Origin"–as shown in the only figure that exists in his book developed a completely different concept of the species from its predecessors. According to him, species originate from common ancestors and equates them with branches in the lines of descent (de Queiroz, 2011). That is, he believed that the classification of organisms should be based on the genealogical relationships of organisms (Padian, 1999) and therefore could be considered a moderate phylogeneticist (Ghiselin, 1985, p. 462).

Darwin (1859) changed the way in which scientists treated species taxa (Wilkins, 2009), which ceased to be real, distinct entities that appeared at a moment of creation and became disputed groups with vague boundaries (Zachos, 2016). Thus, many concepts were developed for the definition of the category of the species, which acquired particular importance in the taxonomy hierarchy and led to a different problem for the species from that encountered by Darwin (1859) himself in "Origin".

SPECIES TAXA AND THE SPECIES CATEGORY

Species taxa are distinct genealogies (Zachos, 2016) and represent animal, plant, bacterial or other entities. Each species taxon has an internal coherence and a historical continuity (Mayr, 1982). They are separated by gaps, due to the natural selection (Dobzhansky, 1937, 1970) and the extinction of intermediate forms (Cohan, 2019), and we call them by binomial names, such as *Homo sapiens, Phlomis fruticosa, Homo habilis,* etc.

Each of these entities can be identified, described and delineated from such other entities with various scientific criteria (Mayden, 2002; Mayr, 2000), despite the apparent difficulties arising from the application of the evolutionary theory (Burma, 1949; Hey, 2006). Thus, for most biologists, species taxa represent real entities in nature (Mayr, 1987, 1996; Mishler & Wilkins, 2018) and exist independently of

(a) the ability of scientists to discover, study (Mayden, 2002), organize and classify them in a classification system (Nathan & Cracraft, 2020) and

(b) our experience or knowledge and of the concepts by which we perceive them or are made understood in the language we use so as to describe them (Zachos, 2016).

As phenomena of nature and evolutionary change, species taxa are scientific assumptions (de Queiroz, 2005a; Natham & Cracraft, 2020). They can appear by speciation, and they participate in natural biological processes, such as selection, modification etc. The species taxa are located in space, extend in timespace, have fuzzy boundaries, and eventually become extinct or give rise to new species (Ellis & Wolf, 2010; Mayden, 2002).

Also, if species taxa are individuals, then their true nature is automatically indicated (Zachos, 2016). In other words, the entities we discover as species taxa in nature really exist in the same sense that a human being does. A man or a woman develops and changes over time while he or she remains the same human being (Ghiselin, 1974) and is recognized by other observers as the same human being (Ellis & Wolf, 2010).

In contrast, the species category, which is defined in terms of the species concept, includes all species taxa and it is either the fundamental ranking in the hierarchical classification system of living organisms, introduced by Linnaeus (Devitt, 2008; Ellis, 2011; Ellis & Wolf, 2010; Mayr, 1996) or one of the basic categories of the organization of biological entities (de Queiroz, 2005b, 2011). However, in both cases the species concept is important because it determines the way in which entities that exist in nature are placed at the appropriate level of classification or at the appropriate level of organization.

The question that arises in this case is whether there is a single or more concepts, which can be applied to all species taxa and includes all biological diversity (Mayden, 1997). So, since there are more species concepts, each of these can be applied to different kinds of entities that are represented by species taxa in nature (Mishler & Donogue, 1982). Regarding the latter, there are several arguments that support this view. First, biological entities are not directly comparable with each other (Mishler & Donoghue, 1982; Zachos, 2016). Second, these entities can be identified in different ways, which also represent different definitions of the species concept and therefore of the species category (Ereshefsky, 1998; Stanford, 1995), without being able to unify (Hazelwood, 2018). Third, they can be involved in lateral gene transfer even in taxa that are considered distant from each other, either by hybridization or by horizontal gene transfer (Mallet et al., 2016). Finally, the species category is no different from the other categories of the hierarchical classification system, it only represents a lower degree of difference (de Queiroz, 2005b).

This approach has resulted in the development of many concepts for the species category and the questioning of the species category in the taxonomic system as a real scientific category, because in such a case it must be defined by necessary and sufficient properties and at the same time meet terms and conditions of each scientific category. Therefore, treating the term species to describe the taxonomic category in which we can classify the entities we have discovered in nature, is a completely different thing from treating the term species as entities in nature.

THE SPECIES PROBLEM

The species concept is fundamental to biology (Dobzhansky, 1937) and is involved in almost every discipline (Mishler & Wilkins, 2018). However, even today it provokes intense debate among both biologists and philosophers (Nathan & Cracraft, 2020; Wilkins, 2010), with no signs of any mutual agreement (Hausdorf, 2011; Naomi, 2011). This discussion has led to the inflation of species concepts (de Queiroz, 2007; Mayden, 1997, 2002; Minelli, 2015; Wilkins, 2009; Zachos, 2016), which has significant implications for the treatment of species by various fields of biology, such as biodiversity (Agapow et al., 2004), conservation biology (Claridge et al., 1997; Garnett & Christidis, 2017), taxonomy (Thomson et al., 2018), evolutionary biology (Cracraft, 2000), etc. Some species concepts are useful criteria for species delimitation (de Queiroz, 2007; Mayr, 1996), while others are not explicitly defined (Mayden, 1997). The species concepts were developed to serve different purposes (Hull, 1997). They served to identify species belonging to very different categories, however, few of them apply for microorganisms and fungi (Christenhusz, 2020).

One of the main reasons for the “species problem” is the lack of the required conceptual separation when using the term “species”. It essentially lies in

(a) the distinction to be made between the species category and species taxa (Ghiselin, 1974; Mayr, 1982),

(b) the answer to the question of the ontological status of species taxa (Ghiselin, 1974; Hull, 1976),

(c) how to deal with species, that is, whether it represents a real scientific category or not (Ereshefsky, 2009; Richards, 2010),

(d) whether it is a category in the hierarchical classification system of species taxa or is a higher level of organization of biological systems (de Queiroz, 2005b, 2011), and last

(e) the way we treat species taxa in relation to time, i.e., whether they are synchronic or diachronic entities (Stamos, 2003).

Also, the notion that species are units of both taxonomy and evolution intensifies the confusion because a concept has been shown to be designed to primarily satisfy one of the two disciplines and can rarely be compatible with both. Finally, another source of controversy is the structuring of the science of biology into branches, where each branch employs a concept for the species category according to its own methodological criteria, thus separating biological diversity in different and incompatible ways (Nathan & Cracraft, 2020; Richards, 2010; Stamos, 2003).

Classes and Individuals

People, and especially children, intuitively treat species taxa as categories made up of members, which share common, essential, observable, or not, characteristics and properties, and each of these categories is given a unique name (Dawkins, 2009; Hey, 2001; Shtulman, 2006). Also, biologists consider species taxa to be categories (Brigandt, 2009) and special natural kinds (Reydon, 2005) from the time of Aristotle (Hull, 1976) and continue to treat them in the same way even today (Pušic et al., 2017).

Natural kinds represent a form of scientific category, which refers to sets of things that do not depend on human interests, energies, and purposes (Bird & Tobin, 2008; Reydon, 2005; Richards, 2010; Zachos, 2016) and are defined by the common possession of some properties that have theoretical significance (Dupré, 1981). However, it is now clear that whatever species taxa are, they certainly are not categories (Hull, 1976; Kluge, 1990), because as such they are immutable and do not fit evolutionary theory (Ghiselin, 1987).

The classical view of natural kinds is insufficient to explain the nature of species taxa, mainly because the latter are historical entities, subject to evolutionary change and extinction (Brigandt, 2009). That is, species taxa are spatiotemporarily limited entities. For example, *Homo habilis* appeared, spread and eventually extinct under natural conditions and processes and cannot reappear anywhere in the universe under natural conditions as *Homo habilis* (Mayden, 2002). On the contrary, natural kinds, in the classical sense of the concept, are independent of space and time, that is, they are eternal (Boyd, 1991, 1999). Thus, if the organisms of a species must be causally related and cannot be similar to each other then they are not natural kinds of any form, but are individuals (Ereshefsky, 2010). Therefore, the alternative proposition for the ontological status of species taxa is that they are tangible individuals and the organisms that make them up are their parts (Richards, 2010). These entities are identified by names such as: "this group of organisms is *Homo sapiens* and this is *Phlomis fruticosa*" (Ghiselin, 1974, 1987; Hull, 1976; Zachos, 2016). They show coherence and continuity as they participate in natural processes such as evolution, speciation, and common origin. Individuals can change in space and time and may not always have a precise definition, because their boundaries may in some cases be blurred, although they may be discovered, described, and diagnosed (Ellis, 2011; Ghiselin, 1974, 2002; Hull, 1976; Mayden, 2002; Mayr, 1987; Zachos, 2016).

In species taxa, some organisms can change, disappear, and be replaced without affecting the entity (Ellis, 2011; Ghiselin, 1974, 1987; Hull, 1987; Mayden, 2002). That is, organisms participating as part of a species taxon must be thought of as the cells of an organ (Hull, 1976). Just as cells in one organ can be replaced by other cells without affecting the existence and functions of the organ, so organisms can replace other ones without affecting the species taxon. However, as the generations succeed each other, there comes an indefinite moment, when the specific name we have given to the species taxon no longer represents the organisms-parties, because they have changed so much, that they represent one or more, different entities and need to give them different names (Dawkins, 2009).

The treatment of species taxa as individuals has some consequences. An important effect of the above position is that it can lead to a lack of understanding of natural selection, because it acts on organisms (Mayr, 1987). However, natural selection does not only affect organisms, but also any level of biological organization that may be composed of organisms, such as a population (Hull, 1976). Furthermore, individuality of the species taxa as a concept is a philosophical term that includes any spatiotemporary entity and it is not be confused with the concept of an individual organism (Ghiselin, 1974; Rieppel, 2010).

The most important consequence is that they do not have clear boundaries. Thus, there should be many criteria for defining and delimiting them, and in many cases there is a considerable disagreement over scientists which criteria to use. These criteria may be subjective (Mayden, 2002) or serve various purposes, which do not concern the scientific delimitation of species taxa but economic, social, etc. (Garnett & Christidis, 2017). In other cases, the boundaries may be artificial in a process that is continuous (de Queiroz, 2007). The existence of vague boundaries is not a counter-argument to the position that species taxa are real individuals, because then there will be no such entities in nature (Hull, 1976), since several of them have vague boundaries (Mayden, 2002).

Universality of the Species Concept

In addition to the conceptual issues developed above, the inflation of the concepts that define the species category was also a result of the confusion caused by the existence in almost every definition of two different properties. Firstly, the conceptual characteristics that define the category as a scientific one and the methodological criteria used for the delimitation and identification of species taxa, in order to be classified in the species category (Camargo & Sites Jr, 2013). Secodly, the treatment of the species category as another one of the hierarchical classification system (de Queiroz, 2005b) and not as a supra-atomic entity (Dobzhansky, 1970; Mallet, 2020), which represents a higher level of biological organization than that of the organism (de Queiroz, 2005b, 2011).

A concept that is developed and used to define the species category must meet at least certain criteria: Firstly, it must be evaluated for its role in relation to evolutionary theory and not be separated from it. That is, it must base its theoretical significance on evolutionary theory and interpret the species taxa within its framework, as this constitutes the unifying theory of Biology. Secondly, it must have universality, which means that it must be tolerant of many different phenomena related to species taxa, such as speciation, hybridization and genetic material exchange, reproduction, morphological and genetic differences, etc. Thirdly, it must be applicable, that is, it must include all biological diversity in time and space and not exclude some of the entities that exist in nature, as is the case, for example, with many concepts, as far as asexually reproducing organisms are concerned. Forth, it is not required to have functionality, because the criteria used to identify species taxa relate to the ease with which this can be done. Depending on the emphasis placed on these criteria, some types of taxa are excluded, but which are equally valid if other similar criteria are used (Claridge et al., 1997; Dobzhansky, 1973; Hull, 1997; Mayden, 1997; Mishler, 1985). A typical example is the application the phylogenetic species concept (PSC) of various groups of organisms, which greatly increases the species taxa that are being recognized by scientists (Agapow et al., 2004). Finally, the species concept should not be a relationship concept, like the "brother", but should be comparable to the "human" concept. This means that species should not be defined in relation to other species (Ghiselin, 1974).

Table 1. Concepts developed to define species category (they are distinguished according to main feature of their definition & in each subcategory are presented in alphabetical order)

No	Characteristic	Concept	A	Reference
1	Morphology	Agamospecies species concept	ASC	Turesson (1929) as referred to in Wilkins (2009, p. 177)
2		Genotypic cluster criterion	GCC	Mallet (2007)
3		Morphological species concept	MSC	Cronquist (1978) as referred to in Mayden (1997, p. 402)
4		Phenetic species concept	PhSC	Sneath (1976)
5	Reproduction	Biological species concept	BSC	Mayr (2000)
6		Genetic species concept	GSC	Baker and Brandley (2006)
7		Henigian species concept	HSC	Meier and Willman (2000)
8		Recognition species concept	RSC	Paterson (1993)
9		Reproduction competition species concept	RCSC	Ghiselin (1974)
10	Evolutionary history	Cladistic species concept	ClSC	Ridley (1989)
11		Ecological species concept	EcSC	Van Valen (1976)
)12		Evolutionary significant units	ESU	Moritz (1994)
13		Evolutionary species concept	ESC	Wiley and Mayden (2000
14		Genealogical species concept	GeSC	Baum and Shaw (1995) & Baum (1998)
15		Internodal species concept	ISC	Kornet (1993)
16		Least inclusive taxonomic unit	LITU	Pleijel and Rouse (2000)
17		Phylogenetic species concept (diagnosable version)	PSC1	Wheeler and Platnick (2000)
18		Phylogenetic species concept (monophyly version)	PSC2	Mishler and Theriot (2000)
19		Unified or general species concept	USC	de Queiroz (2011)
20	Adaptation	Differential fitness species concept	DFSC	Hausdorf (2011)
21		Genic species concept	GcSC	Wu (2001)
22	Combinatorial concepts	Biosimilarity species concept	BiSC	Stamos (2003) as referred to in Zachos (2016, p. 80)
23		Cohesion species concept	CSC	Templeton (1989)
24		Genealogical concordance species concept	GCSC	Avise and Ball (1990) as referred to in Zachos (2016, p. 86)
25		Phylo-phenetic species concept	PPSC	Rosselló-Mora and Amann (2001)
26		Pragmatic species concept	PrSC	Seifert (2014)
27		Gen-morph species concept	GMSC	Hong (2020)

Note. A: Abbreviation

The species concepts, presented in **Table 1**, may have applicability and functionality in various fields of biology. However, not all of them fit the evolutionary theory in the same way since species taxa are not treated as the basic units of evolutionary change. At the same time, some of them do not have the universality required by the concept defined by a scientific category, as they do not fit all models of speciation. Thus, most concepts consist of criteria for delimitation and identification of species taxa (de Queiroz, 2007; Mayden, 1997, 2002).

Therefore, prioritizing the concepts that define the species category and recognizing that in almost all concepts there is a general principle that treats species as segments of evolutionary lineages at the population level was an important step in further understanding the species problem and led to a comprehensive framework for the species concept (Naomi, 2011). At the same time, the treatment of species taxa as individuals is clearly more consistent with evolutionary theory, and a consensus seems to be developed by the biologists dealing with the species problem (Richards, 2010).

The above conditions are met by the definition of the species category by de Queiroz (1998), as *segments of evolutionary lineages at the level of population* and other concepts, as criteria for the delimitation of species taxa. This definition generally describes the species category and explains the fundamental nature of the species taxa, without specifying the causes that are responsible for their existence, but since implies their common origin and cohesion, it only recommends lineages (de Queiroz, 1999). The treatment of the species concept as a sequence of ancestral and descendant populations fits better with the adoption of the phylogenetic approach in the systematic and evolutionary theory, as it includes all the current scientific data on speciation.

The initial separation of a lineage may be due to internal or external barriers and their subsequent divergence may be the result of various factors, which affect the phenotypic characters. The lineage divergence continues and crosses a threshold, where the separation is no longer irreversible (de Queiroz, 1998), without the need for genetic isolation to be present, as the divergence can continue, although in some cases divergent groups may come into contact and there may be gene flow (Poelstra et al., 2014; Wang et al., 2020; Wu, 2001).

Lineages are a level of organization that represents populations -with the wide use of the term-, which extend over time and should not be confused with branches and clones, even though they can all be depicted in phylogenetic trees (**Figure 1**). A branch is a unit, consisting of the ancestral species and all its descendants. In contrast, the lineages, depicted in the phylogenetic tree, represent a set of branches, which constitute a path from the starting point of the tree to the end (de Queiroz, 1998). The definition of the species as segments of evolutionary lineages essentially treats the species category as a level of biological organization, analogous to organisms (de Queiroz, 1999, 2011). As a result, all species taxa are directly comparable and can be identified in the same way, because they are involved in a process similar to cells and organisms, which is also responsible for producing entities of the same kind, that is speciation (de Queiroz, 2005b).

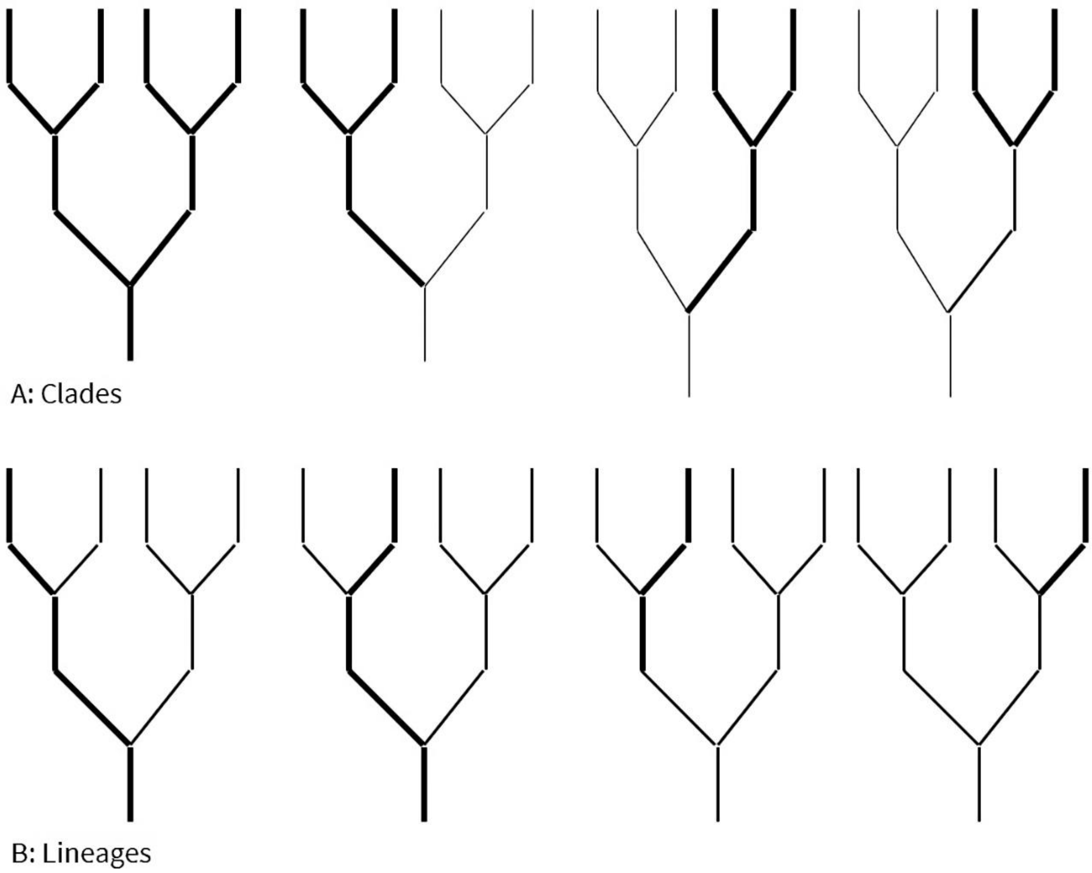

Figure 1. Clades & lineages in same phylogenetic tree (**bold** lines represent clades in A & lineages in B; clades are branched & exclusive, on the contrary lineages are non-branching & overlap with each other; lineages are essentially paths that can start from different locations within phylogenetic tree) (modified by de Queiroz, 1998).

THE SPECIES PROBLEM IN EVOLUTION EDUCATION

Concepts are the fundamental connections between the observed patterns and are applied in various scientific disciplines, to help in the understanding, perception, and revelation of natural phenomena (Mayden, 2002). Thus, if evolution is a phenomenon of the biological world (Stamos, 2003) and the scientific theory that interprets and explains this phenomenon, is the unifying theory of biology (Dobzhansky, 1973) so then the notions employed should be comprehensive to the pupils and the students. At the same time, however, they must be accepted despite the obstacles that may exist due to religious, political, and other non-scientific factors (Dunk et al., 2019; Pobiner, 2016). Also, if evolutionary theory is the theoretical framework within which important phenomena of the biological world are understood, then the bleak picture of levels of acceptance and understanding of evolution by the general public worldwide (Dawkins, 2009; Miller et al., 2006) can have a significant impact on scientific literacy. They also have a negative impact on various contemporary social challenges related to people's daily lives, such as the management of new infectious diseases, bacterial resistance to antibiotics, insect resistance to insecticides, the development of vaccines, climate change (Dunk et al., 2019).

Evolutionary theory includes various concepts, such as natural selection, adaptation, speciation, common origin, extinction, geological time, which must be taught in order to achieve the goal of understanding evolution and consequently of biological phenomena. Curricula in evolution education, however, include almost exclusively the mechanisms of natural selection (AAAS, 2011) and there is considerable literature on how these mechanisms are understood (Gregory, 2009; Price & Perez, 2016).

The central role of natural selection in the understanding of evolutionary theory is not disputed by anyone, because it offers a causal interpretation of the existence of the diversity of living organisms and makes unnecessary the need for any form of teleology (Mayr, 1982), which is one of the most important obstacles to the understanding of evolution by students of different ages (Bishop & Anderson, 1990; Gregory, 2009; Kampourakis & Zogza, 2008, 2009; Nehm & Reilly, 2007; Sinatra et al., 2008). However, there seems to be a tacit agreement, suggesting that knowledge of the mechanisms associated with natural selection leads to knowledge and understanding of all the mechanisms and concepts related to evolutionary theory (Novick et al., 2014). Thus, important concepts are ignored, as a result there is a poor understanding of the history of life on the planet and a complete picture of evolution is not provided (Catley, 2006). If students' teleological interpretations are one of the main conceptual obstacles to understanding evolution, another major obstacle is the essentialist perceptions of people and especially children (Gelman & Rhodes, 2012; Kampourakis, 2014). According to them, a child believes that a thing that belongs to a category, has the necessary and sufficient qualities so as to be recognized as a member of the category to which it belongs, and these qualities are unchanged (Sinatra et al., 2008). These essentialist notions concern not only the understanding of natural selection, which is related to evolutionary phenomena within species, but are directly related to the treatment of species and speciation, the teaching of which in the context of evolutionary theory is at least incomplete. Speciation phenomena explain the ways in which new species emerge and teaching of these phenomena as well as treatment of term "species" can be crucial for understanding and accepting evolution.

The lack of teaching important aspects of evolutionary theory is perceived not only in the curricula, but also in the educational research on the way pupils and students think, learn, and understand the evolutionary issues (Dial et al., 2019; Ziadie & Andrews, 2018). Research on the acceptance and understanding of evolution is based partly on pupils and students views on species and speciation (Anderson et al., 2002; Nadelson & Southerland, 2009; Shtulman, 2006; Shtulman & Schulz, 2008) and the assumption that species taxa represent categories (Shtulman, 2018; Shtulman & Schulz, 2008) or are natural kinds (Berti et al., 2010; Samarapungavan & Wries, 1997), without taking into account that adoption of such notions about species taxa does not fit with modern evolutionary theory as mentioned in previous section. In addition, the same studies use different concepts for the species category (Catley, 2006; Meisel, 2010; Shtulman, 2006). Some consider that only the BSC fits the theoretical approach of evolutionary change as a result of two processes of mutation and selection (Shtulman, 2006), while others use some form of the PSC as appropriate for understanding of the evolutionary process (Catley & Novick, 2008) and in some cases species are considered the smallest independently evolving unit (Nadelson & Southerland, 2009), resulting in incomparable results.

The curricula and the instructions given to the teachers for the teaching of the species concept do not specify what it refers to and at the same time treat the species taxa as categories of things, thus reinforcing the misunderstandings that the students already have about the evolution. This is because children intuitively construct rankings, which are arbitrary e.g. pets, including taxa that are evolutionarily distant from each other. Students also use–like adult–the popular classifications of organisms, in which, however, the name of a species represents various taxonomic levels from species to families or classes (Berlin et al., 1966; Coley & Muratore, 2012). However, the use of such classifications does not help the conceptual change required for the correct understanding of evolution and must be done carefully, both in the educational process and in the educational research, because students do not understand the unit of evolutionary change, phenomena related to natural selection and common origin (Coley & Muratore, 2012; Shtulman & Schulz, 2008)

Thus, the use of the hierarchical classification system should be done with special care, because it does not represent and treat taxa as evolutionary entities, but as categories that are integrated into other categories. As mentioned in a previous section, rarely a concept that has been developed to fit taxonomy can be successfully applied to evolution (Stamos, 2003). Thus, it is necessary in the teaching of evolutionary concepts to classify the species as a level of biological organization superior to organisms and not as another level of the classification system of organisms (de Queiroz, 2005b, 2011; Dobzhansky, 1970).

Treating species taxa as categories means that they can be transformed as a whole by drastically changing their essential properties in response to changes in their environment. Such a treatment of species taxa has the effect of enhancing students' intuitive and spontaneous essentialist perceptions and beliefs and at the same time can strengthen students' perceptions of the transformation of organisms as a whole and not with gradual slow modifications. The treatment of species taxa as categories creates a contradiction in the understanding of evolutionary theory and it is at the same time one of the biggest obstacles to the acceptance of evolution (Mayr, 1987), because it is difficult to reconcile the view of origin of species taxa with modification from ancestral species with the metaphysical view that species represent invariant and fixed categories (Mayden, 2002).

Therefore, the introduction to education for the evolution of "species problem" could help pupils to perceive species taxa

(a) as real individuals in nature (Ellis & Wolf, 2010), which can be scientific assumptions (de Queiroz, 2007; Mayden, 2002) and as such can be presented with phylogenetic trees in the classroom (Catley, 2006), as examples of the nature of science (Nyléhn & Ødegaard, 2018) and

(b) as the units of the evolution (Dobzhansky, 1937; Ellis & Wolf, 2010).

Specifically, such a section could include:

(a) a brief history of the nature of species,

(b) terminology related to the species,

(c) different concepts that have been developed (Ellis & Wolf, 2010) and the purposes that they serve (Hull, 1997),

(d) implications of treating species taxa as classes of things or as individuals (Mayden, 2002), and

(e) treatment of species taxa as a higher level of organization and not as categories of the taxonomic system (de Queiroz, 2011).

The integration of the above in the educational process for evolution could help pupils to understand important aspects of evolutionary theory related to speciation and natural selection and as it has been confirmed that the essentialist interpretations of students' about biological taxa may lead to misunderstandings such as transformation and anthropocentrism (Gregory, 2009; Shtulman, 2006).

In addition, the implications in the literature from using the species concepts on evolution education seem to be too poor (Nyléhn & Ødegaard, 2018). Each textbook uses almost exclusively BSC and MSC for defining the species category (Mayden, 2002; Nyléhn & Ødegaard, 2018), which in fact are criteria for delimiting species taxa for taxonomic purposes (Mayden, 1997). However, both of them may not be the appropriate concept for understanding evolution because they treat species taxa as classes of things in nature (Mayden, 2002), which does not fit modern evolutionary theory (Ghiselin, 1974, 2002; Mayr, 1987; Richards, 2010).

Especially, MSC

(a) does not address the diversity of individuals of the same species and the morphological similarity of individuals belonging to different species (Mayr, 1982, 1991),

(b) treats species as synchronous entities and if so it could not establish lineages (Mayden, 1997), and

(c) is consistent with the stability of diagnostic characters of the species taxa (Mayr, 1991).

Thus, it introduces a typological interpretation of the appearance of species taxa that is more compatible with essentialist conceptions and creationism beliefs than with evolutionary theory (Mayr, 1991).

On the other hand BSC, first it does not help students understand species taxa as the units of evolution that occur by natural biological processes, are modified, changed and eventually become extinct or create new species with speciation phenomena (Catley, 2006; Mayden, 2002). Second, it implies that there are no species taxa, for more than half of the life that exists on the planet, despite the fact that there is evolution, because the sexual reproduction has not yet appeared (Hull, 1997). Third, it alters evolutionary history because it allows populations of one species taxon to be more related to another species taxon than to populations of the same species (Velasco, 2008). Fourth, it can be applied with success only in contemporary, sexually reproduced populations located in the same area (Seifert, 2014). Fifth, it reinstates a form of essentialism for species taxa (Mallet, 2007), and proposes a typological way of thinking (Mendelson & Shaw, 2012) because it presupposes clear separations in the construction of the mechanisms of reproductive isolation and not a gradual accumulation of characteristics (Mallet, 2020). And lastly genetic isolation is not necessary for the continuity of the divergence between the two groups of organisms (Poelstra et al., 2014; Wung et al., 2020; Wu, 2001).

Finally, biology education should focus on teaching all aspects of evolution both as a phenomenon of biological world and as a scientific theory, which includes many others subtheories and not imply that it runs through curricula, with no clear teaching and learning objectives, or focusing only on specific components–such as adaptation and natural selection–as is the case in Greece (Stasinakis & Kampourakis, 2018). The above, in combination with the fact that the teaching of evolution is considered to be incomplete to non-existent for various reasons (Athanasiou & Papadopoulou, 2012) makes it easy to understand why levels of understanding of evolutionary phenomena are low among high school students, despite the fact that they have a positive view of evolutionary theory (Prinou et al., 2008).

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