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Review Article

How do pesticides affect bats? – A brief review of recent publications

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Abstract

Increased agricultural production has increased the use of pesticides worldwide, which poses a threat to both human and environmental health. Recent studies suggest that several non-target organisms, from bees to mammals, show a wide variety of toxic effects of pesticides exposure, including impaired behavior, development and reproduction. Among mammals, bats are usually a neglected taxon among ecotoxicological studies, although they play important ecological and economical roles in forest ecosystems and agriculture through seed dispersal and insect population control. Considering their wide variety of food habits, bats are exposed to environmental pollutants through food or water contamination, or through direct skin contact in their roosting areas. In order to better understand the risk posed by pesticides to bats populations, we compiled studies that investigated the main toxicological effects of pesticides in bats, aiming at contributing to discussion about the environmental risks associated with the use of pesticides.

Keywords: bioaccumulation, Chiroptera, ecotoxicology, eating habits, physiological changes.

Como os pesticidas afetam os morcegos? - Uma breve revisão de publicações recentes

Resumo

O aumento da produção agrícola tem levado ao aumento do uso de pesticidas em todo o mundo, o que representa uma ameaça para a saúde humana e ambiental. Estudos recentes sugerem que vários organismos não-alvo, de abelhas a mamíferos, apresentam uma grande variedade de efeitos tóxicos após a exposição aos pesticidas a pesticidas, incluindo alterações de comportamento, no desenvolvimento e na reprodução. Entre os mamíferos, os morcegos geralmente são negligenciados entre os estudos ecotoxicológicos, embora desempenhem importantes papéis ecológicos e econômicos nos ecossistemas florestais e na agricultura por meio do controle de dispersão de sementes e de populações de insetos. Considerando sua ampla variedade de hábitos alimentares, eles estão expostos a poluentes ambientais através da contaminação de alimentos ou água, ou através do contato direto com a pele em seus abrigos. Para entender melhor o risco que os agrotóxicos representam para as populações de morcegos, compilamos estudos que investigaram os principais efeitos toxicológicos de agrotóxicos em morcegos, visando a discussão sobre os riscos ambientais associados ao uso de agrotóxicos.

Palavras-chave: bioacúmulo, chiroptera, ecotoxicologia, hábitos alimentares, alterações fisiológicas.

1. Introduction

Environmental contamination is one of the main global concerns of the recent years, as an increasing number of studies are associating the exposure to various environmental pollutants with deleterious and often synergistic effects on living organisms (Cedergreen, 2014). Since the green revolution, there has been an increase in agricultural production accompanied by stagnation or a decline in crop yields. The increased population demand for food culminated with the increased use of pesticides, in order to improve crop productivity (Liu et al., 2015).

Pesticides are chemical substances that act against any agent that can damage the production, storage, processing of agricultural products, pastures, and vectors. They contribute to agricultural production as they are used to protect crops and livestock from various pests, diseases, weeds, and parasites. Being an alternative to lower economic costs, pesticides help farmers to survive in a competitive market (Choudhary et al., 2018).

While target organisms absorb a large proportion of the pesticides, a considerable amount is still disseminated in the environment by air and water, and is continuously found in soil, surface water, and groundwater. As several pesticides persist and accumulate in the environment, non-target organisms are continuously exposed through its residues or byproducts, including organisms that play key ecological roles in ecosystems (Aktar et al., 2009).

Bats comprise a wide variety of species inhabiting nearly the entire planet, exhibiting important ecological and economic roles as seed dispersers in natural ecosystems and insect populations control of agricultural pests (Boyles et al., 2011). However, only a few ecotoxicological studies addressed the effects of pesticides on aspects of bats behavior, development or reproduction. Although studies are scarce, recent research articles have contributed to advance knowledge in this area. In this review, were compiled studies on the effects of pesticides in bats, aiming at contributing to the discussion about the environmental risks associated with the use of pesticides.

2. Effects of Pesticides in Non-Target Organisms

After the rise of pesticide use, several population declines of non-target organisms were associated with these compounds. Contamination of non-target organisms in the environment occurs through leaching, runoff, evaporation, erosion, and feeding (Köhler and Triebskorn, 2013). Volatile chemical components are rapidly transported to the atmosphere and can reach regions far from the application areas (Carvalho, 2017). Dichlorodiphenyltrichloroethane (DDT) residues and their metabolites, for example, can be found in the soil, surface water, air and in tissues of wild animals such as fish, mammals, and birds (Köhler and Triebskorn, 2013).

Pesticide residues have been associated with delays in the metamorphosis of anurans, bioaccumulation in wild birds and mammals, and reduction in bee and bird populations (Eqani et al., 2013; Freitas et al., 2017; Köhler and Triebskorn, 2013; Mullin et al., 2016). The American Bald Eagle is a classic example of population decline induced by pesticides. The intensive use of DDT in the USA caused eggshell porosity and prevented the development of the offspring, leading to their premature death. This species entered the list of endangered animals and was only seen again 45 years after its use was banned in the country (Aktar et al., 2009; Banaszkiewicz, 2010).

Recently, new molecules have emerged in the marked with the promise of lower toxicity. Currently, there are in the world approximately 2400 products commercially available, divided into 434 different active ingredients. These products are classified according to their chemical composition in organochlorines, organophosphates, pyrethroids, carbamates, neonicotinoids, chlorophenoxyacids, triazines and glycines. Within each chemical group there are various types of commercial products with different purposes, such as insecticides (for the control of insects), acaricides (acarids), nematicides (nematodes, plant parasites), molluscicides and rodenticides (rodents). In addition, there are two separate chemical groups - the herbicides, whose purpose is controlling weeds, and the fungicides and bactericides, used to prevent fungal and bacterial diseases (Aktar et al., 2009; Banaszkiewicz, 2010).

The global use of pesticides has reached large proportions, especially in developing countries (Figure 1) (FAO, 2019). Brazil, for example, has increased the use of pesticides in the last decade (Figure 2), and since 2008 is considered the largest consumer of pesticides in the world, (Albuquerque et al., 2016) with emphasis on the use of herbicides (Figure 2) (FAO, 2019). Indiscriminate use and improper application are often observed in the crops, since frequency and recommended doses by manufacturers are not always respected (Schiesari et al., 2013).

On top of that, Brazil also does not have programs for adequate monitoring for the use of chemical components and pesticide residues in the environment, especially in freshwater (Barbosa et al., 2015). The monitoring is restricted to only five states, which show data with low credibility and high risk of bias (Albuquerque et al., 2016). Another aggravating factor for the country is the use of pesticides that are proven to be toxic and are already banned in other regions of the world. Among the 50 best-selling commercial products in Brazil, 22 are banned in Europe, such as trichlorfon, 2,4-D, paraquat, and some triazine herbicides.

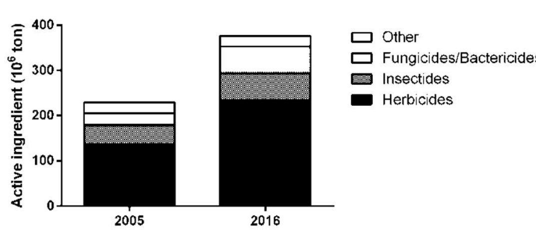

Figure 1. Average consumption in ton of active ingredient of fungicides/bactericides, insecticides and herbicides used or sold in the World between 2005 and 2016. Compiled data from FAOSTAT (Food and Agriculture Organization of the United Nations).

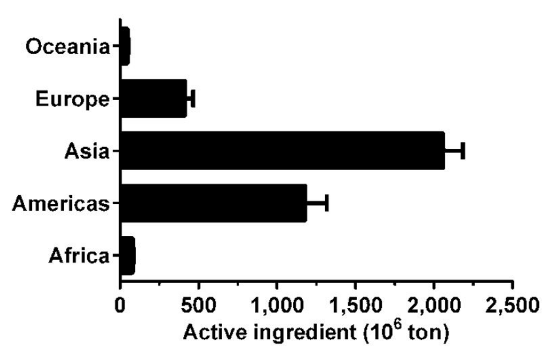

Figure 2. Consumption in ton of active ingredient of fungicides/bactericides, insecticides, and herbicides used or sold in the agricultural sector for crops and seeds in Brazil. Compiled data from FAOSTAT.

3. Bats and Pesticides Exposure

In order to assess the state of knowledge about the effects of bat exposure to pesticides, we performed a bibliographic search on the main search platforms (pubmed, scielo, scopus), using several keywords (bats, toxicology, pesticides, organochlorine, ecotoxicology, insecticide, pyrethroid, fungicide, herbicide). We selected all articles that met the main criteria 1) written in English, 2) published between 1964-2019 and 3) studied the effects of pesticides on bats. Our main goal was to analyze the works published in this area, in each country, and which food guilds have been studied during these years. After compiling these data, we describe the main findings below.

Taken together, the main characteristics found were that, among the studies found (n = 28), most of them were about insectivorous bats (n = 19), followed by studies with fruit bats (n = 7). A few studies analyzed species richness and had no defined species (n = 2). The bat genuses most used in the studies were *Pipistrellus* (n = 6) and *Artibeus* (n = 6). The countries that carried out most of the studies are Brazil (n = 7) and the United States of America (n = 7), followed by United Kingdom (n = 3), South Africa (n = 2), Germany (n = 2), Australia (n = 1), France (n = 1), Spain (n = 1), Mexico (n = 1), Sweden (n = 1), Taiwan (n = 1), and Finland (n = 1). Among the main endpoints, the most described analysis were the quantification of pollutants in tissues such as liver and lipids (n = 18), biometric analyzes such as body weight, analysis of energy reserves, bioacoustics, plasma glucose, antioxidant enzymes, food consumption, genotoxicity tests, histology and others (Table 1).

Table 1. Description of papers with studied species, country of study, type of pollutant, and main outcomes.

Author/Year	Animal studied	Eating habit	Country	Toxic compound	Analysis
Allinson et al. (2006)	*Miniopterus schreibersii bassanii*	insect-eating bats	Australia	pesticides and metal	biometric analysis, metal and pesticide quantification in tissue
Amaral et al. (2012a)	*Artibeus lituratus*	fruit-eating bats	Brazil	pesticides	histology, plasma biomarkers of damage and quantification of energy reserves in tissue
Amaral et al. (2012b)	*Artibeus lituratus*	fruit-eating bats	Brazil	pesticides	histology, plasma biomarkers of damage and quantification of energy reserves in tissue
Barré et al. (2018)	Several	-	France	pesticides	bioacoustic analyzes
Bennett and Thies (2007)	*Tadarida brasiliensis*	insect-eating bats	USA	pesticides	pesticide quantification in guano
Boyd et al. (1988)	*Pipistrellus*	insect-eating bats	UK	pesticides	biometric analysis, food consumption, pesticide quantification in tissue
Brinati et al. (2016)	*Artibeus lituratus*	fruit-eating bats	Brazil	pesticides	plasma biomarkers of damage, pesticide quantification in tissue and quantification of energy reserves in tissue.
Buchweitz et al. (2018)	*Eptesicus fuscus*	insect-eating bats	USA	pesticides	pesticide quantification in tissue
Clark and Krynitsky (1983)	*Eptesicus fuscus, Myotis lucifugus, Pipistrelle oriental and Pipistrellus subflavus*	insect-eating bats	USA	pesticides	pesticide quantification in tissue
Eidels et al. (2016)	*Eptesicus fuscus*	insect-eating bats	USA	pesticides	behavioral assessment, body temperature, ChE activity in plasma and tissue and pesticide quantification in tissue
Fernández et al. (1993)	*Miniopterus schreibersii, Rhinolophus ferrumequinum and Pipistrellus pipistrellus*	insect-eating bats	Spain	pesticides	pesticide quantification in tissue

Table 1. Continued...

Author/Year	Animal studied	Eating habit	Country	Toxic compound	Analysis
Gerell and Gerell Lunderg (1993)	*Pipistrellus pipistrellus*	insect-eating bats	Sweden	pesticides and metal	body temperature and metal and pesticide quantification in tissue
Hill et al. (2016)	*Neoromicia nana*	insect-eating bats	South Africa	environmental polluters	antioxidant capacity in tissue, biometric analysis and fatty acid profile
Hsiao et al. (2016)	*Hipposideros terasensis*	insect-eating bats	Taiwan	pesticides	analysis of flight paths, immunohistochemical analysis, TUNEL labeling, and westernblot analysis
Kannan et al. (2010)	*Perimyotis subflavus, Myotis septentrionalis, Myotis lucifugus and Myotis leibiic*	insect-eating bats	Brazil	environmental polluters	polluents quantification in tissue
Lilley et al. (2013)	*Myotis daubentonii*	insect-eating bats	Finland	biocides	antioxidant capacity in tissue, biocide quantification in tissue, plasma biomarkers of damage, measurement of the alternative complement
López-Hoffman et al. (2014)	*Tadarida brasiliensis mexicana*	insect-eating bats	USA	pesticides	math analysis
Machado-Neves et al. (2018)	*Artibeus lituratus*	fruit-eating bats	Brazil	pesticides	histology
Naidoo et al. (2015)	*Neoromicia nana*	insect-eating bats	South Africa	environmental polluters	antioxidant capacity in tissue, genotoxicity analysis and plasma biomarkers of damage
Oliveira et al. (2017)	*Artibeus lituratus*	fruit-eating bats	Brazil	pesticides	antioxidant capacity in tissue, biometric analysis, food consumption, histology and pesticide quantification in tissue
Oliveira et al. (2018)	*Artibeus lituratus*	fruit-eating bats	Brazil	pesticides	antioxidant capacity in tissue, biometric analysis, food consumption, histology, plasma biomarkers of damage and quantification of energy reserves in tissue
Shore et al. (1996)	*Pipistrellus pipistrellus*	insect-eating bats	UK	pesticides	mortality, pesticide quantification in tissue
Stahlschmidt and Brühl, (2012)	Several	-	Germany	pesticides	bioacoustic
Stechert et al. (2014)	*Chaerephon pumilus, Mops condylurus and Molossidae*	insect-eating bats	Germany	pesticides	pesticide quantification in tissue
Swanepoel et al. (1999)	*Pipistrellus pipistrellus*	insect-eating bats	UK	pesticides	biometric analysis, food consumption, metabolic rate taxa and pesticide quantification in tissue

Table 1. Continued...

Author/Year	Animal studied	Eating habit	Country	Toxic compound	Analysis
Thies and McBee, 1994	*Tadarida brasiliensis*	insect-eating bats	USA	pesticides	pesticide quantification in tissue
Thies et al. (1996)	*Tadarida brasiliensis*	insect-eating bats	USA	pesticides	biometric analysis, genotoxicity analysis, nuclear DNA content, pesticide quantification in tissue
Valdespino and Sosa (2017)	Phyllostomidae family	fruit-eating bats	Mexico	pesticides	community ecology (species richness, abundance and species composition) and pesticide quantification in tissue

Bats belong to the order Chiroptera, the second largest order in number of species among mammals. They represent 25% of existing mammal species (Altringham, 1996). Occurring in all continents, there are currently approximately 1120 species described (Nowak et al., 1994).

Chiropterans are of great relevance to the ecosystems balance. Most species have developed morphological adaptations and eating habits that allowed them to occupy different niches and a complex relationship of interdependence with the environment. The greatest variety of eating habits is found among microchiropterans, including hematophagous, fruit-eating, insect-eating, piscivorous, polinivoros, nectarivorous and omnivorous species (Nowak et al., 1994). This particular diversity allowed them to offer ecological services essential to ecosystems balance, such as insect control, seed dispersal and pollination.

Recent studies have suggested that bats may be at greater risk regarding pesticides exposure than previously expected. Pesticide exposure in bats can occur through food and water contamination or through skin contact in their roosting areas. Residues can bioaccumulate in their tissues and compromise their health. Low breeding rate and seasonal reduction in food availability are among the factors contributing to the vulnerability of bat species regarding exposure to pesticides (Stahlschmidt and Brühl, 2012; Stechert et al., 2014). Here, we observed that the number of investigations that portray the effects of pesticides on bats still has several gaps and is concentrated in the temperate regions of the globe (Table 1). Central and South America present a great diversity of bat species, and although some countries from these regions consumed a high amount of pesticides in the last 10 years (Figure 1), little is known about their effect on Neotropical bat populations.

Insect-eating bats are considered more susceptible to pesticides due to the fact that they are at the top of the food chain. Insect-eating bats help control insect populations, including vectors of diseases such as dengue, leishmaniosis, and malaria, as well as agriculture pests. Declines in insect-eating bats in North America represents a loss of billions of dollars in agricultural cultivation (Boyles et al., 2011; Cleveland et al., 2006; López-Hoffman et al., 2014). When they feed on preys (insects, arthropods and others) contaminated with pesticides, insect-eating bats end up bioaccumulating residues in their tissues (Gerell and Gerell Lunderg, 1993; Stahlschmidt and Brühl, 2012). Residual concentrations of organochlorines, dieldrin, endosulfan, lindane, pyrethroids, organophosphates and carbamates were recorded in several tissues of insect-eating bats (Clark and Krynitsky, 1983; Eidels et al., 2016; Fernández et al., 1993; Gerell and Gerell Lunderg, 1993; Kannan et al., 2010; Lilley et al., 2013; Stechert et al., 2014). We observed that insect-eating bats are the most studied (Table 1) and apparently accumulate more pesticides compared to bats with different eating habits. However, this information probably does not depict reality, since most surveys do not portray other food guilds (Table 1).

Fruit-eating bats, on the other hand, are large seed dispersers contributing to reforestation and forest conservation (Altringham, 1996). These animals are also in constant exposure to environmental contaminants and their almost exclusive fruit diet makes them good indicators of the presence and magnitude of pesticide contamination (Valdespino and Sosa, 2017). Nevertheless, from 1964 to 2019 research on bioaccumulation and the effect of pesticides on fruit-eating bats is still scarce (Table 1).

Besides food, water is another route of exposure of bats to pesticides. Contamination can occur directly through drinking water, or indirectly when feeding on insects. In addition, water quality is a selective factor for the species, since some may prefer to forage in places with less polluted water than others (Korine et al., 2015). Despite the importance of water quality for the species, to our knowledge, no studies show a direct association of pesticide residues in water bodies and its bioaccumulation in bat tissues, although studies involving heavy metals managed to prove this direct relashionship (Hill et al., 2016; José Zocche et al., 2010; Naidoo et al., 2015, 2016).

Bat populations have been declining in some regions of the world, and some authors are associating this decline with the bioaccumulation of pesticides in their tissues (Bennett and Thies, 2007; Dennis and Gartrell, 2015). In New Zealand and Spain, analysis of bats carcasses found in their roosting areas reveled high concentrations of pesticides (Dennis and Gartrell, 2015; Fernández et al., 1993). In the United States, forty years after the pesticide

DDT was banned due to its persistence and adverse effects on the environment, a large group of insect-eating bats was found dead and a high concentration of DDT was reported in their brain, kidneys, and liver (Buchweitz et al., 2018).

4. Main Effects of Pesticides in Bats

Once ingested, xenobiotics are metabolically converted to more water-soluble compounds, easier to excrete. This biotransformation may alter the chemical´s pharmacodynamic or toxic effect. Some metabolites derived from the original compounds can also bioaccumulate in tissues and induce immunotoxicity, oxidative stress, endocrine disruption and reproductive failure in wild animals even after the exposure period (Berny, 2007).

The highest concentrations of pesticides in bats are found in the adipose tissue, followed by the liver and the brain. Bats can be 30 times more sensitive to pesticide bioaccumulation than exposed rats (Shore et al., 1996).

In several bat species, organochlorines were found to increase the basal metabolic rate with a consequent reduction in body energy reserves (Brinati et al., 2016; Kannan et al., 2010; Swanepoel et al., 1999). Energy reserves mobilization, especially from lipids, increases blood concentration of pesticides, which increases its effects in more sensitive tissues, such as liver and brain (Boyd et al., 1988). In the brain, organochlorines may impair the regulation of several processes such as hibernation (Chen et al., 2008) and prey capture during flight (Schwartz and Smotherman, 2011; Wenstrup and Portfors, 2011). In the liver, this class of pesticide may impair the detoxifying ability (Hill et al., 2016). Moreover, the reduction of energy reserves may also impair reproductive processes, especially in females, and makes awakening of torpor difficult (Eidels et al., 2016). Decreased energy reserves also may induce an increase in foraging time, which involves a higher energy expenditure and make individuals more susceptible to predation (Allinson et al., 2006; Swanepoel et al., 1999).

Organochlorines typically interfere with acetylcholinesterase activity, which may impair their echolocation performance (Eidels et al., 2016; Hsiao et al., 2016). Considering the importance of this feature for bats navigation, this single effect can impair a wide variety of their nocturnal activities. In fact, among insect-eating bat species monitored in agricultural areas with different degrees of herbicide exposure, populations observed foraging in organic crop areas showed a higher foraging time and a greater species richness when compared to those found in areas near crops treated with pesticides (Barré et al., 2018).

Exposure to organochlorines also caused several pathologies in bats' liver, such as vacuolization, necrosis and apoptosis (Amaral et al., 2012a, b; Oliveira et al., 2017). In addition, they induced oxidative stress (Oliveira et al., 2018) and decreased the total hepatic antioxidant capacity (Oliveira et al., 2017), which, depending on the severity of the liver lesions, can cause death (Dennis and Gartrell, 2015).

Besides the effects of pesticides in cells and tissues, some chemicals also interfere with the endocrine system of non-target organisms, impairing hormone secretion, transportation and/or biding to target cells. Several organochlorine and pyrethroid insecticides are considered endocrine disrupters, altering the reproduction axis mediated by testosterone in rats (Thies and McBee, 1994; Thies et al., 1996). In bats, only a few studies have been contributing to this important area, including the reported incidence of several testicular and epididymal pathologies followed by the exposure to the fungicide tebuconazole in Neotropical fruit-eating bats (Machado-Neves et al., 2018).

Immunotoxicological effects of pesticides are also a neglected area regarding studies with bats, although the white-nose syndrome has been killing millions of bats in temperate regions. Pesticides toxicity leads to immunosuppression and makes the individual more susceptible to infections by pathogenic organisms (Afonso et al., 2016). A direct association to pesticides exposure was suggested by Kannan et al. (2010), who reported a reduced complement system activity induced by organochlorine bioaccumulation in insect-eating bats (Kannan et al., 2010) (Lilley et al., 2013). Insect-eating bats were found to have more ectoparasites when foraging under polluted waters (Korine et al., 2015). The main endpoints observed are summarized in Figure 3.

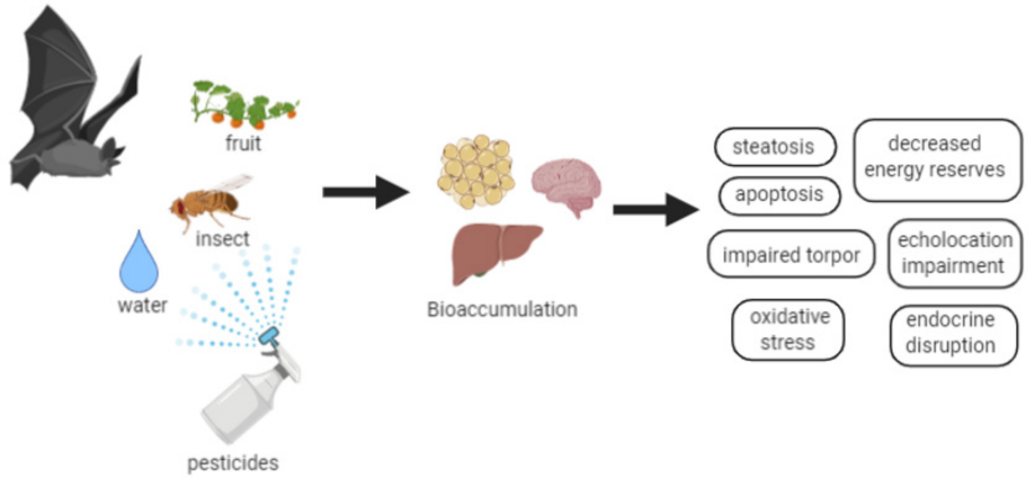

Figure 3. Major endpoints of the consequences of bats exposure to pesticides.

Given the aspects afore mentioned, we conclude that bats are sensitive to pesticide exposure and may act as a model for pesticide risk assessment programs (Stahlschmidt and Brühl 2012). Specific characteristics such as high metabolic rate, high longevity and high oxygen consumption contribute to the importance of evaluating pesticides effects in key bat species.

5. Conclusion

Many studies have yet to be done to understand the degree and exactly how pesticides act in the physiology of bats, but impacts are high for these animals and may reduce populations' survival capacity, and may result in large losses for both conservation and economy efforts. Future research is needed for increasing the conservational effort of this taxon.

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