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# The Plasticity of Organisms: Some Examples of the Adaptations of Small Vertebrates to Various Environments All Around the World

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## Abstract

At a time when the decline of biodiversity is serious, many organisms currently live in different biotopes, even the most unexpected. For this, organisms have adapted to all environments, often developing very specialized anatomical and physiological characteristics. Looking at nature when traveling around the world, it is obvious that the adaptations to the environment are specific. In this short review, we propose a trip around the world to meet small vertebrates having acquired anatomical, physiological or reproductive specializations, in order to live at best in environments that are a priori incompatible with life. Some species encountered during this excursion have been studied for a long time by our group, others, with very specialized adaptations; have been studied by other teams. The wealth of these adaptations is currently threatened by climate change. Thus, specializations can sometimes become a handicap for the life of the species. New adaptations will certainly develop in the future, but will species have time to adapt to quickly evolving biotopes?

**Keywords:** Adaptation; Anatomy; Physiology; Reproduction; Fish; Amphibians; Reptiles; Rodents

## Introduction

Biodiversity decline is a serious current issue. Nevertheless, life is everywhere, even in the most unexpected places. This permanence is directly linked to the immense plasticity of organisms capable of adapting to all environments. In this short overview, I propose to meet, during a trip around the world, some small vertebrates having acquired anatomical, physiological or reproductive specializations sometimes strange, to live at best in environments sometimes *a priori* incompatible with life. For that we will start from South America, to reach, Central America, Canada, Siberia, Sub Saharan Africa, Sahara, and Europa. A part of these examples will be made to the work carried out for a long time by our laboratory and our collaborations, the others were chosen from literature.

## In South and Central America

### The Reproduction of *Typhlonectes Compressicauda*, a Caecilian Amphibian

In South America, and more particularly in French Guiana, *Typhlonectes compressicauda*, a gymnophionan (caecilian) amphibian, otherwise totally harmless, is adapted to life in the marshes. It is subject to a seasonal

alternation characterized by a period of rain between January and June followed by a relatively dry period between July and December. The breeding cycle begins in October. In the males, during the rainy season, the amount of germ cells decreases in the testes. At the end of breeding, in June, spermatogenesis will fill the gonads with a new germ cell stock ready for use next season. The cycle of males is annual. Females are viviparous with a biennial cycle. From breeding, gestation lasts 6 to 7 months and the young are born in September-October, at a time when the rain has stopped and the water has withdrawn, leaving the savannahs out. *Typhlonectes* are now buried in the mud waiting for the next rainy season. At the time of reproduction, female genital tract is prepared to a new reproduction but it quickly returns to a resting state throughout the second year of cycle [1-3]. Internal fertilization leads to the formation of several intrauterine embryos which develop placental-like structures. At the end of gestation, females give birth to 6 to 8 youngsters perfectly similar to their parents [2].

The burial period in the mud is an essential factor in starting the breeding cycles in both males and females. Indeed, animals raised in the laboratory, under conditions where the drought period was not represented, never managed to reproduce because the female reproductive cycle was strongly disturbed [4]. Examination of diuretic and antidiuretic hormones (mesotocin and vasotocin) show significant differences between dry and wet seasons. In kidneys, Bowman spaces and blood capillaries are wider at rainy season than dry one [5-7] and receptors of both mesotocin and vasotocin also vary in kidneys accordingly to the season. In many vertebrates, these hormones of the hydromineral regulation also have an effect on reproductive functions allowing one to perceive the importance of this period of drought during which the animals live in the mud for the triggering of the reproduction phenomenon [8].

This example of adapting a Gymnophionan amphibian to a zone with a marked seasonal alternation is a special case. Other Gymnophiona exist on the whole intertropical belt, in South and Central America, as well as in Asia and Africa and their modes of reproduction can be very different [1]. In several other viviparous species living in South and Meso America, reproductive modalities are different from *T. compressicauda* [3,9-12].

## Shimmering and Deadly Frogs

Adaptations to a hostile and complex environment led some South and Meso American anuran amphibians to develop extremely powerful poisons secreted by the skin glands. These frogs, the *Phyllobates* and the *Dendrobates* genera, carry very bright colors that make them spotted by predators. But predators "know" the danger they run if they accidentally consume that choice. Their color so visible is a means of protection of these amphibians. *Phyllobates* are found in Nicaragua, Costa Rica, Panama and Colombia. Some of them carry violent batrachotoxins, secreted by the glands of their skin. These batrachotoxins prevent the transmission of nerve impulses leaving the muscles relaxed, especially the heart muscle [13]. *Dendrobates* live from southern Nicaragua to northern Brazil. Among them, *Ranitomeya imitator* is weakly poisonous, and it exists in several forms whose color makes them similar to other species of the same genus [13]. Some species with little or no toxicity can be strangely similar to highly toxic species and thus benefit from their bad reputation for protection.

## Fish Living Out of Water

The strategy of bonefish dipnoans, living in areas with dry and rainy seasons in South America, but also Africa, and Australia, has been to acquire lungs, such as terrestrial vertebrates [14-16]. The dipnoans also carry gills. In addition, the structure of their ventral fins, although reduced, is close to that of the members of the tetrapod. These fish are thus able to breathe freely in the open air and to descend deep into the water. They can also crawl in the mud. When the season becomes dry, some dipnoans dig a burrow and lock themselves in a cocoon of mucus they secrete themselves. They breathe through a hole, the siphon, which communicates the cocoon with the open air [17].

## A Neotenic Species

Between 1799 and 1804, a German naturalist established in France, Alexander Von Humboldt travelled to South and Central America. During this trip, he discovered the axolotl and brought it back to the National Museum of Natural History of Paris (France). This animal was already described by Cuvier in 1811 [18], first classified among reptiles as all amphibians have been, and alternately considered such as a proteus, a weird animal with cavernous life, or a triton larva. The reading of Duméril and Bibron's treatise [19] clearly shows the confusion that reigned at that time concerning these species. In Museum, these animal laid eggs, from which were born embryos which became young axolotls. Some of these new axolotls metamorphosed to give animals looking like the American *Ambystoma* salamanders. This

phenomenon characterized by an adult with larval characters, received the name of "neoteny" [20-23].

The phenomenon of neoteny is also found in other anuran amphibians, such as the Siren and Amphiuma, live urodelan amphibians in the southern United States or the Proteus, a cave species of Slovenia, or still *Necturus* of North America. Neoteny characterizes an extended larval state temporarily or perpetually. Neotenic forms were however been described for a long time. Linné, in 1766, described *Siren lacertina*, found in the swamps of the southern states of the United States and *Proteus,* a cave-dwelling species found in Slovenia. Linnaeus considers this animal as the larva of an amphibian but he does not know which one. Some newts can also become neotenic according to the external conditions [24,25].

## North America

### Canadian Frozen Frogs

Subject to the icy climate of Alaska (less than -20°C in winter and still less than 0°C the rest of the time), some frogs like *Lithobates sylvaticus* can remain completely frozen for two months under conditions where most other amphibians could not survive. These animals wake up in the spring, reproduce in puddles of water and lay a thousand eggs that evolve into tadpoles metamorphosing at the end of the summer. In winter, *Lithobates sylvaticus* is able to freeze completely and then wake up when outside conditions become favorable. All the organs of the frog will freeze and the animal becomes hard and can also be broken like an ice cube. But that's not all, he goes into cardiac arrest, the blood is no longer circulating. To be protected against the effects of freezing, glucose is accumulated and enters into the constitution of antifreeze that allows the internal liquid of the body to freeze between and in the cells without destroying them. In fact, when a liquid or a biological tissue freezes without antifreeze, crystals form and destroy the cells by tearing them. The antifreeze prevents the formation of crystals and the freezing is done smoothly, forming an amorphous ice. *Lithobates sylvaticus* behaves like devices that freeze cells in the laboratory [26-29].

## Russia

### In Siberia, Frequent Salamanders but with Unknown Biology

The Siberian salamander, *Salamandrella keyserlingii*, is a little-known species although it is common in these areas. The sex cycles of males have only been known since the early 1990s. More recent work showed that males had an annual reproductive cycle. In April, male testes contain bundles of spermatozoa, Breeding accurs in April, and the formation of new reproductive cells starts and continues in May and early June. Spermiogenesis, the last phase before sperm formation, takes place in July and spermatozoa occupy the testes in August. Salamanders can hibernate: males are ready for breeding the following spring. In a closely related species, *Salamandrella tridactyla*, living on the seaside, the male cycle is also annual but with different modalities. In females, the cycles are not known. A recent study, published in 2015, examined the composition of ovaries in germ cells. This work shows that the beginning of the reproduction period of females, oviparous, is in the spring. However, there may be annual or biennial cycles depending on the region where the populations of this species live [30-33].

The reproduction study of *Salamandrella tridactyla* shows that when this species lives in altitude, the start of breeding is later, with offsets of two to five weeks compared to the lowland species [34].

## In Sub-Saharan Africa

### More Gymnophiones!

In Kenya, *Boulengerula taitanus* is another Gymnophionan. Unlike its South American cousin, this animal is oviparous with direct development and the females have an annual cycle [35,36]. During the reproductive cycle of males, the testes permanently contain all the cells of the germ line (spermatogonia, spermatocytes I and II, spermatids and spermatozoa). This is a continuous reproduction cycle. When spermatozoa are evacuated during the relatively long reproductive period (November to February, rainy period), they are immediately renewed by active spermatogenesis [37,38]. The cycle of females can be described into three well-defined periods: reproduction from November to February, sexual rest from March to August and preparation from September to October. Ovulation is observed between November and February inclusive. Throughout the year, large atretic follicles with vitellogenic follicles that have not ovulated are observed [39].

The embryonic development is direct, that is to say that the fertilized females lay eggs containing embryos with already advanced development After hatching, the young feed for a few weeks epidermal secretions of their mother [3,40].

### A Hairy Frog that Breathes Through the Skin

Amphibians typically have a larval phase in the water and breathe through gills followed by a terrestrial phase during which animals breathe through the lungs. When resting, amphibians also breathe through the skin or mucous membrane of the mouth. In several African countries, one species *Trichobatrachus robustus* has developed a particularly original mode of breathing through the skin [13]. The first descriptions of this animal made by George Albert Boulenger in 1900, speak of a "hairy frog". In reality, the "hairs" are those thin expansions of the skin that correspond to highly vascularized areas that allow the increase of the exchange surface between the blood capillaries and the ambient air. These excrescences appear in the male at the back of the thighs and on the sides during the period of mating and maturing eggs and they are not permanent. In this species, it is indeed the male who takes care of the eggs. In the early 2000s, a system of retractile claws was discovered in this same animal. These claws are made of bone tissue which pierces the skin of the animal [41].

### Amphibians always Ready to Breed and Viviparous Frogs

In African amphibians, anuran and gymnophionan, males and females, with a few exceptions, frequently have continuous reproduction cycles. In males, the testes are thus permanently filled with spermatozoa and in females, oocyte formation is continuous, the ovarian follicles develop gradually and when they are maturing, either the external conditions allow reproduction (in general, rain is the triggering factor) and females emit oocyte strings, or the conditions are not favorable and the early follicles of maturity degenerate, becoming atretic, the oocytes are then degraded and the vitelline stores recycled in the mother's body. This phenomenon has been observed in *Sclerophrys regularis* (*Bufo regularis*) of Lomé, Togo, in a region where the period of rainfall is fluctuating during the year [42,43]. The males and females are thus ready to breed and the end of the preparation phase for reproduction is triggered by the arrival of the rains. Curiously, other species, such as *Sclerophrys mauritanica* from northern Maghreb show such a cycle even if they are subject to regular seasonal alternations In Gymnophionan *Boulengerula taitanus*, we signaled above continuous sexual cycles [44-46].

Cases of viviparity also exist in some African amphibians. The toad *Nimbaphrynoides* (formerly *Nectophrynoides*) has several species whose development ranges from oviparity to complete viviparity. In *Nimbaphrynoides occidentalis,* a completely viviparous species, the uterus undergoes a series of modifications making it suitable for retaining the tadpoles during their development which is carried out thanks to maternal nutritional contributions. However, there is no placentation, the embryos are immersed in a uterine fluid that they absorb orally. All eggs produced give rise to an embryo, so there is no oophagia or adelphophagia [47-49]. In amphibians, some species adopted marsupialism with different structures already described [3].

### Fish Living Out of Water

Fish living out of water have been already met with dipnoans, but other fish families adopted present forms able to live out of water. *Periophthalmus* is a teleost genus belonging to Gobiidae family that can get out of the water and settle on the roots [50-52]. Several species belonging to these genera are found in Africa, Asia and Australia. Like all other fishes, they possess gills-, but they also use cutaneous and oral-pharyngeal breathing. They have special physiological characteristics because they store air and water in the mouth to extract oxygen during the long periods when they live out of the water. Some come out of the mangrove water and climb into the mangroves [53,54]. In addition, the eyes of these animals are protruding, rotate in all directions independently and they can see both below and above the water. Their anterior fins are turned into crutches that allow them to move on land [55].

## In Sahara Desert

### *Psammomys Obesus*, A Rodent Well Adapted to the Life in Arid Areas.

The sand rat *Psammomys obesus*, is an animal perfectly adapted to the arid environment [56-62]. Not only is this rodent herbivorous, but it feeds exclusively on Chenopodiaceae under which it digs its burrow. Its breeding cycle begins in autumn and ends in early spring. Sexual rest occurs in summer [63]. In order to better understand its biology, *Psammomys obesus* has been caught, farmed and fed with the usual food given to the mice or to laboratory rats feeds. This diet being totally different from its usual one, *Psammomys obesus* became obese, with pathologies usually associated with obesity such as type II diabetes or atherosclerosis Finally, *Psammomys obesus* has become an animal model that is increasingly used to study obesity and related pathologies [64-66].

### *Uromastyx Acanthinura*, A Reptile Well Adapted to the Life in Arid Areas

In Sahara lives *Uromastix acanthinura* a lizard has adapted to life in arid zones by adopting a herbivorous diet. Its reproductive cycle has been the subject of several investigations [67-73]. *Uromastyx acanthinura* digs a burrow deep enough to keep the temperature below 30°C. When he is outside, he straightens his head, which keeps the latter off the ground at times when it is the hottest. *Uromastyx* does not drink and is able to conserve water from the plants it eats. His urine is very concentrated. And he is even able to fast for a year! The water regulation of this animal is under the effect of neuro-hormones already seen above. Studies have shown that the latter are particularly abundant and undergo variations according to the seasons [74].

## North of Algeria

### Fish that Change Sex!

*Barbus callensis* has an economic interest, since it concerns a consumable species. Its reproductive cycle has been specified [75,76]. The breeding season is in the spring and the period of sexual activity is in June, early in the summer. In addition to this aspect directly related to the adaptation of these animals to their environment, studies have shown that *Barbus callensis* could be considered as a biomarker of pollution. Indeed, some individuals that have been collected in polluted areas compared to other areas where the same species lives, present gonad malformations such as the coexistence on the microscopic scale of male gametes and females within the same gonad. There are even macroscopic gonadal complexes composed of both spermatozoa and ovaries. These intersexed animals could be the result of the presence of endocrine disruptors in their environment [77].

## Europa

### A Lizard Becoming Vegetarian

This amazing example of adaptation is represented by lizards that have radically changed their mode of nutrition. This is a strange case of recent evolution that was found in *Podarcis sicula*, met in southern Europe, as far as Turkey in the East and where he lives in very diverse biotopes ranging from temperate forests to rocky areas. Like most lizards, his diet is insectivore. In 1971, five pairs of this species were deposited on a small island in the Adriatic. About 35 years later, most individuals became vegetarians. Moreover, at the end of these years, these animals had developed expansions of their digestive tract allowing them to feed on plants. These lizards have adapted so well to their new biotope that they are even considered responsible for the disappearance of the initial population of lizards belonging to the species *Podarcis mellisellensis*. Mitochondrial DNA analyzes of the insular population of *Podarcis sicula* have proven beyond any doubt that lizards were the offspring of the imported species [78]. Was there a simple adaptation or speciation, or the formation of a new species? The intervention of an epigenetic phenomenon is certainly involved. In any case, in the present context, this lizard is a good example of adaptation to a new biotope that has led to profound anatomo-physiological changes.

### Adaptations to Altitude: The Pyrenees Salamander and the Alpine Salamander

*Salamandra salamandra*, the Pyrenean salamander and its subspecies, can practice oviparous or viviparous reproduction depending on the altitude [3]. In the plain, salamanders are oviparous but they become ovoviviparous at altitude, that is to say they retain the embryos for a longer or shorter time in their oviducts. Most of these ovoviviparous forms have an annual reproductive cycle, characterized by ovulation between May and July followed by gestation. Parturition occurs at the end of September to November in western regions and in spring in areas with a continental climate. In *Salamandra fastuosa*, a very close species, at 1000 m altitude, the cycle is biennial, that is to say that ovulation occurs every two years. It takes place in June and the gestation lasts about a year. During this period, the oocytes no longer grow. In the second year, the oocytes complete their growth and vitellogenesis [79-82].

In *Salamandra atra*, the situation is different. Vivipary is obligatory. Gestation starts in the spring, although the spermatophore has been admitted before, and sperm kept in a seminal receptacle for a few weeks or even several months if mating takes place in summer. The duration of gestation varies according to altitude: 2 years at 650 m, 4 to 5 years between 1700 and 1850 m. A similar cycle is found in *Salamandra lanzai* [83-85].

### In Fish: The Black Bass Modulates its Reproductive Cycle According to the Altitude and Density of the Population

The black bass *Micropterus salmoides*, is fish originating from North America, whose import in France

dates from the early twentieth century. This fish is a consumable species with obvious economic interest. Studies on its breeding have shown that it is able to modulate its reproduction both in terms of altitude and density of the population. Three samples of the same black-bass population were transported for two years under three different conditions: a first batch in a temperate climate (in the lowlands) but with a low density of animals. The animals then reproduced in May-June and the remaining oocytes all degenerated at the time of summer and a second breeding was initiated the following year. A second group was also raised in the lowlands but with a high population density. This time, the animals did not reproduce and the oocytes contained in the ovaries degenerated. Finally, animals raised at higher altitudes, at colder temperatures, did not reproduce immediately, and oocyte degeneration did not begin until autumn, at the same time as the maturation of younger oocytes. This evolution lasted until the spring and ended only in autumn. In this case, the breeding cycle has become biennial [86].

## Conclusion

After this virtual journey around the world, what can be concluded? To begin with, through these few arbitrarily chosen examples, it is obvious that living forms are able to cope with all external conditions, even the most difficult ones, by developing adaptations of various aspects of their physiology, behavior, of the diet, of the modes of reproduction. Of course, this is only a tiny glimpse of what life can do to persist. We could as well have talked about the adaptation of the penguins to the cold, polychaeta worms of the abyssal thermal springs which developed huge sizes to live in extreme conditions. And there are also parasitic forms, such as the so-called flukes, tapeworms, ascaris and other pinworms, which adapt to an anaerobic life in the intestine, liver or other organ of a host animal , the latter being a human being, of course.

What lesson to remember? Life is wonderful, full of surprises. Observation of the living world can bring many lessons. Knowledge of the biology of living beings makes it possible to better understand their position in the whole of the living, of the biosphere. This knowledge makes it possible to better choose the action to be taken when a species must be protected, or on the contrary, limited.

Many of the living creatures have not yet delivered all their secrets and some will never deliver them before disappearing or being modified. The external conditions are constantly changing and if this change can be maintained in a reasonable way, perhaps many species will be able to adapt like these salamanders which modulate their reproduction modes according to the climatic conditions or, even better, this Italian lizard which became herbivorous in such a short time.

In other hands, studies can now take into account the rich collections of animals preserved in the cellars of museums, faculties around the world, adapting the powerful modern means of investigation (microscopy, molecular biology) to fixed material [87]. The comparison between samples taken at different dates according to what is known about changes in biotopes makes it possible to understand the adaptations that living beings have acquired in order to live better in a changing world.

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