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Review

Poisonous birds: A timely review

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ABSTRACT

Until very recently, toxicity was not considered a trait observed in birds, but works published in the last two decades started to shed light on this subject. Poisonous birds are rare (or little studied), and comprise Pitohui and Ifrita birds from Papua New Guinea, the European quail, the Spoor-winged goose, the Hoopees, the North American Ruffed grouse, the Bronzewings, and the Red warbler. A hundred more species are considered unpalatable or malodorous to humans and other animals. The present review intends to present the current understanding of bird toxicity, possibly pointing to an ignored research field. Whenever possible, biochemical characteristics of these poisons and their effects on humans and other animals are discussed, along with historical aspects of poison discovery and evolutionary hypothesis regarding their function.

1. Introduction

The discovery of poisonous birds in early 1990s (Dumbacher et al., 1992) led to a reassessment of chemical defense distribution among animals. Previous works had investigated the unpalatability of many bird species, as well as the supposed presence of poisons in some of them, and this new discovery sparked interest in this topic (as reviewed by Dumbacher and Pruett-Jones, 1996; Bartram and Boland, 2001). The interest, however, was short-lived, despite many new discoveries in this field, including putative sources of poisonous compounds and evolutionary motivations for poison acquirement by birds.

Poison has been ascribed to at least four species of the *Pitohui* genus, one of the *Ifrita* genus, the European quail, the red warbler and the spoor-winged goose. Other six species are thought to be poisonous, one is confirmed to 'maleficently' use toxic compounds, and 95 are considered unpalatable or malodorous (with experimental confirmation of aversion for thirteen of them) (Dumbacher and Pruett-Jones, 1996; Bartram and Boland, 2001).

Poisonous birds are often called *toxic*, and both terms are included in the descriptions of *chemical defense* in birds. Frequently, all designations encompass the same idea. For this review, we are following the definition of chemical defense as proposed for birds by Dumbacher and Pruett-Jones (1996): "chemical defense occurs when an individual contains or uses behaviorally one or more chemical substances that deter predators and/or parasites". According to Mebs (2002), poisonous animals produce toxic compounds or take them from the environment, store and accumulate them in their body, and use these compounds in a passive manner. Such toxic compounds are called poisons. This description is in accordance with previous proposals, as in Bücherl (1968). Poisons are often secondary products or metabolites, and may be acquired from the environment (Mebs, 2002). Therefore, the overlap in these definitions allows their interchangeable use.

Taking into account the amount of data on bird toxicity, the following sections outline different groups of birds, based on the degree of knowledge available regarding the chemical compounds used by them. Whenever possible, the pharmacological effects of these molecules are presented, and ecological implications are drawn. Potential reasons for the overlooking of toxicity in birds are also discussed.

2. Pitohui and Ifrita

2.1. General aspects

The isolation of toxic compounds from the skin and feathers of *Pitohui* spp. birds (Dumbacher et al., 1992) was a breakthrough in the study of chemical defense in animals. It led to responses from zoologists, praising this new finding while presenting other

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examples of bird toxicity (Diamond, 1992; Wrangham, 1992; Pough, 1992; Berkowitz, 1993), or questioning the real effect these toxins could have in non-laboratorial settings (Glendinning, 1993; Poulsen, 1994).

Endemic of New Guinea, these birds were long held by the natives as inappropriate for consumption unless skinned and prepared in particular ways, especially the Hooded pitohui (*Pitohui dichrous*), branded 'rubbish bird' for its bitter taste and sour odor (Dumbacher et al., 1992; Diamond, 1992). Natives also described other effects of contact with the bird skin, such as numbness of mouth and lip (Majnep and Bulmer, 1977).

There are six species of pitohui, and the toxicity levels vary among them (Dumbacher et al., 2000). The Hooded (*P. dichrous*) and the Variable pitohui (*P. kirhocephalus*) are significantly more toxic than the other species (Fig. 1, A and B). The Black (*P. nigrescens*) and the Crested pitohui (*P. cristatus*) have traces of toxicity, while the Rusty (*P. ferrugineus*) and the White-bellied pitohui (*P. incertus*) are devoid of toxins.

Another bird from New Guinea, *Ifrita kowaldi* (or Blue-capped ifrita) (Fig. 1C), was added to this group for having the same toxins as pitohuis in its skin and feathers (Dumbacher et al., 2000). The toxins identified in *Pitohui* and *Ifrita* are from the batrachotoxin family (Bartram and Boland, 2001).

2.2. Toxic compounds and their effects

When collecting bird specimens for research, Dumbacher et al. (1992) experienced sneezing with numbness and burning of oral and nasal tissue. He and his team suspected that these unpleasant reactions could be due to some unknown compound and sent bird tissue samples to J.W. Daly, at the U.S. National Institutes of Health (Daly, 1998). In 1963, Daly discovered alkaloids in the skin of dendrobatid frogs, and studied the molecular variety of skin compounds in amphibians until his death, in 2008 (Fitch and Bewley, 2010).

The analysis of skin and feathers from *Pitohui* revealed the presence of a single, highly toxic alkaloid (Dumbacher et al., 1992). This alkaloid, homobatrachotoxin (Fig. 2), was thought to only exist in the skin of dendrobatid frogs from South America (Daly, 1998). Afterwards, at least six different variations of batrachotoxins were discovered in passerine birds (Dumbacher et al., 2000), but homobatrachotoxin was far more abundant than the other forms, such as batrachotoxin and batrachotoxinin-A (Dumbacher et al., 2004).

Batrachotoxins (BTXs) are one of the most toxic natural substances (250-fold more toxic than strychnine), being the most potent nonprotein poison known for vertebrates (Myers et al., 1978). BTXs are both neuro- and cardiotoxins (Brown, 1988),

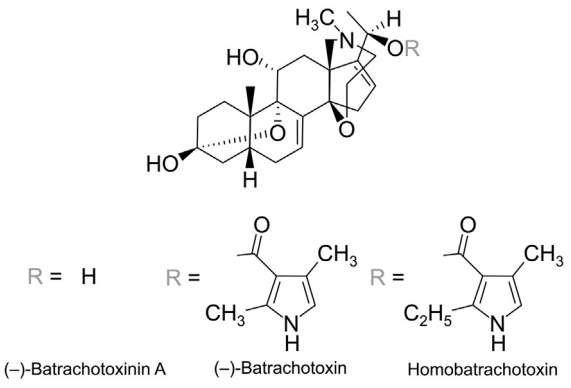

Fig. 2. Main types of batrachotoxins (BTXs) found in Pitohui and Ifrita birds. Based on Daly et al. (2005).

binding with high affinity to voltage-gated sodium channels in the membrane of muscle and nerve cells, 'locking' these channels in an open state (Albuquerque et al., 1971). The potency and specificity of BTXs turned these molecules into tools for the study of sodium channels (Strichartz et al., 1987; Brown, 1988; Dumbacher et al., 2004).

The effects and mode of action of BTXs from dendrobatid frogs have been extensively studied (e.g. Myers et al., 1978; Daly, 1998) and are beyond the scope of this review. The point that should be stressed, however, is that BTXs from *Pitohui* and *Ifrita* have much milder effects when compared to those observed for the toxins obtained from frogs. While contact with frog-derived BTXs cause arrhythmias, fibrillation, cardiac arrest, convulsion, strong muscular contractions, gagging, and dyspnea (Myers et al., 1978), contact with BTX-containing birds is known to cause numbness, burning, sneezing, nausea, and lip puckering, besides the bitter taste their flesh presents to humans (Bartram and Boland, 2001; Dumbacher et al., 2009). The most likely explanation for this difference in toxic effect is that birds have BTXs in lower levels than do Amazonian frogs (Dumbacher et al., 1992).

When tested for toxin identification and confirmation, homobatrachotoxin from Rusty, Variable, and Hooded pitohui had the same effects as those observed from the toxin obtained from frogs. By subcutaneous injection into the hindquarters of mice, low dosages (under 0.01 μg) caused locomotor difficulties, partial hind limb paralysis and prostration, while higher dosages (over 0.3 μg) causes tonic convulsions and death in periods as little as 15 min (Dumbacher et al., 1992).

Fig. 1. (A) Hooded pitohui (*Pitohui dichrous*); (B) Variable pitohui (*P. kirhocephalus*); (C) Blue-capped ifrita (*Ifrita kowaldi*). (Pitohui photographs by Katerina Tvardikova; Ifrita photograph by Suzanne Tomassi).

Additionally, feathers containing homobatrachotoxin were tested against chewing lice (Order Phthiraptera), based on the hypothesis that BTXs could act deterring ectoparasites rather than predators (see Section 2.3). These tests revealed that lice preferred non-BTX feathers for sheltering and that BTX significantly shortened the life span of lice cultured in laboratory (Dumbacher, 1999).

There is also evidence, based on direct observations made by New Guinea natives, that BTXs effects are deterrent to different *Pitohui* predators. These include green tree pythons, brown tree snakes, raptors, arboreal marsupials, and human hunters (Dumbacher et al., 1992; Diamond, 1992; Dumbacher, 1999; Dumbacher et al., 2009).

2.3. Biological and evolutionary aspects

When BTXs were discovered in *Pitohui*, it was proposed that these toxins would deter predators, by depolarizing nerve and muscle cells (via sodium channel activation), leading to irritation of sensory neurons in their buccal tissue (Dumbacher et al., 1992). This proposal was quickly challenged based on the concentration of BTXs detected in the birds (Glendinning, 1993). This led to the suggestion that BTXs would be a defense against ectoparasites (such as lice) (Poulsen, 1994; Mouritsen and Madens, 1994; Dumbacher, 1999). Reevaluation of previous data suggests that tick infestation in pitohuis is one of the lowest among the sampled bird species (Mouritsen and Madens, 1994). The use of BTXs as a parasite-control asset (instead of an anti-predator defense) was strengthened by the observation that pitohuis have a concentration of BTXs three orders of magnitude lower than the one observed in dendrobatid frogs (Poulsen, 1994; Bartram and Boland, 2001). Nevertheless, as Mouritsen and Madens (1994) and Dumbacher et al. (2009) stressed in their works, defense against predation and defense against parasitism are not mutually exclusive and should be taken together when considering *Pitohui* birds.

Dumbacher et al. (2000) observed that breast and belly contour feathers are the ones with highest toxin concentrations in Pitohui and Ifrita. They speculated that these feathers would be rubbed off onto eggs (or deposited in the nest) to protect them from egg-eating predators. These authors also argue that, since human hunters recognize the bright plumage of these birds and avoid them because of their toxin content, other predators would do the same. Based on the pressure that parasite resistance may have on sexual selection in birds, Mouritsen and Madens (1994) proposed that Pitohui birds would employ feather coloring and sour odor as a proxy for the parasite resistance conferred by BTXs.

Molecular phylogeny studies found that the *Pitohui* genus is polyphyletic, consisting of five lineages, with the bright-colored phenotype evolving more than once among these birds (Dumbacher and Fleischer, 2001; Dumbacher et al., 2008; Jønsson et al., 2008). The observed variation in toxicity among corvoid birds, though, is interpreted differently among authors. Jønsson et al. (2008) argue that much more birds are expected to be toxic, taking toxicity as an ancestral trait, while Dumbacher et al. (2008) interpret this polyphyly as evidence for convergent evolution of toxicity among these birds. This convergence is thought to be a form of mimicry, either Müllerian or Batesian. In the first case, multiple toxic species would resemble each other in order to share the costs of educating predators, while in the second case non-toxic species would mimic the toxic ones in order to deceive predators (Diamond, 1992; Dumbacher et al., 2008). More studies are required to test these observations. The proposed mimicry would work on visual predators, since it has long been proposed (and confirmed in some cases) that conspicuous birds constitute unprofitable prey (Baker and Parker, 1979; Götmark and Unger, 1994). The fact that different species of pitohuis associate with birds from at least seven other families in the so-called “brown and black flocks” of New Guinea supports this idea. These itinerant foraging flocks are nucleated by pitohuis and include some species of birds of paradise, which are considered unpalatable to humans (Diamond, 1992; Mebs, 2002; Dumbacher et al., 2008).

Another key point regarding BTXs-containing birds is the source of the toxin. In the case of amphibians, the animals themselves do not synthesize the majority of the protective compounds identified so far, including BTXs (Daly, 1995, 1998). Dendrobatid frogs kept in captivity have no trace of BTXs, leading to a putative dietary source for the toxins that would not be available in lab conditions (Daly et al., 1980). Lending power to this hypothesis, the feeding of these frogs with artificial meals of batrachotoxinin-dusted flies increased their toxin content, despite the animals not being able to convert this compound into the more toxic BTX or homo-BTX (Daly et al., 1994).

Restrictions to field work in Colombia prevented searching dietary sources of BTXs for dendrobatid frogs. It is therefore somewhat curious that the putative identification of such a source came from studies of Pitohui and Ifrita. Different approaches were taken in the attempt to identify the source of BTXs in these birds, including radiotelemetry, examination of stomach contents, survey of plants and insects that could take part in their diets, and investigation of leads by local naturalists. Based on such leads, Dumbacher et al. (2004) identified BTXs in the little-studied beetles from the *Choresine* genus (Melyridae family) in the Eastern Highland Province of Papua New Guinea. These beetles are locally known as *nanisani*. This is the same native term used for the Blue-Capped Ifrita, and describes tingling and numbing sensations. Natives warn that alighting of these insects on eyes or their contact with facial perspiration can cause severe burning sensation (Dumbacher et al., 2004). A common third toxin source for both insects and birds seems unlikely, since the beetles were found in stomach contents of Pitohui and Ifrita. The insects however may take some of the molecular scaffold for BTX from other source, which may be a plant (Daly, 1998; Dumbacher et al., 2004).

It is unknown how Pitohuis and Blue-capped Ifrita resist the toxic effects of BTXs, since the toxins are also found in their heart and skeletal muscle tissue (Dumbacher et al., 2009). Voltage-gated sodium receptors are highly conserved among vertebrates and invertebrates (Albuquerque et al., 1971), with one exception being the dendrobatid frogs. In these frogs, the BTX recognition site of the sodium receptor is not functional due to a point mutation (Daly et al., 1980; Dumbacher et al., 2009). A similar mutation is expected to occur in these birds, but this has not been demonstrated so far.

The precise location of the toxin storage in Pitohui birds has been elucidated recently (Menon and Dumbacher, 2014). The use of osmium-staining techniques on transmission electron microscopy revealed that the alkaloids were restricted to multigranular bodies, organelles considered homologues of mammalian lipid-enriched lamellar bodies, located in the epidermis. Reaffirming a previous hypothesis (Dumbacher et al., 2009), this discovery supports the concept that Pitohui birds make up a “toxic mantle” from their epidermal permeability barrier. The feather toxins are most likely taken from epidermal storages (or secondarily from the preen gland secretion), since no incorporation of alkaloids has ever been observed for the keratinized structure of any feather, no matter how specialized (Menon and Dumbacher, 2014).

Considering the phylogenetic and geographical distances between poisonous birds and poisonous frogs combined with the rarity of BTX uptake by animals in general, it is likely that this evolutionary trait was independently acquired by these two groups (Dumbacher et al., 1992; Bartram and Boland, 2001). The discovery that poisonous frogs from Madagascar use arthropod sources for

their toxins that are different from the ones used by American frogs reinforces the convergent acquisition of BTX by different vertebrate groups (Clark et al., 2005).

3. Quails and coturnism

3.1. General aspects

Coturnism, or quail poisoning, is a rare cause of rhabdomyolysis (striated muscle tissue breakdown) with potentially lethal complications such as renal failure and shock. The toxicological syndrome is associated with the consumption of the European subspecies of migratory quails (*Coturnix coturnix coturnix*) (Fig. 3) during autumn in rural Mediterranean areas of Algeria, France, Greece, Italy and Spain (Giannopoulos et al., 2006; Uriarte-Pueyo et al., 2009).

The African (*Coturnix corturnix africana*) and Asiatic (*Coturnix coturnix japonica*) subspecies are not considered toxic, whereas the European subspecies seems to be toxic only when migrating in a specific direction. These quails migrate twice a year, flying semi-northward from lakes in East Africa to Egypt, then splitting in the Eastern and Western flyways. The first flyway follows a route covering Israel to southwestern Russia, while the second crosses the Mediterranean Sea, through Greece, finally breeding in Eastern Europe. Intoxication by quails is observed only when the birds are migrating southward, back to Africa. In Greece, for instance, coturnism is majorly observed in the Island of Lesbos, a stop point for one day in the migration flyway (Kennedy and Grivetti, 1980; Giannopoulos et al., 2006).

The location-specific toxicity led to the proposal that quails become poisonous by eating some toxic compound, possibly from plant origin, to which the birds themselves are resistant. So far, no culprit has been ascribed (see section 3.2). Some authors (Ouzonellis, 1970; Berkowitz, 1993; Bartram and Boland, 2001) consider the massive death of Israelites after consuming quails, described in the Old Testament, as the first major report on coturnism. This segment (Num. 11: 31–34) reads “Now there went forth a wind from the Lord and it brought quail from the sea, and let them fall beside the camp, about a day's journey on this side and a day's journey on the other side, all around the camp and about two cubits deep on the surface of the ground. The people spent all day and all night and all the next day, and gathered the quail (he who gathered least gathered ten homers) and they spread them out for themselves all around the camp. While the meat was still between their teeth, before it was chewed, the anger of the Lord was kindled against the people, and the Lord struck the people with a very severe plague. So the name of that place was called Kibroth–hattaavah, because there they buried the people who had been greedy.” Others have questioned this assumption, proposing other forms of food poisoning or direct divine intervention (Rosner, 1970, 1978; Tullis, 1977). Additional records of quail poisoning are present in the works of Didymus of Alexandria, Lucritius, Plinius (the elder), Cassianos Vassos, Galen and Avicenna. In these works, the toxicity is attributed to poisonous seeds eaten by the birds (Rutecki et al., 1998; Giannopoulos et al., 2006). As of 2014, coturnism remains widely understudied, with genetic, biochemical, epidemiological and experimental data still in need (Gokhan et al., 2014).

Fig. 3. European quail (*Coturnix coturnix coturnix*), female. (Photograph by Luis Miguel Bugallo Sánchez).

3.2. Toxic compounds and their effects

The association of intoxication and the bird's diet has been proposed since Medieval times (Bartram and Boland, 2001). Many (toxic) plants have been listed as culprits, based mainly on observed symptoms. These include seeds from poison hemlock (*Conium maculatum*), henbane (*Hyoscamus niger*), black nightshade (*Solanum nigrum*), and hemlock water dropwort (*Oenanthe crocata*) from which quails can absorb and accumulate secondary metabolites (such as the solanin glycosides and the alkaloids coniine and hyoscyamine) (Mebs, 2002). There is negative evidence for *Galeopsis ladanum* seeds (especially its lipidic compound stachydrine) being responsible for the observed toxicity in animal models (Uriarte-Pueyo et al., 2009; Salman et al., 2012). It has also been suggested that mycotoxin(s) may act synergistically with plant toxins to produce coturnism (Uriarte-Pueyo et al., 2009). There seems to be no way of telling if a quail is toxic based on smell or taste, and cooking seems unable to detoxify the meat (Gokhan et al., 2014).

There is an alternative (or additional) mechanism for the observed toxicity. Originally proposed by Ouzonellis (1970), such mechanism would explain why only a few members of a population feeding on quails get sick (especially after muscle fatigue). The selective toxicity would be explained by a genetic deficiency in some muscle cell enzyme, a view that is supported by recurring syndromic events in the same individuals (Billis et al., 1971). This deficiency has been considered analogous to McArdle's syndrome (absence of muscle phosphorylase) and fava bean intoxication (absence of glucose-6-phosphate dehydrogenase in red blood cells) (Ouzonellis, 1970; Billis et al., 1971; Papapetropoulos et al., 1980) but no specific enzyme has been identified so far (Papadimitrou et al., 1996). This putative enzymatic condition may be exclusive to humans, hampering studies on other animals models (Uriarte-Pueyo et al., 2009).

The symptoms observed in coturnism are the same as those found in acute rhabdomyolysis. As summarized by Giannopoulos et al. (2006), the symptoms develop in 1–9 h after quail consumption, and muscular fatigue after the consumption accelerate the onset, while rest seems to prevent it. The syndrome starts with sharp, intense muscle pain in limbs and trunk, which intensifies and spreads, sometimes leading to or co-occurring with paralysis. Colored urine (brown or red) may appear soon afterwards. Laboratory findings are consistent with skeletal muscle injury. Although of short duration and of general good prognosis, coturnism may lead to acute myoglobinuric renal failure, requiring hospitalization and dialysis. More rarely, there is a risk of severe complications, such as intravascular coagulation, hyperkalemia, and acute cardiomyopathy, as observed for non-coturnism rhabdomyolysis.

Besides being rare and geographically restricted, the differential diagnosis for coturnism must exclude usual causes of rhabdomyolysis. These include many factors, such as infections (herpes simplex virus 1 and 2, Epstein–Barr virus, cytomegalovirus),

trauma, thermal extremes, epilepsy, connective tissue diseases, other myopathies, metabolic disorders, thyroid dysfunctions, and drug intoxications (Giannopoulos et al., 2006; Mazokopakis, 2008; Korkmaz et al., 2011).

3.3. Biological and evolutionary aspects

The restricted nature of quail toxicity (rare even within the same subspecies) seems to limit its putative evolutionary advantage of deterring predators. It is possible that quails have an adaptive gain by being able to eat from food sources that would be otherwise toxic for birds. To the best of the authors' knowledge, however, there is no study on this subject, rendering such observations speculative.

4. Other poisonous birds

With the exception of the Spoor-winged goose (*Plectropterus gambensis*), which acquires the toxic cantharidin from *Meloidae* beetles (Eisner et al., 1990), and the Hoopees (*Upupa epops* and *Phoeniculus purpureus*), which harbor symbiotic bacteria in their preen gland producing obnoxious volatile compounds (Burger et al., 2004; Martín-Vivaldi et al., 2010), descriptions of toxicity are superficial or preliminary for other birds. Some of them had their toxic compounds traced back to putative plant sources. These include the North American Ruffed grouse (*Bonasa umbellus*) which acquires andromedotoxin from the mountain laurel (*Kalmia latifolia*), and the Bronzewings (*Phaps elegans, P. chalcoptera*), which are suspected to acquire monofluoroacetate from *Gastrolobium* spp. and *Oxylobium* spp. (Dumbacher and Pruett-Jones, 1996; Bartram and Boland, 2001). Alkaloids of unknown origin have been detected on feathers of the Red warbler (*Ergaticus ruber*), considered distasteful by natives (Escalante and Daly, 1994).

Besides acquisition of toxic compounds, there are some other uses of chemical defenses by birds. Some species of woodpecker flap their wings on anthills to induce the insects to spray formic acid, used to eliminate parasites (Clayton and Wolfe, 1993; Mebs, 2002). This behavior, considered by some authors as self-medication, has been observed for other birds, which use volatile compounds from animal and plant origin for similar purposes (Dumbacher and Pruett-Jones, 1996).

In a separate category, the Northern fulmar (*Fulmarus glacialis*) sprays partially digested fish oils on competitors and predators (Swennen, 1974). This behavior has been classified as maleficent use of chemicals, since the chemicals per se are not toxic, but are able to inflict injuries or damage on the target animal (Dumbacher and Pruett-Jones, 1996).

It has been proposed that animals may employ plant secondary metabolites as responses to many homeostatic challenges, including parasite mitigation, reproduction enhancement, thermoregulation, predation resistance, and alertness resistance (Forbey et al., 2009). In such framework, bird toxicity would be just one aspect of a much broader phenomenon, with reflections in animal management and possible active compound discoveries.

5. Unpalatable or malodorous birds

The more recent reviews on bird toxicity do not include unpalatable or malodorous birds in their classification of poisonous birds (Bartram and Boland, 2001; Mebs, 2002). There is, however, an extensive body of evidence on this subject, chiefly from experimental work carried out by Cott (Cott, 1945, 1946, 1948, 1954; Cott and Benson, 1970), and by surveying field and museum ornithologists (Weldon and Rappole, 1997).

The British zoologist Hugh B. Cott presented bird carcasses and eggs to different predators, such as hornets, rats, cats, hedgehogs, and human evaluators, then scored the preference of consumption (or aversion) for different species. More recently, Weldon and Rappole (1997) gathered personal recounts from researchers, in an attempt to confirm or expand the original list from Cott's work. There are some differences among these works, as well as when comparing preferences from Egyptian and American human evaluators (Goodman and Hobbs, 1990).

It is interesting to note that Pitohui birds were considered unpalatable by Papuan natives, and so were Ifrita ones (Diamond, 1992). This may indicate that many more birds, currently cataloged as non-edible based on taste may actually be new occurrences of toxicity in birds. For detailed listings of the observed cases of unpalatability in birds (reaching one hundred species), the reader is referred to the works by Dumbacher and Pruett-Jones (1996) and Weldon and Rappole (1997).

6. Concluding discussion

Until the discovery that pitohuis were poisonous, toxicity was not considered a trait observed in birds, at least not by the general zoology community. This is an intriguing fact, considering that hints about this feature were described since Ancient Greek times. Efforts to recollect previous descriptions of bird toxicity list different forms of chemical defense, unpalatability and poison production. Still, apart from the inspection of Papuan birds by Dumbacher and collaborators, very few studies were dedicated to this subject in recent years and it is not clear why so many works in this area have been overlooked (Dumbacher and Pruett-Jone, 1996). The same trend has been observed for venomous mammals (Ligabue-Braun et al., 2012), which were disregarded by mainstream biologists until very recently.

The research on bird toxicity is considered to be in its beginnings (Mebs, 2002). If we take amphibians as an indication of what may be found in birds, there is still much ground to cover, since more than eight hundred alkaloids have been found in amphibian skins so far (Daly et al., 2005). As new cases of toxicity or negative chemosensory responses are reported, birds become attractive as a source for biologically active natural products (Weldon and Rappole, 1997; Weldon, 2000; Rajchard, 2010). Even reptiles have little-studied poisonous occurrences in addition to the well-known venomous ones. That is the case of chelonitoxism, a rare intoxication from eating sea turtle flesh, not related to any known environmental substance accumulation (Fussy et al., 2007), pointing to uncharted lands for toxinologists. In addition to that, the recent discovery that African crested rats (*Lophiomys imhaus*) accumulate toxins from plant sources in their hair (Kingdon et al., 2012) is considered evidence for convergent evolution of poisonous integuments in both mammals and birds (Plikus and Astrowski, 2014).

Despite cultural differences, the fact that so few bird species are domesticated and raised for food production may be an indication of a more widespread toxicity (or unpalatability) among birds. There are many criteria that an animal must fulfill in order to become domesticated, and these justify why so few large mammals are raised in farms today (Diamond, 1997, 2002). In theory, humans already had time to sample all animal species surrounding them in terms of domestication suitability (Diamond, 1997), leading to the speculation that the limited number of domesticated birds may be explained in part by their little-studied toxicity.

Whether for their biotechnological value or sheer scientific knowledge, poisonous birds should not remain at the shores of mainstream zoology. For instance, pitohuis birds were taken as toxic by native New Guineans for more than forty thousand years, and only yesterday modern scientists rediscovered this fact. If one

takes the unpalatable birds, there are dozens of cases just waiting to be studied in depth. Additionally, as Diamond (1992) reasoned, "there is a broader moral to this tale". Discoveries are being lost by the minute, as each hectare of felled rainforest may be taking with it jewels of toxinology, along with local cultures that are being rapidly 'modernized' and losing touch with their ancestral knowledge.

Ethical statement

The authors declare to have agreed upon the content and form of the manuscript, which has not been published previously nor is it being submitted, entire or parts of it, to any other journal. No experiments with live organisms were conducted to provide data for this work.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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