Threatened Holarctic Treefrogs, and Special Consideration on the Causes of Decline of the Suweon Treefrog

Amaël Borzée, Laboratory of Animal Behaviour and Conservation, College of Biology and the Environment, Nanjing Forestry University, Nanjing, China; IUCN SSC Amphibian Specialist Group, Toronto, ON, Canada

Abstract

Amphibian populations are declining worldwide, at an accelerating rate. The principal reason is the plethora of threats they are facing, ranging from habitat loss, to pathogens, pollution, climate change and introduced species. Here I highlighted the shared origin and geographic unity of two genera of treefrogs, *Dryophytes* and *Hyla*, and determined the correspondence of threats for the two genera, despite the variety of habitat. A unifying point is that species on all four continents where the two genera occur rely on rice paddies as breeding habitat, and that the threatened species are the ones with the smallest ranges. This mainly pertains to the fact that these threatened species are more likely affected by stochastic variables, and thus more broadly impacted by localized threats, while species occurring over a broad range benefit from behavioral flexibility and a variety of habitat to occupy and shift from. I also illustrated the impact of all the threats affecting the Suweon treefrog, *Dryophytes suweonensis*, a species endemic to the Korean peninsula. The main reason for the decline of the species in the Republic of Korea is habitat loss, the species now being restricted to rice paddies, while population size and abundance in the Democratic People's Republic of Korea is comparatively high, likely due to different land use and management systems.

Amphibians are among the most threatened group of species, and most treefrogs from the Holarctic Hylid group are under similar threats despite being distributed over four continents. Most threats can be exemplified through one threatened Hylid, the Suweon treefrog (*Dryophytes suweonensis*), from the Korean Peninsula. Mainly, the threats can be divided and summarized by land use, pollution, invasive species, climate change, pathogens, exploitation, and solar radiation. However, all threats act in synergy, resulting in complex causes that are difficult to mediate.

Introduction to Holarctic treefrogs

Amphibians are declining worldwide, at a rate surpassing that of all other vertebrates and background extinction rates. This generalized decline in biodiversity has been termed the sixth mass extinction (Pievani, 2018). Amphibians are doing worse than other groups because of a broad spectrum of causes (Beebee and Griffiths, 2005; Blaustein et al., 2011), along with some yet-undetermined reasons of population decline.

Species of interest

Here "treefrog" refers to the small hylids, generally green, found in the northern hemisphere. Treefrog is a general word used for a broad range of species including some Rhacophoridae in Asia and Africa, and Pelodryadidae in Oceania. These "treefrogs" possess somewhat similar ecological requirements but they belong to deeply segregated families and are generally concerned by different threats and pressures. Here, I focus on species present in the Holarctic realm and some contiguous regions. I do not include all species from the Hylidae family (735 species within seven families) as they also distribute in tropical regions, and I do not include all species from the Hylinae sub-family (173 species within 18 genera) for the same reason; threats to tropical species are generally dissimilar to that to species from temperate regions (https://amphibiansoftheworld.amnh.org/; accessed Feb 6, 2021).

Here I focus on the species within the *Dryophytes* Fitzinger, 1843 (20 species) and *Hyla* Laurenti, 1768 (17 species) genera because of their distribution generally restricted to the temperate regions of the Holarctic realm (Fig. 1). I am not including the Acrisinae sub-family (21 species in two genera), despite being part of a geographically and morphologically coherent unit, because of the deep split between the genera (35.6 mya), and the close phylogenetic relationship between *Hyla* and *Dryophytes* (Duellman et al., 2016).

Taxonomy

The *Dryophytes* and *Hyla* clades diverged from the other Hylinae about 22.6 mya (Duellman et al., 2016) and they are now distributed in North America and northern Eurasia, from where two southward expansion resulted in the colonization of South East Asia and extreme northern Africa. The clade originates from central America, from where it expanded into North America, and later in Eurasia. Colonization of Eurasia occurred in two waves across the Bering pass, first by the *Hyla* genus (22.6 mya; Duellman et al., 2016), which is now the main genus in Eurasia. Colonization of the Eurasian landmass was however followed by aridification of central Asia, resulting in a gap in the distribution of the genus. The second invasion across the Bering pass (8.7 mya; Duellman et al., 2016) followed the recolonization of North America by the *Dryophytes* genus (isolated 15.4 mya; Duellman et al., 2016), which did not colonize Eurasia further than North East Asia.

Biogeography

Currently, 20 *Dryophytes* species and 17 *Hyla* species are described. The species are distributed such as 16 species of *Dryophytes* in North America and four species in North East Asia; while there are eight *Hyla* species in Asia, seven in Europe and two in Africa—although one of them, *H. meridionalis*, is also introduced in Europe (Fig. 1).

Here, I used the extinction risk such as defined by the IUCN Red List of Species. For species that are listed as Data Deficient (*D. arboricola* and *H. zhaopingensis*) as well as species that have not been assessed yet (*D. flaviventris*, *H. carthaginiensis*, *H. felixarabica*, *H. molleri*, *H. orientalis* and *H. perrini*), I used the range provided by the IUCN Red List website (www.iucnredlist.org) or the literature and applied the criteria relying on the extant of occurrence. The criteria states that a species should be listed as critically endangered

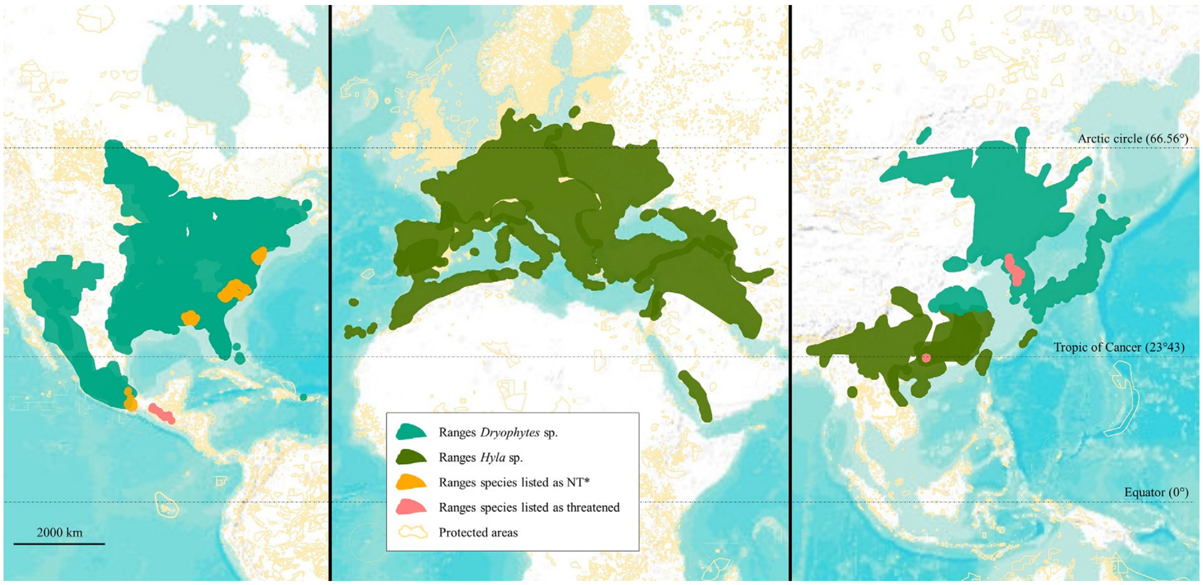

Fig. 1 Range of all *Dryophytes* and *Hyla* species. *NT stands for Near Threatened and threatened categories include Critically Endangered, Endangered and Vulnerable, following the definition of the IUCN Red List of species (https://www.iucnredlist.org/). The map is also overlaid with all types of protected areas (extracted from https://www.protectedplanet.net). Map created in ArcMap 10.6 (ESRI, Redlands, United States).

if its extent of occurrence (EOO) <100 km^2, Endangered if EOO <5000 km^2 and Vulnerable if EOO <20,000 km^2. For the listing to be valid, the species however needs to qualify for two of the three following points: severe fragmentation, decline in area of occurrence (AOO), population size or habitat quality or extreme fluctuation of the AOO, population size or habitat quality (see www.iucnredlist.org for details). Following the criteria explained above, *D. bocourti*, *D. flaviventris*, *D. suweonensis*, *D. walkeri* and *H. zhaopingensis* were threatened, and *D. andersonii* and *D. euphorbiaceus* were Near Threatened, for a total of seven out of the 37 species of *Hyla* and *Dryophytes*. Four of the threatened and Near Threatened species are distributed in North America, and three in Asia (Fig. 1). The area with the highest percentage of protected land, Europe (www.protectedplanet.net), here correlates with the geographic area without threatened species.

Behavioral ecology

The species selected here have generally similar breeding requirements, with males calling to attract females. Males usually call from the substrate or low vegetation around water bodies, but some species such as *D. suweonensis* and *H. meridionalis* call while holding onto vegetation (Fig. 2). Mate selection is generally done through the quality of call properties although some species such as *H. arborea* also rely on visual cues including the amount of yellow in the skin pigments. Males amplex with females when in proximity, but females are also sometimes intercepted by satellite males. Once in amplexus, females lay several clusters of eggs attached to the vegetation and substrate. The duration of egg development is linked to temperature, similar to tadpole development and metamorphosis. Dispersion post metamorphosis generally happens in fall, and individuals disperse from a few hundred meters to a few kilometers. Some species migrate to a hibernation site (e.g., *D. japonicus*; *H. arborea*) while others hibernate in the vicinity of their breeding site (e.g., *D. flaviventris*; Borzée, 2018). Individuals generally breed from 3 years old, but males in adequate habitat can breed during the spring after hatching (e.g., *D. suweonensis*).

Despite their communalities the species selected here differ in the habitat used. Most species breed in temporary wetlands surrounded by deciduous vegetation, and some species are resilient to some habitat disturbance such as *D. japonicus*, *D. plicatus* and *H. arborea*. Some species also take advantage of flooded ditches (*D. chrysoscelis*) and rice paddies (*D. immaculatus*; *D. suweonensis*, *D. flaviventris*, *D. japonicus*, *H. chinensis*, *H. meridionalis*, *H. simplex*, *H. annectans*, *H. intermedia*, *H. sanchiangensis*). Habitat use includes grassland, fir forest (*D. plicatus*, *D. wrightorum*), pine-oak woodlands (*D. arenicolor*, *D. japonicus*, *D. eximius*), grassy meadows, banana plants (*H. zhaopingensis*), bromeliads (*D. bocourti*, *D. euphorbiaceus*, *D. eximius*), wooded (*D. avivoca*) and cypress swamps (*D. femoralis*), and sandy areas in pine savannahs (*D. gratiosus*). However, divergences do exist, and some species are also present in arid (*D. arenicolor*, *H. savignyi*) and even xeric habitats (*H. felixarabica*). Other variations come from some species being arboreal and living in high treetops (*D. femoralis*, *H. simplex*, *H. annectans*) or breeding in slow flowing river sloughs (*D. chrysoscelis*) and oasis (*H. savignyi*).

Introduction to *Dryophytes suweonensis*

Specificity of amphibian habitats on the Korean peninsula

In North East Asia, 7000 years of rice agriculture have resulted in the transformation of the landscape, and the species inhabiting them, as a result of the regulated hydroperiods (Borzée, 2018). Some of the species managed to adapt and have subsequently flourished, while others are declining. Natural wetlands are rare in the lowlands of Republic of Korea as they have been developed

Fig. 2 *Dryophytes suweonensis*. Picture take in Asan, Republic of Korea on 7 June 2020. Note the way this male is holding a rice seedling while producing advertisement calls, a behavior restricted to a few species of the two focal genera. Credit: A. Borzee.

for rice agriculture. This shift in landscape and hydrological period originally benefitted amphibians as it provided more wetlands with elongated hydroperiods. However, mechanization of agricultural practices from the 1970s and the use of chemicals for pesticides and fertilizers resulted in increasingly hostile environments for amphibians, and in the decline of species restricted to agricultural wetlands. In addition, landscape modifications in areas between rice paddy complexes resulted in *D. suweonensis* and *D. flaviventris* becoming restricted to this type of habitat. Finally, the increasing value of the tertiary sector compared to rice production has resulted in the conversion of rice paddies into urban areas, industries, or agriculture in greenhouses. Consequently, the population size of *D. suweonensis* started dropping tremendously in the Republic of Korea, and the species is predicted to become extirpated because of habitat loss. In comparison, rice paddies in the Democratic People's Republic of Korea (hereafter DPR Korea) are still numerous and well maintained from an amphibian standpoint, and the environment there is championing the conservation of lowland amphibians relying on agricultural wetlands for their life cycle, such as *D. suweonensis*. It is however important to point out that agricultural wetlands are only substitute habitats and amphibians populating them are doing so because of the absence of natural wetlands.

Paleo-phylogenetic history and taxonomy

Dryophytes suweonensis is clustered with *D. immaculatus* and *D. flaviventris* in the *D. immaculatus* group. The three species diverged between 0.97 and 1.02 mya, and the group split from the *D. japonicus* group around 5.1 mya. *Dryophytes suweonensis* was described as *Hyla suweonensis* in 1980, taking its name from its type locality, the city of Suwon in the Republic of Korea (Borzée et al., 2020; Fig. 2).

The range of *D. suweonensis* is delineated by the Chilgap hills in the south and the Taeryong river to the north (Fig. 3). The range is however not continuous with many isolated inland populations, and a bottleneck restricting gene flow at Seoul's latitude because of landscape urbanization. The distribution of the species in the DPR Korea is not as clearly defined as the one in the Republic of Korea, but based on landscape preferences and the elevational restriction of the species, predicted presence is unlikely to be resulting in false positives.

Populations have drastically declined in the Republic of Korea because of a wealth of environmental pressures, and especially encroachment. The population in DPR Korea is comparatively stable, and the highest number of individuals recorded at a single site was in this nation, in Mundeok (Fig. 3). In addition, the low encroachment of sites resulted in better landscape connectivity, and maintenance of gene flow between populations.

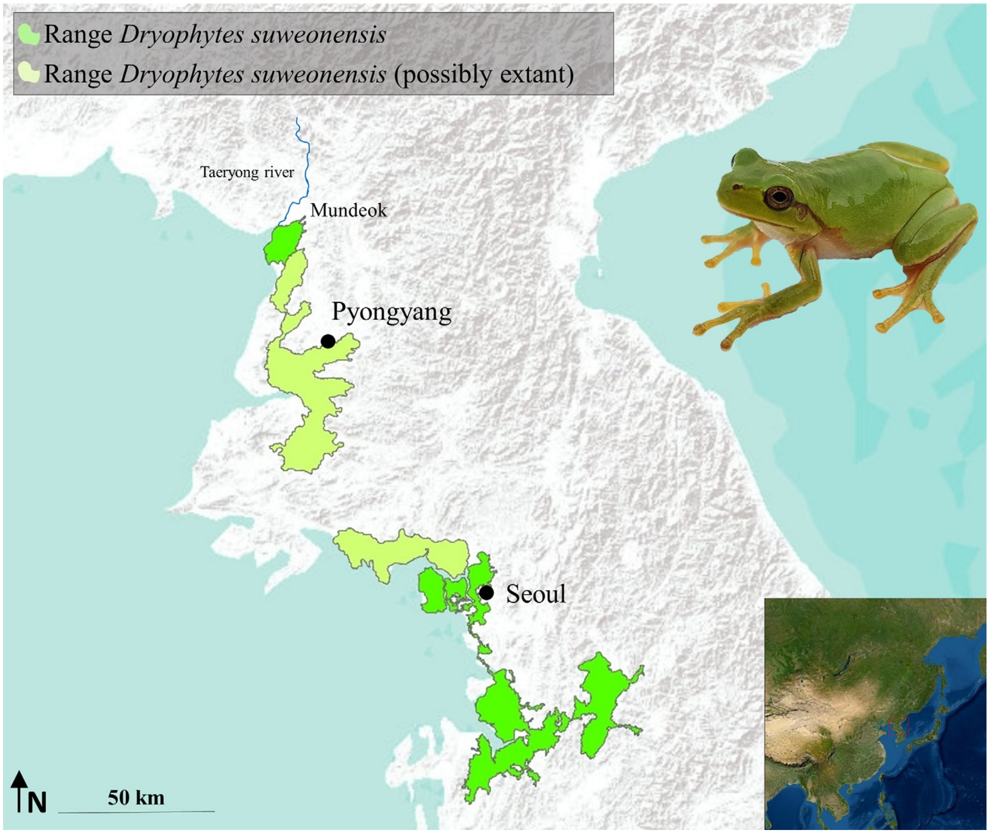

Fig. 3 Distribution of *Dryophytes suweonensis* in the Republic of Korea and the People's Democratic People's Republic of Korea. The range defined as "possibly extant" is determined based on the ecological requirements of the species. Map created in ArcMap 10.6 (ESRI, Redlands, United States).

Conservation status

Dryophytes suweonensis was thought to be endemic to the Republic of Korea until new populations were found in the DPR Korea in 2018. The range of the species was however later split in two, with the southern part of its range assigned to *D. flaviventris*. In addition, the range of *D. suweonensis* has strongly contracted compared to its historical range as sub-populations at numerous sites were extirpated during the last decade. For instance, the species was historically present on most of the area where the city of Seoul now stands, and it is also now absent from its type locality following the development of the city of Suwon (Borzée et al., 2020). The species EOO is between the Vulnerable (VU) and Endangered (EN) thresholds but it crosses the threshold to be listed as EN under the criteria based on the decline in populations size (IUCN Red List criteria C2a(*i*)b).

Species specific behavior

Dryophytes suweonensis exhibits a specific calling behavior, with males holding on rice seedlings a few centimeters above the water when producing advertisement calls (Fig. 2; Borzée, 2018). Males are generally forced towards the center of rice paddies when calling because of competition for calling space with *D. japonicus* (Borzée, 2018). As a result, there is a barrier of *D. japonicus* males that the *D. suweonensis* females need to cross to access conspecific males. Hylid males being non-specific in the species they amplex with, this often results in cross-species amplexus, and hybridization at such a scale that it threatens *D. suweonensis*.

Threats to Holarctic treefrogs

Threats to amphibians can be first dichotomized between background natural threats experienced by all species, and the threats of human origin. Threats of human origin began during the Holocene, with landscape modification by prehistorical humans (Haberle, 2007), followed by a sharp increase since the pre-industrialization period. Habitat exploitation and destruction are the main threats amphibians have been facing since human populations expanded.

Current threats to amphibians are generally divided into six (Collins, 2010) to eight (Beebee and Griffiths, 2005) or nine categories (Blaustein et al., 2011). It is however important to note that the synergy of threats is often the last straw resulting in the catastrophic decline of species and populations, while each of these threats could be potentially faced by species on their own (Green et al., 2020). Here I retain the following causes of declines (Beebee and Griffiths, 2005; Collins, 2010; Blaustein et al., 2011; Fig. 4): exploitation, introduced species, habitat loss, pollution, climate change, diseases, radiations and complex causes. I decided not to include behavioral shifts as they are generally caused by external factors, and inherently linked to other threats highlighted here. Most causes of declines are linked, for example, introduced species can result in habitat loss, behavioral shifts, and diseases.

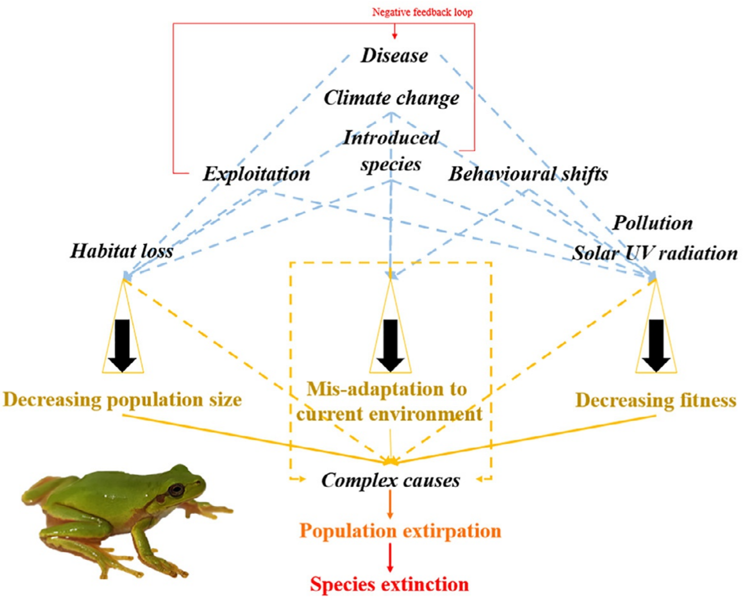

Fig. 4 Synergy of threats to amphibians, relying on the nine categories stated in the text, plus behavioral shifts. A negative feedback loop exists from exploitation and introduced species to diseases as pathogens are spread by frog farms and introduced species. Habitat loss does not directly cause mis-adaptation in the current environment because amphibian populations are rarely displaced but rather extirpated. Exploitation decreases fitness because of the selection of large individuals by harvesters. Introduced species feeds into mis-adaptation because individuals are generally lacking the means to recognize threats. Pollution does not feed directly into population decreases because direct death is more common than decreased fitness. Please note that all variables feed into complex causes, even if indirectly.

The lack of data is one factor that limits species threat assessments. Some species are little studied because of the difficulty to access the area, the lack of resources, or the difficulty of conducting research. This is the case of *D. arboricola* which is presumed to be a montane forest species breeding in temporary pools. As a result, logging in the area could threaten the species. Similarly, very little is known about the ecological requirements of *H. zhaopingensis*, making it difficult to assess the threats to the species.

Land use change and habitat destruction

Land use shifts and the resulting habitat change or destruction are the principal threats to most Hylid populations. It is the principal threat to *D. andersonii* (Oswald et al., 2020), where habitat destruction or alteration due to residential, agricultural, and industrial development results in a loss of habitat. This very common threat is listed for *D. euphorbiaceus*, *D. immaculatus*, *D. walkeri*, *H. annectans*, *H. chinensis*, *H. intermedia*, *H. sanchiangensis*, *H. simplex*, *H. tsinlingensis*, *H. meridionalis* and *H. savignyi*, highlighting the commonality of threats to Holarctic Hylids.

Some habitat changes may also negatively impact species, even when retaining their primary structure. For instance, *D. gratiosus* is threatened by the conversion of native pine habitat to high-density monocultures of loblolly pine, and *D. immaculatus* is threatened by a switch from rice to wheat agriculture (Borzée et al., 2020). However, some species do manage to cope with some levels of habitat disturbance, including for instance *D. chrysoscelis*, *D. plicatus*, *D. squirellus*. Other species such as *D. japonicus* and *H. hallowelli*, which now breeds in city parks, seem to have adapted to environmental changes. Finally, the impact of landscape transformation varies between regions for some species. For instance, *H. arborea* has declined in parts of its range in western Europe due to agricultural practices and fragmentations, while it is present on weakly modified environments in other areas.

In the case of *D. suweonensis*, regional variations are also present. In the Republic of Korea, landscape changes have resulted in the restriction of *D. suweonensis* to rice paddies, with 40% of the current population present in rice paddies set on land reclaimed from tidal flats (Borzée, 2018). In addition, land changes and mechanization of rice paddies reduce the amount of microhabitat available for hibernation, further impacting the species. In the DPR Korea, the species benefits from human modification of the landscape due to the increase in wetland cover and the regulated hydroperiod. Similarly, the absence of mechanized harvest and the very uncommon use of pesticide and fertilizer results in a better environment for the species.

Agrochemicals and chemical pollution and contamination

Numerous amphibians are threatened by chemical pollution, although in situ experiments are difficult to conduct due to the synergistic effect of the environment, and most of the data may differ from in-lab experiments. Some Hylids species can cope with variable water qualities, and thus sensitivity to chemicals may vary accordingly. For instance, *D. japonicus* tadpoles can be found in weakly saline environments and *D. andersonii* breeds in acidic ecosystems (Oswald et al., 2020). Generally, most Hylid species are impacted by agrochemical pollution, directly or through run-offs. In some cases, the cause of pollution is unknown, e.g., *D. immaculatus*, *D. japonicus*, *H. intermedia*, *H. savignyi*, *H. tsinlingensis*, *H. annectans*—although an indirect link with the chemicals used for the crops where the species lives is generally present. In other cases, the origin of the pollutants is clearly determined. For instance, *D. bocourti* is impacted by the pesticides and fungicides used by the ornamental plant industry. Generally, species are also impacted by a combination of pollutants, such as *H. arborea* and *H. meridionalis*, the latter being also threatened by chemicals used for mosquito control. In the case of *D. suweonensis*, a clear link between population size, dynamics and chemicals has been seen, and while these chemicals are likely to be agricultural run-offs, no evidence has been produced yet.

Introduced and invasive species

Introduced species have a negative impact at several levels. A worldwide threat is the American bullfrog (*L. catesbeianus*), which predates on any animal that can fit its gape, including Hylids. Predation results in a loss of ecological space to predated species, while also modifying the behavior of local species through competition for both larvae and adults. Another threat linked to the presence of this invasive species is the pathogens it carries (Yap et al., 2018), and *L. catesbeianus* is often carrying Batrachochytrids and Ranaviruses. Another risk associated with invasive species is that species do not necessarily associate invasive species and threats. For instance, Eiffinger's treefrogs (*Kurixalus eiffingeri*) do not recognize the invasive slug (*Parmarion martensi*) and parents do not remove the invasive slugs feeding on eggs, despite removing a local slug species.

Hylids are impacted by a large number on invasive species, and generally larvae are sensitive to introduced fish. For instance, *D. versicolor* larvae abundance might be declining because of introduced Bluegill sunfish, *H. arborea* is sensitive to the presence of invasive fish such as goldfish (*Carassius auratus*) and *H. meridionalis* is under threat because of introduced predatory Louisiana Crayfish (*Procambarus clarkii*) and mosquitofishes (*Gambusia holbrooki*). *Dryophytes japonicus* is also impacted by the invasive Louisiana Crayfish (*P. clarkii*), which feeds on its eggs, and similarly to all hylids with alien *L. catesbeianus* on their range, the species is under threat both because of the risk of predation and pathogen transmission.

Hylids can be invasive themselves. *H. meridionalis*, a native African species, is now present in Europe. The species sometimes hybridize with *H. arborea* and *H. molleri*, resulting in individual with intermediate traits. In other regions, *D. japonicus* has been introduced to Israel, and is also present on the range of *D. suweonensis* and *D. flaviventris*, resulting in hybridization and competition for resources.

In the Republic of Korea, *L. catesbeianus* is known for preying on smaller amphibians and modifying the behavior of co-occurring species. In the case of *D. suweonensis*, the presence of *L. catesbeianus* resulted in the decrease in population size and extirpation of some populations. The presence of *L. catesbeianus* also correlates with a higher prevalence of the Chytrid fungus in *D. suweonensis* and *D. japonicus* (Borzée et al., 2017).

Climate change

Climate change impacts all amphibian species and sometimes in ways that are not easy to demonstrate due to subtle changes over a long term and interactions with other variables. The most common impact is a shift in breeding phenology, when species lose synchrony with other aspects of their requirements such as prey availability (Green, 2017). In addition, climate change results in the loss of habitat suitability, or shift towards northern latitudes or higher elevations (Blaustein et al., 2010), which amphibians cannot follow due to their weak dispersal capabilities.

Some of the most impacted species are the ones living in xeric habitats, such as *H. savignyi*, as drought have multiplied impacts. Hylids living in more humid areas can however be impacted similarly, such as *H. tsinlingensis*, and *D. japonicus* in the northern parts of its range.

Dryophytes suweonensis is indirectly impacted by climate change, as the shift in temperature indirectly result in the loss of the only breeding habitat used by the species. Farmers can plant rice later in the season due to climate change, as it grows faster, but the direct link between hydroperiod and breeding in the species (Borzée, 2018) may result in rice paddies not being flooded when the species is ready to breed.

Emerging and infectious disease

Another significant and threatening factor to amphibian decline is the Batrachochytrids. Several pathogens affect amphibians worldwide, but the Chytrid fungus (*Batrachochytrium dendrobatidis*) is the principal vector for the decline of over 500 species. Due to the likely Asian origin of the anuran Chytrid fungus (O'hanlon et al., 2018), species that have co-evolved with the fungus are less likely to be impacted. This pattern is true in that *D. versicolor* is impacted by the Chytrid fungus (Hanlon and Parris, 2014), as well as *D. chrysoscelis* and *D. bocourti*. The Chytrid fungus has been found on Asian Hylids, such as *D. japonicus* and *D. suweonensis* (Borzée et al., 2017). However, the impact of the infection is unknown and no mass die-offs have been recorded, but prevalence is higher in *D. suweonensis* than *D. japonicus* (Borzée et al., 2017). The difference in fitness and boldness seen between *D. suweonensis* and *D. japonicus* is not known to be linked to the infection by the Chytrid fungus.

Exploitation and commercial use

Historically, and until today, amphibian exploitation for consumption has been a threat to the species resulting in numerous population crashes across the world (e.g., *Rana pipiens*, *Rana esculenta*, *Hoplobatrachus tigerinus*, *Euphlyctis hexadactylus*, etc.). More recently, harvest of wild individuals for dissection classes have also become a threat. The most recent threat comes from pet keeping. Having "exotic" amphibian pets is an increasing worldwide hobby, and has resulted in a significant threat to amphibian populations.

Hylids have not been spared and several species are in the trade for medicinal, food and pet keeping purposes. In the case of *H. annectans*, the species is over collected for food and medicinal reasons in Nagaland and Meghalaya in India. This species is also found in pet shops in China, but the risks have not been studied. Numerous other species are also collected to be used as pets: *D. cinereus*, *D. gratiosus*, *D. japonicus*, *D. versicolor*, *H. arborea*, *H. sanchiangensis*, *H. simplex*, *H. tsinlingensis* and *H. zhaopingensis*, although the magnitude of the trade is unknown, as well as the resulting threat to the species.

Following the Korea war (1950–53), amphibians were part of the human diet to address the period of food restrictions. As a result, amphibian farms were set-up, and *Rana* farms are still active. Due to their size, treefrogs were never the target of such trade, but stories of individuals being eaten, and even gobbled alive in the case of young metamorphs, are abundant when conversing with elderly people. *D. suweonensis* is not found in the pet trade and is not known to be harvested for this purpose. The trade of other species is however a threat, and the presence of North American Hylids in the pet trade in the Republic of Korea inherently correlate with the risk of release and the establishment of invasive populations, which can compete and hybridize with native species.

Solar UV radiation

Solar UV radiation is also a threat to amphibians, linked to human activities as it results from the stratospheric ozone depletion. It impacts the behavior and survival of Hylidae in general, resulting in developmental and physiological abnormalities in species such as *Pseudacris regilla*. Consequently, solar UV radiation is linked to the decline of Hylids. The impact of solar UV radiation has not been studied on *D. suweonensis*, but the species is likely to be as sensitive as other Hylid species.

Complex causes

The threats described above can also have cumulative impacts when in synergy, sometimes with unexpected outcomes. For instance, the presence of pesticides can result in increased stress in developing larvae, which in turns results in rapid development, and diminishing the impact of the Chytrid fungus (Hanlon and Parris, 2014). Unfortunately, negating effects are not the norm and most human activities result in changes in the distribution and behavior of species. Similarly, pathogens, land use and global change are also linked, with climate change affecting vegetation and hydrology, resulting in changes in food availability, predator-prey relationships, competitive interactions and pathogen-host dynamics (Blaustein et al., 2010). When these variables act in synergy, or with other stressor such as solar radiations and contaminants, they have an even stronger negative impact on species.

In hylids the interaction between stressors have been shown in a few species. For instance, in presence of UV-B, *D. versicolor* larvae that are also in presence of pollutants do comparatively poorly (Hanlon and Parris, 2014). Species such as *D. chrysoscelis* are also impacted by the synergy of Chytrid fungus, insecticides, and herbicides. As a result of synergetic threats, species may also lose access to a resource or microhabitat. Shifts resulting from increased competition or predation generally lead to morphological changes in Hylid larvae, and behavioral alterations in both larvae and adults.

This happens with *D. suweonensis*, which is under stress because of habitat loss, character displacement, and fitness loss because of competition, hybridization, pollution, climate change, invasive species and pathogens. The exact interactions of all stressors are unknown, but some relationships are understood; for example, habitat restriction and competition with *D. japonicus* result in a temporarily limited access to specific vegetation types. As a result of the combination of all threats, *D. suweonensis* is likely to become extirpated from the Republic of Korea if some stressors are not eliminated.

Conservation of Holarctic treefrogs

The presence of a focal species within a protected area is a generally important factor to mitigate threats, but the absence of known populations in a protected area does not always mean that the species does not occur in the area and the lack of data is widespread for amphibians. In addition, conservation programs for amphibians are not as widespread as those for the charismatic megafauna. Some species do however benefit from the presence of non-focal protected area, and other umbrella programs. For instance, *D. andersonii* occurs in a wildlife refuge, protected areas, and military bases, where the population is stable. Many of the European *Hyla* species are also protected through their listing in the Appendix II of the Berne Convention (*H. arborea*, *H. intermedia*, *H. meridionalis*, *H. sarda*—with the understandable exception of the newly described species), and other national legislations. Populations of *H. arborea* have also been supplemented in Sweden, bringing the population from 2000 individuals in 1980 to 50,000 in 2008, and the species has been restored on the totality of its historic range in the country. Interestingly, *H. meridionalis* also benefits from being protected in Europe, and the species is present in protected area in its native range in Africa, as well as in Europe. *Hyla simplex* occurs in two National Parks in Viet Nam and many protected areas in China. The opposite is also unfortunately true, with *D. euphorbiaceus*, *D. immaculatus* and *H. zhaopingensis* not known to occur in protected areas.

Dryophytes suweonensis is also nationally listed as protected in the Republic of Korea, although it does not occur within any protected area. More accurately, none of the habitat where the species occurs is protected, highlighting a weakness in the conservation plans for the species. The species was translocated to a terraformed island where an insurance population was meant to be established, but the island was later redesigned, and the species was extirpated from the area. Policy recommendations do exist for the species, for instance suggesting regulations on the height at which weed in the vicinity of rice paddies should be cut to provide a diurnal microhabitat to the species, but implementation has so far not been seen. In contrast, the species is locally abundant in the DPR Korea, where is also occurs in protected areas.

Conclusions

In conclusion, the *Dryophytes* and *Hyla* groups are under the same threats as all other amphibians on earth, and some sub-populations are under accentuated threats. The general outlook for these species is however not as bleak as that for some other amphibians. One of the strengths of these Hylids is the ability to exploit somewhat modified landscape and express a behavioral flexibility sufficient to cope with some of the threats. It is however important to note that the increase in threats and pressure has a multiplicative effect, and conservations contingency plans for these species, such as the cryopreservation of gametes for the threatened species, is becoming necessary.

In the case of *D. suweonensis*, protecting the species will require the involvement of farmers as climate change mostly affects rice agriculture, resulting in the asynchrony of flooding for agriculture and the breeding season of the species. Alternative examples could be taken from the DPR Korea as lowland landscapes in the nation have also been transformed into rice paddies, but the weak mechanization of agricultural practices and the non-reliance on pesticides and fertilizers (and the inability to use them because of UN sanctions) benefits the species.

References

Beebee TJC and Griffiths RA (2005) The amphibian decline crisis: A watershed for conservation biology? *Biological Conservation* 125: 271–285.
Blaustein AR, Walls SC, Bancroft BA, Lawler JJ, Searle CL, and Gervasi SS (2010) Direct and indirect effects of climate change on amphibian populations. *Diversity* 2: 281–313.
Blaustein AR, Han BA, Relyea RA, Johnson PT, Buck JC, Gervasi SS, and Kats LB (2011) The complexity of amphibian population declines: Understanding the role of cofactors in driving amphibian losses. *Annals of the New York Academy of Sciences* 1223: 108–119.
Borzée A (2018) *Why Are Anurans Threatened? The Case of Dryophytes Suweonensis*. Ph.D dissertation Seoul, Republic of Korea: Seoul National University.
Borzée A, Kosch TA, Kim M, and Jang Y (2017) Introduced bullfrogs are associated with increased *Batrachochytrium dendrobatidis* prevalence and reduced occurrence of Korean treefrogs. *PLoS One* 12: e0177860.
Borzée A, Messenger KR, Chae S, Andersen D, Groffen J, et al. (2020) Yellow Sea mediated segregation between north east Asian *Dryophytes* species. *PLoS One* 15: e0234299.
Collins JP (2010) Amphibian decline and extinction: What we know and what we need to learn. *Diseases of Aquatic Organisms* 92: 93–99.
Duellman WE, Marion AB, and Hedges SB (2016) Phylogenetics, classification, and biogeography of the treefrogs (Amphibia: Anura: Arboranae). *Zootaxa* 4104: 1–109.
Green DM (2017) Amphibian breeding phenology trends under climate change: Predicting the past to forecast the future. *Global Change Biology* 23: 646–656.
Green DM, Lannoo MJ, Lesbarrères D, and Muths E (2020) Amphibian population declines: 30 years of progress in confronting a complex problem. *Herpetologica* 76: 97–100.
Haberle SG (2007) Prehistoric human impact on rainforest biodiversity in highland New Guinea. *Philosophical Transactions of the Royal Society, B: Biological Sciences* 362: 219–228.
Hanlon SM and Parris MJ (2014) The interactive effects of chytrid fungus, pesticides, and exposure timing on gray treefrog (*Hyla versicolor*) larvae. *Environmental Toxicology and Chemistry* 33: 216–222.
O'hanlon SJ, Rieux A, Farrer RA, Rosa GM, Waldman B, Bataille A, Kosch TA, Murray KA, Brankovics B, and Fumagalli M (2018) Recent Asian origin of chytrid fungi causing global amphibian declines. *Science* 360: 621–627.
Oswald KJ, Roberts MA, Moler PE, Arndt RG, Camper JD, and Quattro JM (2020) Wetlands, evolution, and conservation of the pine barrens Treefrog (*Hyla andersonii*). *Journal of Herpetology* 54: 206–215.
Pievani T (2018) Earth's sixth mass extinction event. In: Dellasala DA and Goldstein MI (eds.) *Encyclopedia of the Anthropocene*, pp. 259–264. Amsterdam, Netherlands: Elsevier.
Yap TA, Koo MS, Ambrose RF, and Vredenburg VT (2018) Introduced bullfrog facilitates pathogen invasion in the western United States. *PLoS One* 13: e0188384.