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Abstract
The commercial trade in frogs and their body parts is global, dynamic, and occurs in extremely large volumes (in the thousands of tonnes/yr or billions of frogs/yr). The European Union remains the single largest importer of frogs' legs, with most frogs still caught from the wild. Among the many drivers of species extinction or population decline (e.g., due to habitat loss, climate change, disease, etc.), overexploitation is becoming increasingly more prominent. Because of global declines and extinctions, new attention is being focused on these markets, in part to try to ensure sustainability. While the trade is plagued by daunting realities of data deficiency and uncertainty, and the conflicts of commercial interests associated with these data, one of the only things that is clear is that EU countries are most responsible for the largest portion the international trade in frogs' legs of wild species. Over decades of exploitation, the EU imports have contributed to a decline in wild frog populations in an increasing number of supplying countries, such as India and Bangladesh, as well as Indonesia, Turkey, and Albania more recently. However, there have been no concerted attempts by the EU and the export countries to ensure sustainability of this trade. Further work is needed to validate species identities, secure data on wild frog populations, establish reasonable monitored harvest/export quotas and disease surveillance, and ensure data integrity, quality, and security standards for frog farms. Herein, we call upon those countries and their representative governments, to assume responsibility for the sustainability of the trade. The EU should take immediate action to channel all imports through a single centralized database and list sensitive species in the Annexes of the EU Wildlife Trade Regulation. Further listing in CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora) can enforce international trade restrictions. More joint-efforts are needed to improve regional monitoring schemes before the commercial trade causes irreversible extinctions of populations and species of frogs.

Keywords
Amphibians, biodiversity, CITES, disease, over-exploitation, sustainability, taxonomic status, wildlife trade

INTRODUCTION

Three decades ago, initial signs of global declines in amphibian populations were reported (Blaustein and Wake 1990, Pechmann and Wilbur 1994). Thirteen years ago, Stuart et al. (2008) edited their compendium "Threatened World of Amphibians" as a result of the Global Amphibian Assessment and synthesized knowledge on the science and threats detrimentally impacting amphibian species on a global scale. Threats such as habitat destruction (Cox et al. 2006), pollution (Blaustein and Johnson 2003), domestic use and trade (Mohneke 2011; Turvey et al. 2021), international trade (Andreone et al. 2006; Carpenter et al. 2014; Auliya et al. 2016), and climate change (Blaustein et al. 2010) have been well studied in many areas, but amphibians are also particularly vulnerable to pathogens, such as ranaviruses (Cunningham et al. 1996; Daszak et al. 1999; Miller et al. 2011; Bayley et al. 2013), mycotic diseases (Daszak et al. 1999; Fitzpatrick et al. 2018), and parasites (Kim et al. 2016). A recent study also revealed that frogs act as intermediate hosts of the parasite *Alaria alata*, and human consumption of frogs' legs containing larvae of the parasite can promote alariosis, a potentially deadly parasitic infection (Korpysa-Dzirba et al. 2021). However, it has also been emphasized that these threats can causally and synergistically interact (Ficetola et al. 2007; Sodhi et al. 2008; Hayes et al. 2010; Ford et al. 2020). As early as 1993, amphibian mortalities were attributed to the chytrid fungus, *Batrachochytrium dendrobatidis*, *Bd* (Berger et al. 1998), with several possible extinctions and its spread across central America up to the late 1980s (Cheng et al. 2011). In the years that followed, the scale of this panzootic disease (chytridiomycosis), became apparent and scientific papers highlighted the fungal disease with more than 500 amphibian species around the world affected by *Bd* (Scheele et al. 2019). In addition, a new fungus specifically affecting salamanders, *Batrachochytrium salamandrivorans* (*Bsal*), was also identified (Martel et al. 2013). Notably, during a human pandemic, commercial trade is both the principal source and the most viable means of spreading emerging zoonotic diseases (see Vora et al. 2022).

The international trade of live amphibians infected with either *Bd* or *Bsal* has since been highlighted (e.g., Fisher and Garner 2007; Kriger and Hero 2009, Catenazzi et al. 2010; Yuan et al. 2018; Fitzpatrick et al. 2018; Hughes et al. 2021; Thumsová et al. 2021), and its detrimental impact threatens naïve populations with extinction (Martel et al. 2014; Stegen et al. 2017). To date, considerable research has contributed to an increased understanding of regional, national, and global declines of amphibians and understanding of the spread and pathogenicity of diseases. However, the impact of wildlife trade and associated diseases on local populations remains poorly understood.

While the international amphibian pet trade includes a broader range of species with many frogs still coming from the wild (Auliya et al. 2016; Hughes et al. 2021), species harvested for consumption as food (e.g., frogs' legs trade), represent only a small number of species. However, annual exports for the food trade are in the thousands of tonnes, or hundreds of millions of individuals (Kusrini and Alford 2006; Gratwicke et al. 2010). Notwithstanding the considerable implications on species survivorship, we know less about the impacts of trade than most other threats in terms of effect on local biotic communities and their ecosystems, the spread of diseases, and issues resulting from the interaction of wild-caught and farmed species (Lutz and Avery 1999; Dökenel and Özer 2019; Ribeiro et al. 2019). While the history of frog farming is marked by many setbacks, it has steadily increased scale in recent years (FAO 2020; Dodd and Jennings 2021). Despite this growth, potential ecological impact of frog farms is often neglected (see below) and over-exploitation of wild-caught frogs is ongoing (Çiçek et al. 2020; Hughes et al. 2021; IUCN SSC Amphibian Specialist Group 2020h). In addition, the taxonomic status of taxa exploited for consumption is not unequivocally clarified [e.g., the *Fejervarya cancrivora* complex at least three species (Kotaki et al. 2010; Kurniawan et al. 2011; Yodthong et al. 2019), taxonomic challenges in *Pelophylax* spp., i.e., *P. lessonae* and *P. ridibundus* (Holsbeek et al. 2008; Holsbeek and Jooris 2010; Hauswaldt et al. 2012), and the *Limnonectes kuhlii* complex (e.g., McLeod et al. 2011; Dehling and Dehling 2017; Stuart et al. 2020; Suwannapoom et al. 2021)]. Likewise, it is necessary to create an accurate and up-to-date database of the role the major consuming countries take in terms of numbers of wild caught/farmed animals, supplying countries, harvest locations, farms involved (cf. with data records of the Law Enforcement Management Information System, LEMIS), mortality figures, etc., with a focus on the European Union (EU) (Veith et al. 2000; Potočnik 2012; Çiçek et al. 2021) and Switzerland (see Dubey et al. 2014; Dufresnes et al. 2018). For example, TRACES is an online platform of the EU established to certify imports of animals and their products according to sanitary standards (https://ec.europa.eu/food/animals/traces_en, see Suppl. Inf. 3) but lacks species-specific data, missing an important opportunity to monitor species in trade.

Enforcement of laws, regulations, and quotas or harvest limits is particularly challenging for transport and trade of frogs' legs. Many species are very similar in their morphology and as products are skinned, processed, and frozen, gross mislabelling is likely and hard to verify

(Veith et al. 2000; Dittrich et al. 2017; Ohler and Nicolas 2017). In fact, it is impossible for enforcement authorities to assign frogs' legs to a species without genetic methods, hence authorities can only check documents enclosed in a consignment and assume that they are true.

Herein, we provide an overview on the EU's central role as primary ultimate destination for the global trade in frogs' legs and its corresponding responsibility for resulting ecological risks and impacts. Furthermore, our review summarizes knowledge on the current status of international trade in both live frogs and parts for human consumption. We primarily outline certainties (e.g., loss of biodiversity, destabilization of ecological communities in their ecosystems, flawed farming operations, genetic pollution) against the manifold uncertainties underlying this trade (lack of documentation to assess sustainability of trade; species identification of individual frozen frogs, skinned frog bodies, or parts thereof; and international regulation of species not listed in the appendices of CITES). Clear identification of these deficiencies should oblige policy makers from responsible consuming countries to follow revised and newly implemented legislation and, where appropriate, apply the precautionary principle as a crucial safeguard for the survival of many amphibian species. Understanding the dimensions of the frogs' legs trade is challenging (since much of the global data is not available after 2009), even when we had better data (Figure S1). Initially, Asia dominated export trade (especially India, Indonesia, and China, but China dropped out in 2007), followed by Europe (until 2006) and the US (a small proportion, almost entirely gone by 2008) (Atlas of Economic Complexity 2022; see Suppl. Inf. 1, Fig. 1). But these trends have not remained consistent and many complexities have revealed themselves more recently. Thus, understanding and updating our knowledge of global trade is paramount to effective interventions if we want to ensure a sustainable trade. We offer these suggestions to enable long-term sustainability of the trade, as well as the amphibian populations it is dependent upon and the humans whose livelihoods are intricately intertwined.

METHODS

Apart from information retrieved from previous studies (Altherr et al. 2011; Auliya et al. 2016), this review is mainly based on a systematic literature survey from conscientiously extracted relevant published information related to the international trade in frogs' legs (e.g., taxonomy, ecology, disease, threats, and conservation). For the identification of relevant publications, we used a number of English [e.g., x-country, x-species (e.g., *Fejervarya*) frog, trade, frogleg / frogs' legs, frog meat, commercial, culture, farming, threats (that could specifically be "pollution" or "climate change"), and Indonesian [katak/kodok (for "frog"), Jawa, x-jenis (scientific name of a given species), dagang (trade), ancaman (threat), kaki (leg), pada (thigh)] search terms in Google Scholar searches. These terms were used because they would be in publications that feature amphibian trade in either English or Bahasa Indonesia. Number and order of terms entered per language was changed during searches. Searches in Bahasa Indonesia were implemented because Indonesia is recognized as the current major supplier of frogs' legs to European markets (e.g., Warkentin et al. 2009; Altherr et al. 2011; Potočnik 2012; EUROSTAT 2020). Also, publications from the International System for Agricultural Science and Technology (AGRIS) of the FAO were scanned for "frog legs" (https://agris.fao.org/, see Suppl. Inf. 3).

Taxonomy largely followed Frost (2021) and relevant papers that outline cryptic, look-a-like species, or where taxonomic status remains uncertain (e.g., Holsbeek et al. 2008; Hasan et al. 2012; Yodthong et al. 2019). With reference to the North American bullfrog, *Rana catesbeiana* listed in the genus *Lithobates* (Dubois 2006), most recent studies now list the genus as *Aquarana* (Dubois et al. 2021) while the trade data still refer to *Lithobates*. In order to avoid confusion, in this study we use *Lithobates*. In addition, AmphibiaWeb (https://amphibiaweb.org/, see Suppl. Inf. 3) was surveyed to filter information relevant to species involved in the commercial food and pet trade. Databases documenting species and volumes imported into the EU include EUROSTAT (https://ec.europa.eu/eurostat/web/main/data/database, see Suppl. Inf. 3), and were filtered from the sub-database "EU trade since 1988 by HS2,4,6 and CN8" (categories 02082000 and 02089070 are frogs' legs fresh, chilled, or frozen) selected for the time 2010 to 2019. Remarkably, imports of live frogs are not specifically documented by EUROSTAT, but assigned to an unspecific customs tariff number, generally describing "animals, other, live". Also, there is distinction between import of "wild" versus "cultured/farmed" specimens. We also extracted import data from the United States Fish and Wildlife Service (USFWS) and LEMIS databases for the period 2015-2020, focusing on species that are traded either in kg or in large numbers and known to be relevant for human consumption (e.g., *Hoplobatrachus rugulosus* and *Lithobates catesbeianus*).

A study was simultaneously conducted for a current snapshot/analysis of the French market (the EU's major consuming nation of frogs' legs). Data were retrieved from the French Customs statistics for the period 2010-21 (LeKiosque.finances.gouv.fr; accessed 16 April 2019 and 26 April 2022). Additionally, in December 2021, an online survey of the French market was carried out. Websites used for this included major supermarkets, frozen food brands, Asian food supermarkets (i.e., Auchan, Cora, Monoprix, Picard, Tang Frères, etc.). Another market survey of e-mail alerts was conducted between 23rd November 2021 – 9th February 2022. The survey was conducted using Google Alert with the keywords "frog legs" in French, and in singular and plural forms, asking to receive all new content regardless of the source (News, Blogs, Web). The commercial offers were sorted and analysed.

An advanced search on “The IUCN Red List” based on the following filters; (a) Taxonomy > Amphibia, (b) Threats > Biological Resource use > Intentional use, and (c) Use and Trade > Food (Human) was also completed. The resulting species were assigned to their native regions/countries and tabulated with information on current IUCN Red List status (IUCN 2021), CITES appendix listing, and information indicating a regional overharvest or overexploitation in general (see Table 3, Suppl. Inf. 2, 4). Subsequently, all CITES-listed amphibian species were filtered in SPECIES+ (https://www.speciesplus.net, see Suppl. Inf. 3), a website developed by CITES and UNEP-WCMC that includes all species in appendices/annexes of CITES (n.b., only 2.5% of amphibian species are CITES listed), the EU Wildlife Trade Regulations, and the Conservation of Migratory Species (CMS).
CITES Appendix listings were checked with the species filtered in the IUCN Red List where international trade for consumption (food) was indicated. Those species were entered in the CITES trade database (https://trade.cites.org/, see Suppl. Inf. 3) to record information on trade (e.g., years, volumes, countries of export and import, and sources of trade), and to check if specific population trends are emerging. Indonesian harvest and export quotas were surveyed in the period 2015 to 2021, according to the annual published quota lists (e.g., Indonesian Ministry of Environment and Forestry 2021).

Once we had a list of species potentially traded for food, we were able to pair that list with the IUCN data mapping species distributions. First, we downloaded amphibian ranges from the IUCN website (https://www.iucnredlist.org/). We then uploaded these into ArcMap 10.8 and selected all species in trade using the “joins and relates” function, before extracting these species. Species ranges were then dissolved so that each species was represented by a single polygon (though this could be a multipart polygon). This was then split into groups of 30 species before overlaps were counted using the “count overlapping polygons” toolbox for each subset, this was purely for processing and all species were included in total. These were then all converted to a raster with a 10km resolution, and each stack was summed using the “mosaic to new raster” function to sum values and map the number of species being consumed in each geographic area.

In addition, we used “union” to combine species’ ranges with a map of the world (from thematic mapper), the species range country combinations dissolved to list each species once for each country it was in, and the summary statistics tool was used to calculate the number of species being traded for consumption for each country. This table was then related to the original country map to show the number of species being traded for consumption per country. This was then repeated for just those species being traded internationally for consumption.

RESULTS

After describing current import volumes of frogs' legs into the EU and the main supply regions, we highlight the species that make up the international frogs' leg trade, describe national consumption trends, and finally provide information on threats impacting species/populations, indicate amphibian population trends, and broader ecological impacts of the frogs’ legs trade.

The role of the European Union and its member States

In the study period 2010 to 2019, total imports of frog’s legs into the EU numbered 40,698,800 kg. This total weight can be converted, when 1 kg equals 20-50 individual frogs (Veith et al. 2000), to at least 814 million and up to roughly 2 billion frogs. According to Indonesia’s annual harvest/export quotas for *F. cancrivora*, for the period 2016-2020, 1 kg equated to 15-22 individual specimens (Indonesian Ministry of Environment and Forestry 2016-2020). Indonesia’s annual quotas appear to be set arbitrarily, there is a complete lack of data as a basis for sustainable trade, including information on the number of individuals that die prior to export. As early as 1986, Niekisch reported an estimated pre-export mortality rate of 10-20%, but mortality during the export process may be highly variable. Herein, we assume that every export also includes an estimated number of dead animals for which the importer is also responsible. Wholesalers of live animals have been found to have mortality rates of around 45% for amphibians, meaning live trade levels may need to be in higher volumes to satisfy demand when many frogs die in transit, with many coming from the wild (Ashley et al. 2014).

In the study period 2010-19 (EUROSTAT 2020) Belgium leads EU countries in imported quantities of frogs' legs, with a total of 28,430 tonnes (69.8%), ahead of France with 6,790 tonnes (16.6%), followed by the Netherlands (2,620 tonnes; 6.4%), Italy (1,790 tonnes; 4.3%), and Spain (923.4 tonnes; 2.2%) (Table 1). Smaller quantities were imported by the United Kingdom (68,8 tonnes), Croatia (28,5 tonnes), the Czech Republic (27,8 tonnes), Poland (12,5 tonnes), Romania (2,8 tonnes), and Germany (1,8 tonnes). Within the EU, Belgium re-exports a large part of its imports to other EU countries. For example, Belgium re-exported 20,920 tonnes to France (>73% of all its imports in the study period) and 1,410 tonnes to the Netherlands (ca. 5% of all its imports in the study period), accordingly, Belgium consumed 21% of its total imports.

Table 1. Main EU importers/consumers and suppliers of frogs' legs (in tonnes) for the period 2010-2019. Source**:** EUROSTAT (2020)

Major EU importers		Major suppliers of frogs' legs into the EU	
Belgium	28,429	**Indonesia**	30,019.4
France	6,794.4	**Vietnam**	8,439.4
Netherlands	2,621.5	**Turkey**	1,593.7
Italy	1,787.2	**Albania**	586,5
Spain	923.4		

France and the frogs' legs trade

Due to the introduction of advanced technologies of freezing methods in the 1970s, storage constraints were reduced, and transport routes of frogs' legs became possible. This transformed traditional frogs' leg trade in France, bringing some local frog populations to the brink of extinction (Ohler and Nicolas 2017 and references therein). Since at least the 1980s, France has historically been considered the main consumer of frogs' legs. According to Le Serrec (1988), France imported a total of 4,522 tonnes of frogs' legs in 1983. Based on this fact, France initiated studies to gain clarity on species composition as well as potential ecological damage from intense commercialized trade (MNHN 2012; Ohler and Nicolas 2017).

From 2010-19 France imported 30,015 tonnes of fresh, refrigerated, or frozen frogs' legs (ca. 600-1,500 million frogs; Veith et al. 2000), according to French customs statistics (https://leKiosque.finances.gouv.fr/). France's main suppliers are Indonesia (24,102 tonnes or 80.3%), Vietnam (3,941 tonnes or 13.1%), Turkey (1,017 tonnes or 3.4%), Belgium (226 tonnes or 0.8%), and Albania (219,6 tonnes, 0.7%). For the same period, the quantities imported from

Belgium to France differ widely depending on whether the data source is Eurostat or French customs due to two different statistical concepts. France seperately lists the country of direct export origin and country of original export when the country of origin is not an EU country. Original origin prevails in the French statistical data. As a result, some frogs' legs are considered by the French methodology as imported from Indonesia and not from Belgium, even if they have transited through Belgium. Annual imports did not fluctuate significantly between 2017 and 2020, with an average of 2,669 tonnes/year. A drop to 1,826 tonnes is prominent in 2021, still a relatively high figure despite the paralysis of international trade due to Covid-19. Similarly, France also is a hub for re-exportation of frogs' legs. From 2017-20, France shipped 385 tonnes of frogs' legs, mainly destined for markets in Belgium (292 tonnes; 75.8% of total tonnage shipped), Luxembourg (24,4 tonnes; 6.4%), and Germany (16,6 tonnes; 4.3%). In 2021, it is notable that France also re-exported 13,9 tonnes (3.6%) to Vietnam.

Results of the online market survey in December 2021 indicate 20 frogs' legs food products readily available. Of these 20 products, 11 originated from Indonesia, three from Vietnam, one from France, and one from the "EEC (Turkey, Albania, etc.)". This last indication is confusing because the European Economic Community (EEC) was dissolved in 1993 excluding Turkey and Albania and both are not EU member States. With regard to the indication of France as a source country, these products are pre-cooked frogs' legs that do not originate from France and the species indicated is "wild *Limnonectes* [*Rana] macrodon*" endemic to western Indonesia (cf. Table 2). Four sources do not provide information on the country of origin within the product description or packaging. Regarding species name, six sources indicate *Rana macrodon*, three *Fejervarya cancrivora*, another three *Hoplobatrachus rugulosus*, one "*Rana macrodon* or *Fejervarya cancrivora"* (here we assume the sourcing from different suppliers, resulting in insufficient traceability for species identification), and one *Rana esculenta*.
For six sources, both product description and packaging do not indicate a species name. With regard to EU legislation, lack of information (species or country of origin) is a violation of EU rules [Commission Regulation (EC) No 2065/2001 of 22 October 2001 detailing rules for the application of Council Regulation (EC) No 104/2000 as regards informing consumers about fishery and aquaculture products; https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32001R2065&from=FR). In eight sources, origin is highlighted as "wild", three refer to "fishing" (e.g., fresh water, rice fields), and in one indicates "collected" as the source. Not a single product, however, indicates a captive bred or farmed source. Besides raw or cooked frogs' legs, "*frairine*" is also offered for sale, a mixture of pork

and frogs' legs seasoned with white wine. For this mixed product, there is no information on the origin or species involved.

An additional market survey through Google Alert for more than 10 weeks (see Methods) identified 38 commercial offers for frogs' legs (20 from Belgium and 18 from France). Regarding the offers from France, trends from the December 2021 study are largely confirmed, with only one offer indicating an origin "Vietnam and/or Indonesia captive bred".

In addition to imports, the French market is also supplied with wild-caught native species. Short marketing circuits, such as local restaurants, are supplied with *Rana temporaria*, a nationally protected species in France (https://www.legifrance.gouv.fr/loda/id/JORFTEXT000017876248/, accessed April 2022, see Suppl. Inf. 3). Despite the legal framework for harvest, numerous exemptions are granted. For example, >2 million *R. temporaria* are legally caught each year in the Franche-Comté region (https://www.bourgogne-franche-comte.developpement-durable.gouv.fr/ranaculture-bourgogne-franche-comte-dossiers-de-a6583.html, accessed June 2022, see Suppl. Inf. 3). An exemption may exist if an offtake of <1500 frogs is requested, as this is considered "familial". Poaching offences are also recorded and a distinction is made between captures without a permit, those exceeding quotas, or if the captures are outside authorised time periods. In October 2018, a couple was fined €2500 for the capture of 4000 *R. temporaria*, even though they possessed a permit for the capture of 1000 specimens (https://robindesbois.org/en/a-la-trace-n23-le-bulletin-de-la-defaunation/RobindesBois, "On the Trail" No. 23, 2019). In the same year, during eight inspections and three searches conducted under a judicial warrant, a total of 171 traps were seized, enabling the release of 17,950 grass frogs (*R. temporaria*) and 10 m^3 of eggs into the natural environment (Office national de la chasse et de la faune sauvage; ONCFS, May 9, 2018).

Major suppliers of species for the frogs' legs industry in the EU

There is no doubt that the trade in frogs' legs for consumption is a global issue, with most countries involved in the trade as exporter, importer, or some combination (Gratwicke et al. 2010; Suppl. Inf. 1, Figs. 2,3). In recent decades there have been four major source regions exporting edible frogs or body parts (wild and/or farmed) into the EU: (1) East Asia, i.e., China and Taiwan (Warkentin et al. 2009; Altherr et al. 2011; Shreshta 2019), (2) Southeast Asia, i.e., Indonesia and Vietnam (Niekisch 1986; Kusrini and Alford 2006; Warkentin et al. 2009;

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Gratwicke et al. 2010; Ohler and Nicolas 2017; Shreshta 2019), (3) South Asia, i.e., India and Bangladesh (Niekisch 1986; le Serrec 1988; Warkentin et al. 2009), and (4) eastern Europe i.e., Turkey and Albania (Warkentin et al. 2009; Şereflişan and Alkaya 2016; Çiçek et al. 2021). The United States, another major importing country for frogs and their body parts, is supplied from Asia and South America (Warkentin et al. 2009; US LEMIS Database 2015-2020). Based on LEMIS data, main suppliers for the US market for *L. catesbeiana* were Mexico (labelled as wc, "wild capture"), Ecuador (farmed), and China (farmed). *Hoplobatrachus rugulosus* was imported from Thailand (farmed) and Vietnam (wc), and *L. forreri* only from Mexico.

For most recent trade routes from source countries to importers and consumers into the EU, see Figure 1.

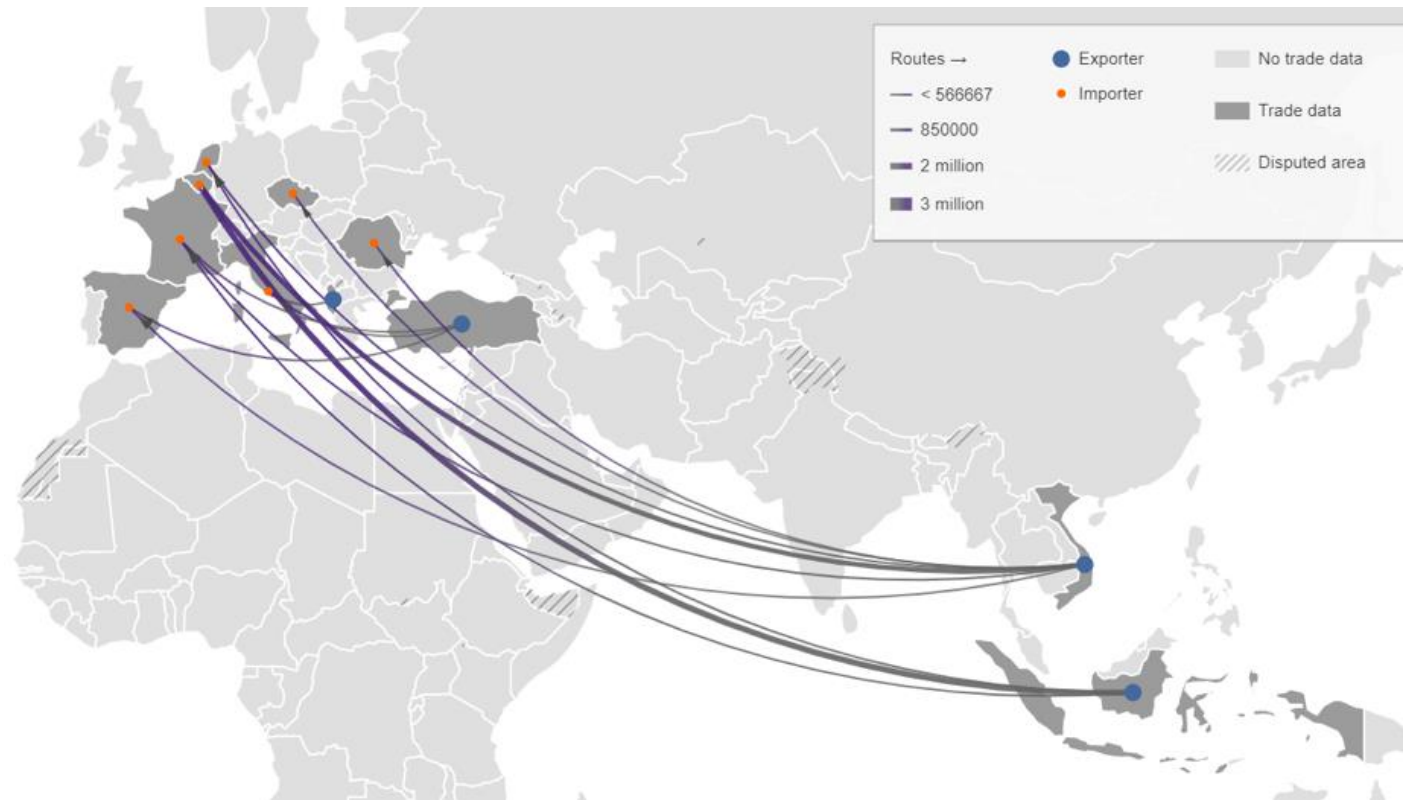

Figure 1. The EU as the major consuming region of frog's legs in the period 2010-2019, with major supplying countries in SE-Asia (Indonesia, Vietnam) and eastern Europe (Turkey, Albania), and major importing countries (Belgium, France, Netherlands, Italy and Spain). Sources: EUROSTAT 2020 and TRAFFIC (2018) TradeMapper - a tool for visualizing trade data.

Within the study period 2010-19, Indonesia clearly represents the leading supplier for the European Union's frogs' legs with 30,019.4 tonnes (74%), followed by Vietnam (8,439.4 tonnes; 21%), Turkey (1,593.7 tonnes; 4%), and Albania (586,5 tonnes; 1%) (Table 1, Fig. 1). Comparatively smaller amounts were supplied by China (37,7 tonnes), India (15 tonnes), Thailand (9,2 tonnes), Malaysia (7,6 tonnes), and South Korea (0,3 tonnes), resulting in less than 1% of the EU's total imports (EUROSTAT 2020).

Indonesia. - Europe has been the major importer of frogs' legs for many decades, with exports from Indonesia contributing to 83% of all European imports (Kusrini and Alford 2006): Already in 1969, Indonesia exported frog's legs (as fishery products; Mikrimah 2009) to Europe, and in the 1970s, Indonesia was considered the third largest exporting country of frogs' legs after India and Bangladesh (Susanto 1994; Warkentin et al. 2009). While EU imports of frog's legs exported from Indonesia amounted to >3 tonnes of frog's legs in 1987, exports in 1993 increased to 4,7 tonnes, corresponding to 94-235 million individual frogs (cf. Veith et al. 2000). Species involved in the international food trade are mainly represented by members of the family Dicroglossidae (*Fejervarya* and *Limnonectes*) (Kusrini 2005). However, at least 14 anuran species are exploited for the food trade, and just four 'species' dominate the trade (*Fejervarya cancrivora*, *F. limnocharis*, *L. macrodon*, and *Lithobates catesbeianus).* Of these, only the latter species, the non-native to Indonesia, *L. catesbeianus*, is cultured from farms (Altherr et al. 2011) (Table 3). According to Kusrini (2005), the export of 28-142 million frogs annually is approximately only one seventh of the animals harvested for the domestic market across Indonesia, with many smaller species consumed in Indonesia (local species are favoured) and larger ones of at least 100 mm snout-vent length (only about one eighth of the frogs caught) are destined for exports (Kusrini 2005; Kusrini and Alford 2006). While major harvest regions in Indonesia include Sumatra and Java (Kusrini and Alford 2006), exploitation of anurans for food in Kalimantan appears to be less common, but frog's legs are traded "from Sulawesi to big exporting cities such as Makassar or Jakarta before leaving the country" (Iskandar 2014). Export quotas within Indonesia list species, but on reaching the EU species level information is not recorded (see Table 2). DNA analysis showed that *Fejervarya cancrivora* was clearly the most dominant species imported into the EU, and imports declaring other species i.e., *Limnonectes macrodon*, *Fejervarya limnocharis*, and *Lithobates catesbeiana*, had been mislabelled (Ohler and Nicolas 2017).

Annual export quotas. - Annually, Indonesian authorities publish harvest and export quotas of CITES and non-CITES species native to the Indonesia (but possibly not the actual export values). For species listed in Table 2, harvest/export quotas issued for the period 2015-2021 were determined (Indonesian Ministry of Environment and Forestry 2015-2021).

Among quotas established for edible frog species, trade for the purpose of "consumption" is indicated for both *Fejervarya cancrivora* and *F. limnocharis*. However, only in 2015, for *F. limnocharis*, a specific number of individuals was designated for consumption (Table 2). While export quotas for *F. cancrivora* in 2015 were only considered for pets (according to the recorded details), in 2016 a 37,155-fold increased quota was set for consumption purposes. From then onwards, quota figures declined steadily, stagnating in the last two years with the collapse in 2019 remaining unexplained. It also remains unclear what reasons the number of individuals per kilo were reduced as of 2018 (Table 2). In 2015-16, export quotas for skins of *Limnonectes macrodon* were established, and thereafter no quotas were allocated to the species. There is no information on the whereabouts or use of the skinned bodies and the fact why no quotas have been established for the species since 2017 (Table 2).

Table 2. Indonesian export quotas of species known to be consumed nationally and internationally; cons=consumption; indiv. = individuals; SVL= snout-vent length. Sources: Indonesian Ministry of Environment and Forestry (2015-2022).

	2015	2016	2017	2018	2019	2020	2021	**2022**
Fejervarya cancrivora	2,250 (pet)	83,599,250 (cons.) [1kg = 22 indiv.]	78,498,000 (cons.) [1kg = 22 indiv.]	72,086,805 (cons.) [1kg = 15 indiv.]	4,100,850 (cons.) [1kg = 15 indiv.]	56,985,845 (cons.) [1kg = 15 indiv.]	56,985,845 (cons.) [SVL ≥ 9 cm]	56.985.845 (cons.) [SVL ≥ 9 cm]
Fejervarya limnocharis	12,150; (10,000 for cons.)	3,600 (pet)	11,270 (pet)	630 (pet)	1, 080 (pet)	1,235 (pet)	1,235 (pet	1.235 (pet)
Limnonectes kuhlii	540 (pet)	540 (pet)	588 (pet)	0	90 (pet)	95 (pet)	95 (pet)	95 (pet)
Limnonectes macrodon	10,350; 10,000 (skin)	10,350; 9,000 (skin); 1,350 (pet)	0	0	0	0	0	0

Farming operations in Indonesia. - In 1982, commercial frog farming was established in Indonesia only involving non-native species (Kusrini and Alford 2006). In 1983, *Lithobates catesbeianus* was introduced to Indonesia for the purpose of commercial farming (Susanto 1994), and despite Susanto's comprehensive booklet on frog cultivation, 20 years later there was no evidence that commercial breeding of this species has shown successful trends (Kusrini 2005). Despite government support programmes for the commercial breeding of frogs, the initiative remained less promising mainly because costs of harvesting wild-caught native species are lower (Kusrini 2005). Not only are high costs of breeding bullfrogs leading many farms to stop breeding *L. catesbeianus*, the susceptibility of the species to disease is also a factor (Kusrini and Alford 2006). More recent information on frog farms in Indonesia is not available but examination of stable isotopes of frogs' legs in the trade from Indonesia indicate that commercial frog farms are still not established and that wild sourced populations are being harvested, not farmed species (Dittrich et al. 2017).

Vietnam. - Indonesia and Vietnam represented the largest exporters of frogs' legs in the period 2003-2007 (Altherr et al. 2011). In 2006 alone, Vietnam exported 573 tonnes of frog's legs (UN Commodity Trade Statistics Database 2010, in Altherr et al. 2011), while in the period 2010-2019, Vietnam supplied the EU with > 8,400 tonnes frog's legs, representing the second largest supplier of frogs' legs into the EU (EUROSTAT 2019).

It is challenging to determine sources of current frogs' legs from Vietnam, whether they are farmed or wild-caught. According to Nguyen (2014), the governmental regulation of frog farming operations in Vietnam was meagre. Exports of frog's legs from Vietnam to Canada are based on permits documenting captive reared *H. rugulosus* (Gerson 2012). Quoc (2012) also states that the harvest of wild sourced individuals is unstable and very difficult to estimate, thus quantities for neither wild caught nor farmed frogs cannot be indicated in a "value chain framework of the frog industry". Nevertheless, forensic research could confirm frog's legs of *H. rugulosus* that have been sourced from farms (Dittrich et al. 2017). Collection of wild individuals is intended to replenish frog farms, still a prospect considered challenging with *H. rugulosus* (Borzée et al. 2021).

Farming operations in Vietnam. - According to Nguyen (2000), households in the provinces of Hanoi, Ha Tay, and Hai Duong have established breeding frog farms, but do not keep up with national demand, and the majority of frogs for national consumption are sourced from wild populations.

The many risks associated in frog farming in southern Vietnam, Tien Giang province, and Ho Chi Minh City, have been highlighted by Nguyen (2014). In particular, private established farms raise concerns about quality standards and risk management. Interviews with representatives of various interest groups revealed that efforts to produce frogs commercially often lack the necessary husbandry for successful breeding, starting with choice of location for such a project, selection of suitable stock and species composition, as well as knowledge of breeding, diseases, hygiene for animals and humans, environmental pollution, etc. (Nguyen 2014). In recent years, frog farming operations in Vietnam experienced an upswing, and the country is considered the second largest producer of farm raised frogs (U.S. Soybean Export Council 2019). Specially trained staff who are familiar with diseases inherent in frog farming as well as the correct application of drugs/chemicals for treatment and prophylaxis are needed to assure required/standardized biosecurity measures (see Thinh and Phu 2021).

India. - India, formerly considered the country with the largest frogs' legs exports (Abdulali 1985), is discussed here only in passing. In 1985, India and Bangladesh listed their main edible frog species i.e., *Euphlyctis hexadactylus* and *Hoplobatrachus tigerinus* in CITES Appendix II, as a result of dramatic population declines (Oza 1990), with exports completely stopped in 1987 and 1989, respectively. In place of India, Indonesia stepped in and became increasingly the main supplier for frogs' legs (see Warkentin et al. 2009) in the late 1980's. However, it is astonishing that in 2018, India apparently exported 5 tonnes frogs' legs to the Netherlands, despite its export ban of 1987. In this case, a confusion of the country codes (ID/IN) in the EUROSTAT database cannot be ruled out but, alternatively, the export ban in India could have been circumvented. Independent of this, Humraskar and Velho (2007) indicate that the trade ban on frogs' legs did not have the desired effect in India. Trade data in the period 2010-2019 indicates that India contributed exports of 15 tonnes into the EU (equal to 0.05% of total imports into the EU [EU imports from Indonesia in the same period amounted to 74%]). According to export data provided by "Seair Exim Solution", frogs' legs (without naming species utilized or how they were sourced) originating from India were shipped to Poland via Thailand (https://www.seair.co.in/frog-legs-export-data/hs-code-73023000.aspx, accessed March 2022, see Suppl. Inf. 3).

Farming operations in India. – In response to the export ban of frogs' legs for the international market imposed in 1987, initial establishment of frog farms was reported one year later. At that time, the frogs' leg trade was organized under the Seafood Exporters Association, who proposed that the Indian government set up frog breeding centres (Vijayakumaran 1988). However, it seems that a nationwide establishment of commercially operating frog farms is still in its infancy in India, compared to some SE-Asian countries. In a more recently published study, possibilities for establishment of commercial frog farming in Goa were explored, based on the known issues of the frog trade (e.g., wild harvest); thus to commercially produce frogs would in turn "minimize illegal poaching" (see D'Silva 2015).

Turkey. - In 2017, Turkey exported 547 tonnes of frogs for the food trade (Turkey Statistical Institute 2017, in Aktas et al. 2019), and according to EUROSTAT (2020), in the same year >107 tonnes were imported from Turkey by France, Italy, and Spain. Between 2010-19, Turkey supplied EU-countries with >1,593 tonnes of frog's legs (EUROSTAT 2020). Şereflişan and Alkaya (2016) note that at the national level, harvest and trade of frog's legs in Turkey appears negligible. The focus is essentially on international trade activities involving five companies exporting frogs' legs as the commodities "frozen frogs' legs", "chilled frogs' legs" and "processed form as live frog" to the EU and Switzerland. The authors reiterate the need for commercial frog farming because the wild harvests signal overexploitation. Species of economic value include four *Rana* spp. (*R. dalmatina, R. macrocnemis, R. camerani, R. holtzi*), and two *Pelophylax* spp. (*P. bedriagae, P. ridibundus*) (Şereflişan and Alkaya 2016). Wild *P. ridibundus* collected for export also include live specimens and frozen legs, 1,000 tonnes of which are exported annually (see Alkaya et al. 2018, and references therein).

Farming operations in Turkey. - According to Dökenel and Özer (2019), *P. ridibundus* is the primary species for EU imports, and in recent years it has been involved in farms of the private and public sectors. However, the occurrence of zoonotic pathogens in frog farms highlights the need for the development of sustainable frog husbandry to protect animal and human health.

Albania. - Between 2010-2019, Albania's share of the EU market was 1% (= 590 tonnes), and according to Jablonski (2011), populations of *Pelophylax epeiroticus* and *P. shqipericus* were utilized both nationally and traded internationally for food. So far, however, there is no conservation management plan in place for the threatened *P. shqipericus* (Eco Albania 2019), and the species is of particular concern as offtake levels for trade purposes are considered unsustainable (Gratwicke et al. 2010).

Farming operations in Albania. - To the best of our knowledge and research, we were unable to uncover any evidence of established farms for the commercial breeding of *Pelophylax* spp. for export, and little documentation exists of export levels. In 1996, a French businessman invested in a frog farm, motivated in part by the fact that in the mid-1990s frogs' legs in France became rare (cf. above). Mainly due to a socio-economic and political crisis, this farming project failed (https://www.discover-cee.com/roadtrip-cee-albania-how-a-french-guy-discovered-tirana-as-best-place-to-start-his-fintech/, accessed May 2022, see Suppl. Inf. 3). Therefore, we conclude that current export figures all refer to wild-sourced individuals.

Trends in EU frogs' legs imports

Import data for the period 2010-19 were compared with data of the previous decade (see Altherr et al. 2011), and three trends stand out: (1) a decrease of roughly 12.3% in EU imports of frogs' legs (now 40,700 tonnes instead of 46,400 tonnes) with marked fluctuations underscoring this decline (Fig. 2), (2) the role of Belgium as the highest importing country with 70% of imports in the period under review (in contrast, France's import volumes decreased from 23% to 17% and those of the Netherlands' from 17% to 7%), and (3) the significant increase in the role of Vietnam in exporting frogs, from 8% to 21% of total imports, with China simultaneously dropping from 3% to less than 1%.

Forensic studies have shown that the species composition and labelling in Indonesia's trade has changed over recent decades (Ohler and Nicolas 2017). *Fejervarya limnocharis* and *Limnonectes macrodon* were among the most common documented species exported (Kusrini 2005), but *F. cancrivora* represents the major species in trade.

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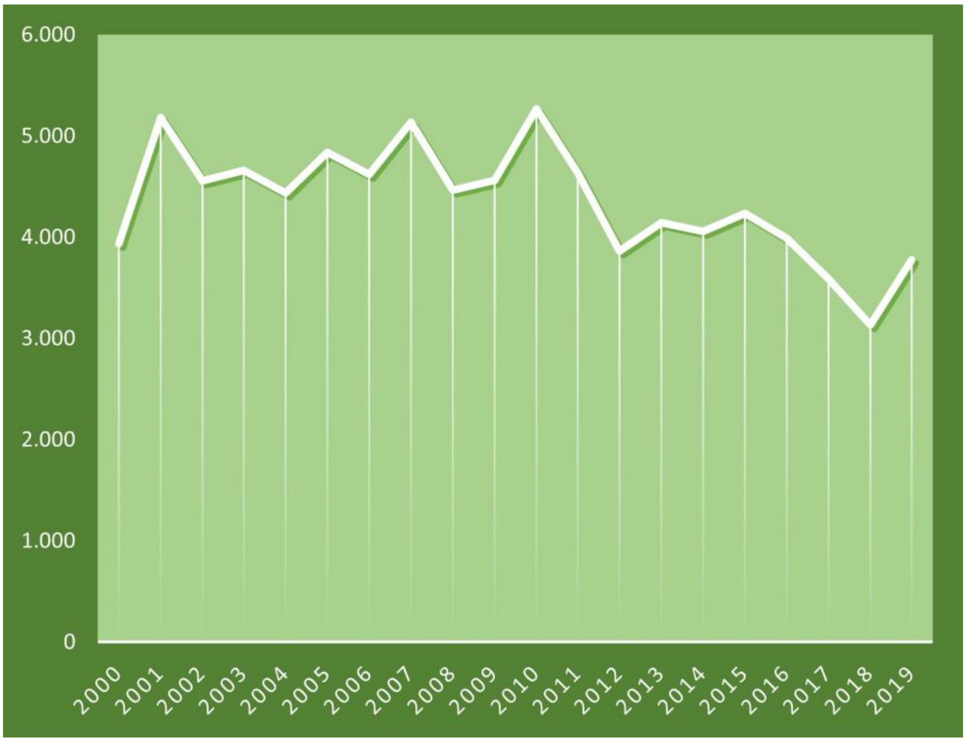

Figure 2. EU's frogs' legs imports (tonnes) during the period 2000-2019. Source: EUROSTAT (2012, 2021).

United States

While this study focuses on the EU, the current role of the United States is briefly highlighted, as the US also represents a major consumer of frogs' legs (cf. Warkentin et al. 2009; Gratwicke et al. 2010; Altherr et al. 2011). In the period 2015-2020, at least four anuran species were imported by the US for consumption, *Lithobates catesbeianus*, *L. forreri*, *L. grylio* and *Hoplobatrachus rugulosus* (US LEMIS Database 2022). *L. catesbeianus* (either alive, dead, or legs only) represented the major species by a large margin, predominantly supplied by Mexico (mainly wild), Ecuador, and China (farmed) (Fig. 3). This species, the American Bullfrog, *Lithobates catesbeianus*, has also been widely introduced into Latin America and Europe for commercial breeding purposes (Carraro 2008). In 2018, imports of *H. rugulosus* emerged and were declared as exports from Thailand either as captive-bred or ranched, while exports from Vietnam also included wild individuals. Mexico exclusively supplied the United States with wild sourced *L. forreri*, shipped as meat or legs. In 2015-16, the US imported more than 90 tonnes of meat of *L. grylio* all noted as captive bred (LEMIS database), but this species is native to the United States (Fig. 3). It is noteworthy that the large quantities of frogs' legs of species harvested in Indonesia and eastern Europe have no sales in the USA.

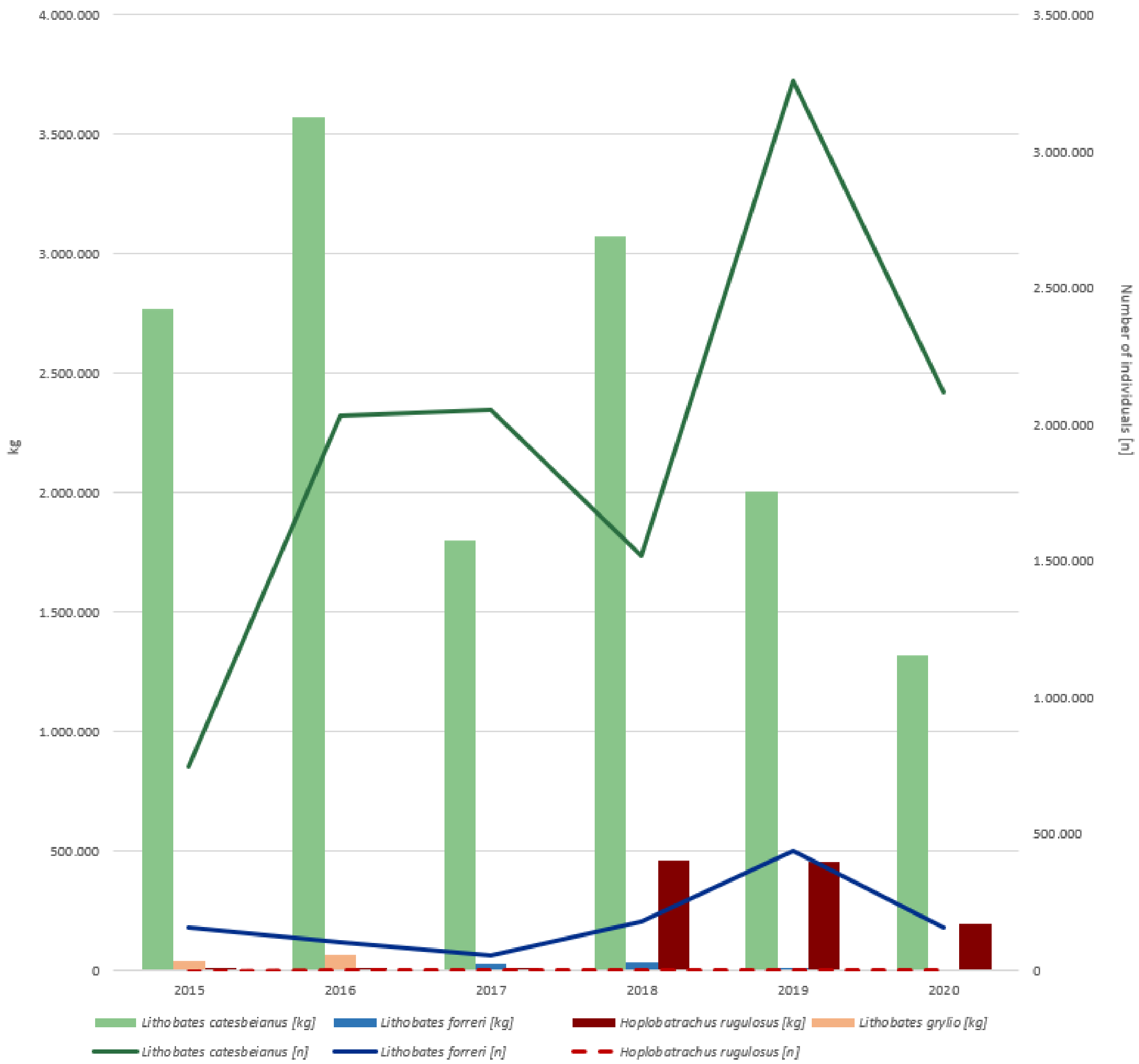

Figure 3. Anuran species imported for the purpose of consumption into the US in the period 2015-20, in which weight (left) is compared to the number of individuals (right) to illustrate how unequally these variables are aligned with each other. Source: US LEMIS database (2022).

National/domestic use

As can be seen in the individual IUCN Red List assessments on exploited amphibian species (Suppl. Inf. 1, Fig. 2; Suppl. Inf. 4), many species are harvested at local/national levels for consumption, medicinal, and/or spiritual purposes (e.g., Nepal 1990). Although this issue is not the focus of this paper, some light can be shed on aspects of local use of frogs for consumption from a conservation perspective. International trade activities can only claim to be sustainable if offtakes for national needs are also managed sustainably. This implies that monitoring of harvest levels for both local/national and international consumption need to be in place (Leader-Williams 2002). There are numerous published examples that describe the domestic trade of amphibians and the impact it may have on local frog populations. Species harvested for consumption within national borders, and across range States, are reported for Greece (Hatziioannou et al. 2022), West and Central Africa (Mohneke et al. 2009, 2010; Akinyemi and Ogaga 2015; Efenakpo et al. 2015), Burundi of eastern Africa (Verbanis et al. 1993), India (Pandian and Marian 1986; Ahmed 2012; Talukdar and Sengupta 2020), Nepal (Shresta and Gurung 2019), PDR China (Zhang et al. 2008; Chan et al. 2014; Turvey et al. 2021), Malaysia (Hardouin 1997), Vietnam (Nguyen 2000), Mexico (Barragán-Ramírez et al. 2021) and the USA (Ugarte 2004, Ugarte et al. 2005), as exemplars of some countries/regions. The proportion of national vs. international trade is of particular interest when some countries document high annual exports for the international frogs' legs industry on a regular basis, while ignoring that some species have been consumed locally for decades/centuries (Angulo 2008; Onadeko et al. 2011; Ahmed 2012). It would not be problematic if species are traditionally consumed at the local/national level and this use was deemed sustainable. However, harvest for international exports (above local/traditional harvest) often means overexploitation of local populations (Oza 1990, and cf. species compiled in Suppl. Inf. 4). In addition, for Indonesia, it has been estimated that offtakes of edible frogs on a national level are up to 142 million frogs, or seven times as much as that of annual international exports (see Kusrini 2005), with no documentation of the impact on wild populations, and highlighting the need for better monitoring of base populations and trade.

Species diversity consumed and evaluated in the IUCN Red List

The conservation of species in trade only makes sense if the species or species complexes are known. Traded species whose taxonomic status is not known or have not been verified is problematic (see below). In order to get an overview of the species involved in the food trade (whether at local, national, or international level), and their respective origins, the IUCN Red List was filtered (Fig. 4; Suppl. Inf. 4). Regions where most species are harvested for consumption are Southeast and East Asia, and it is also these regions that supply the EU market with most of their frogs' legs. Furthermore, many species are consumed in Central America and (northern) South America, all of which are traded either locally, nationally, or, exported to the USA (predominantly *L. catesbeianus* from breeding farms; https://www.fao.org/fishery/en/culturedspecies/rana_catesbeiana/en, accessed March 2022, see Suppl. Inf. 3). Interestingly, the EU is not a consumer of species from these regions. Likewise, all species consumed in Africa, with the West African region forming a species focus, are consumed in Africa, and the EU is not a consumer of African species (Suppl. Inf. 1, Fig. 4).

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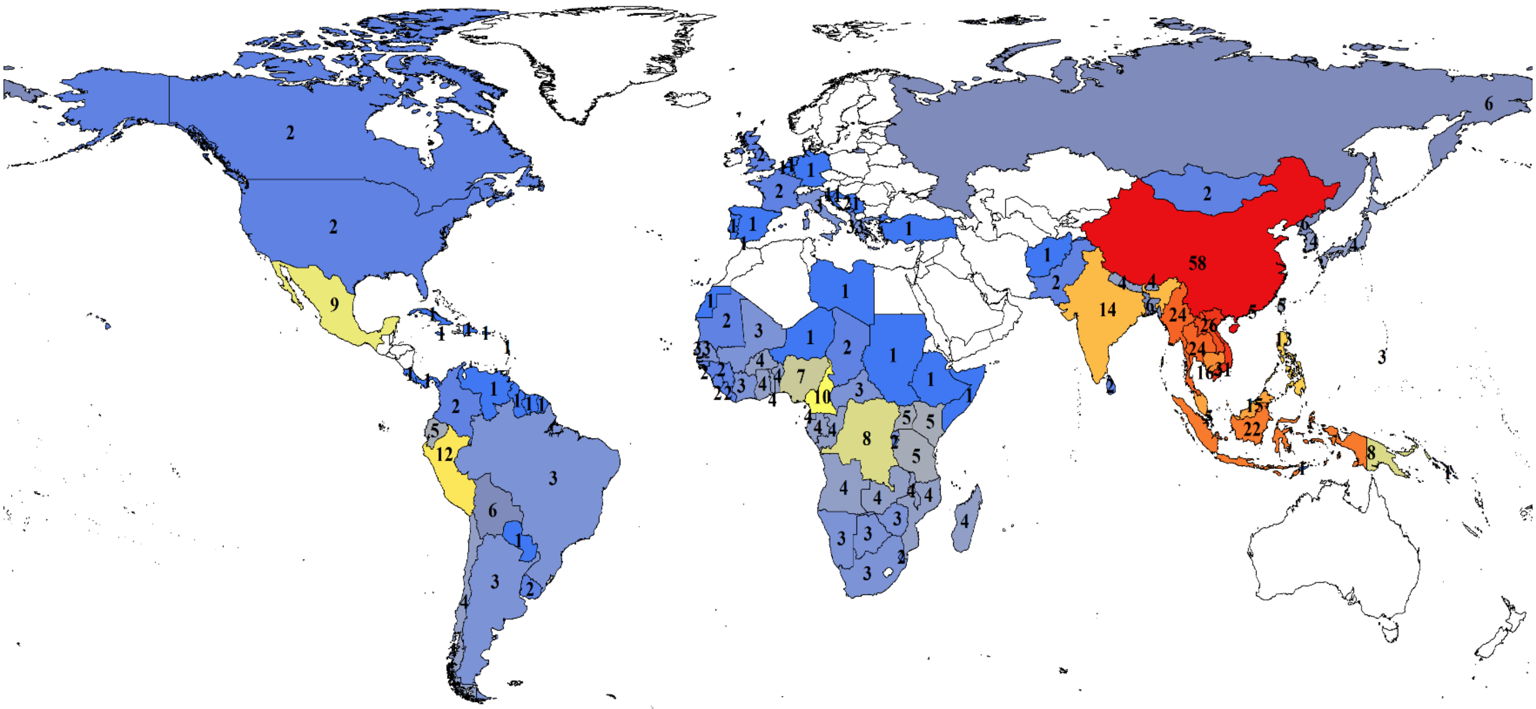

Figure 4. Number of species per country in trade for consumption, see Figure S2 and S3 for more detailed range data and for species in international trade. Notably African species are largely consumed domestically rather than exported (Suppl. Inf. 1, Figs. 2, 4).

At least 187 species of anurans and salamanders/newts are collected locally/nationally for food and for the international frogs' legs industry (Suppl. Inf. 4). According to information of Red List assessments, the local/national use of 13 species (filtered by the search criteria given above) was not explicitly stated, was more generally indicated (i.e., "species in the genus are also commonly used for food"), or the use has been not necessarily considered a threat (e.g., *Leptobrachium hainanense*, IUCN SSC Amphibian Specialist Group 2020d; Suppl. Inf. 4). Of the remaining 174 species, all but two are consumed on a local/national scale. For *Lithobates pipiens*, only international trade is indicated (Hammerson et al. 2004), and in *Ambystoma leorae* (IUCN SSC Amphibian Specialist Group 2020b), it was not possible to confirm if local use was still present. Of all species of amphibians for which we found data, at least 20 species are potentially involved in international trade activities. In some species (for example, *Limnonectes shompenorum*, IUCN SSC Amphibian Specialist Group 2018b), cross-border trade was assumed but not substantiated. In other species, the Red List assessment notes the presence of trade, i.e., *Rana amurensis* (IUCN SSC Amphibian Specialist Group 2020i). For species

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indicating international trade or questioning trade across borders in some species, thus revealing uncertainty in single assessments (Table 3, Suppl. Inf. 2).

Table 3. Anuran species in the European frogs' legs trade where overexploitation and/or taxonomy is/are important limiting factor(s) for sustainable commercial trade. Distribution: Information here is based on IUCN Red List assessments and more recent literature. Country codes follow acronyms provided in the CITES Trade Database, https://trade.cites.org/cites_trade_guidelines/en-CITES_Trade_Database_Guide.pdf; "?" next to country denotes uncertainty; RLA: Red List Assessment and year when the species was most recently assessed, with '**outdated**' used to designate RLAs >10 years old; LC: Least Concern, DD: Data Deficient, NT: near threatened, VU: vulnerable; Pop. trend: population trend (⇧: increasing; ⇨: stable; ⇩: decreasing; ?: unknown); CITES: listed in either the appendices I-III, or in the annexes of the European Union Wildlife Trade Regulations (EU-WTR) A-D; Information: *): Assessment involving uncertainty. Sources: IUCN (2021) and therein published Red List assessments of the species concerned; Indonesian quotas - Indonesian Ministry of Environment and Forestry (2022); Frost (2021) for adjusting English names, taxonomy and distribution.

Species	Distribution	RLA (year)	Pop. Trend	CITES / EU WTR	Information on threat, trade, farming operations & exploitation levels
Fejervarya cancrivora Crab-eating grass frog	BN, KH, CN, IN, ID, LA, MY, PH, SG, TH, VN	LC (2004, **outdated**)	⇧		• assumed overharvest* • utilized locally, nationally and internationally • export quota sharply increased in 2016 to more than 83 million animals for consumption and since then strong fluctuations. • 2022 harvest/export quota Indonesia: 59,985,100/56,985,845 specimens • Imported to the EU by millions as frogs' legs • In need of taxonomic revision
Fejervarya limnocharis Common Asian grass frog	BD, BN, KH, CN, HK, IN, ID, JP, LA, MO, MY, MM, NP, PK, PH, SG, TW, TH, VN	LC (2004, **outdated**)	⇨	-	• harvested for human consumption, found in local and national trade (Van Dijk et al. 2004a; Nguyen 2000) • probably also in international trade • 2021 harvest/export quota Indonesia: 1,300/1,235 specimens for the pet trade, in 2015 also harvest for consumption (cf. Table 2) • cryptic species complex
Fejervarya moodiei Northern Crab-eating Grassfrog	CN, IN, MY, MM, PH, TH, VN	DD (2004, **outdated**)	?	-	• originally thought to be known only from the type locality Manila (Luzon Island, Philippines, with unclear taxonomic validity • identified by DNA barcoding in French frogs' legs imports (Ohler and Nicolas 2017)

Hoplobatrachus rugulosus Asian Rugose Bullfrog	KH, CN, HK, LA, MO, MM, TW, TH, VN	LC (2004, **outdated**)	⇨	-	• large individuals may be overharvested locally • wet rice agroecosystems appear to balance the impact of exploitation • locally, nationally, and internationally traded for food • harvest of large numbers of wild individuals is ongoing, either directly to be marketed or to restock farms, e.g., in Vietnam • large numbers of frogs' legs imported into the EU • meat is considered a delicacy in restaurants in Viet Nam (Nguyen 2000)
Hoplobatrachus tigerinus Asian bull frog	AF, BD, BT?, CN?, IN, MM, NP, PK; introduced to MG	LC (2008, **outdated**)	⇨	II / B	• intense harvest before the 1990s has detrimentally impacted populations (India, Bangladesh) • legal export banned in India & Bangladesh since the late1980s • utilized locally, nationally, internationally (frog leg industry) • taxonomic confusion with *H. rugulosus** • species is farmed (e.g., in Vietnam or Thailand), occasionally hybridization with *H. rugulosus* to increase production
Limnonectes blythii Blyth's giant frog	KH?, ID, LA, MY, MM, SG, TH, VN	NT (2004, **outdated**)	⇩	-	• major threat is consumption (locally / nationally / internationally) • population decline > regional overharvest • taxonomic uncertainty > *blythii* complex*(van Dijk and Iskandar 2004) • relatively large species, attractive for frogs' legs trade • in the 1980s one of the dominating species in Indonesia's exports to Europe (Le Serrec 1988)
Limnonectes ibanorum Rough-backed river frog	BN, ID (Kalimantan), MY (Sarawak)	LC (2018)	⇩	-	• large body size make species attractive for food trade • probably utilized locally and possibly also for the international frog leg trade* • life history traits make this species vulnerable to overharvest • declining populations indicate over-exploitation
Limnonectes ingeri Inger's wart frog	BN?, ID (Kalimantan), MY (Sabah, Sarawak)	LC (2018)	?	-	• large body size make species attractive for food trade • potentially exported for the frog leg industry* • locally consumed in Kalimantan and Sarawak • life history traits make this species vulnerable to overharvest

Limnonectes kuhlii Kuhl's Broad-headed Frog	BN, CN, IN, ID, LA, MY, MM, TH, VN	LC (2004, **outdated**)	⇩	-	• cryptic taxon, species complex* • locally collected for consumption, impact on populations in China may be detrimental • declining populations indicate over-exploitation • meat is highly priced in Viet Nam (Nguyen 2000) • look-alike species of *L. macrodon*, included in EU imports (MNHN 2012; Ohler and Nicolas 2017)
Limnonectes leporinus Giant river frog	BN, ID (Kalimantan), MY (Sabah, Sarawak)	LC (2018)	⇩	-	• potentially exported for the frog leg industry* • regionally > overharvest of large individuals > suggesting demographic change
Limnonectes macrodon Giant Javan frog	ID (Sumatra, Java)	LC (2017)	⇩	D	• locally, nationally exploited as food; Javan populations are exploited for the international market • has been heavily harvested for the frog leg trade (Kusrini and Alford 2006), and between 1988-1991, 17 tonnes were traded for their skins and meat (Kusrini, 2017 in IUCN SSC Amphibian Specialist Group 2018a) https://www.iucnredlist.org/species/58351/114921568#use-trade) • according to Ohler and Nicolas (2017) the species was not traced in the international frogs' legs market
Limnonectes malesianus Malesian river frog	ID, MY, SG, TH	NT (2004, **outdated**)	⇩	-	• significant decline initially reported in 2004 • overharvest is considered a major threat • collected for subsistence use and trade & utilized locally, nationally • sympatric occurrence with the larger *Limnonectes blythii* that is favourably collected • look-alike species of *L. macrodon*, included in EU imports (MNHN 2012; Ohler and Nicolas 2017)
Lithobates catesbeianus American bullfrog	CA, US, MX	LC (2015)	⇧	-	• commercially farmed for food (in non-range countries, e.g., in Thailand, Viet Nam and Brazil) • considered a pest & invasive species, e.g., in large parts of Europe, Central and South America, East and Southeast Asia • it is a possible vector of pathogens*
Lithobates pipiens Northern leopard frog	CA, US, PA, MX?	LC (2004, **outdated**)	⇩	-	• commercial overexploitation is considered a major threat • utilized internationally for consumption

Pelophylax bedriagae Bedriaga's Marsh Frog	CY, EG, GR; IL; JO; LB, SY, TR	LC (2008, **outdated**)	⇩	-	• harvest/exports for food from Turkey to western Europe > considered a significant threat • large numbers are exported from Turkey (Çiçek et al. 2020; Şereflişan and Alkaya 2016) and Egypt • High extinction risk in Turkey until 2032 if exploitation level continues (Çiçek et al. 2020). • utilized local and internationally for consumption (Papenfuss et al. (2009)
Pelophylax caralitanus Beyşehir frog	TR	NT (2008, **outdated**)	⇩	-	• largest edible frog in Turkey; commercially overexploited for the frogs' legs trade in France, Italy, and Switzerland (Çiçek et al. 2020; Şereflişan and Alkaya 2016) > have caused its rapid decline so that the species is now considered endangered (Erismis 2018) • High extinction risk until 2032 (Çiçek et al. 2020).
Pelophylax epeiroticus Epirus water frog	AL, GR	NT (2019)	⇩	-	• locally, nationally utilized for food • intensively was utilized in Albania for consumption, at present no evidence for excessive collections in Albania • *Bd*-infected populations in Albania • Potential hybridization with the sympatric *P. ridibundus*
Pelophylax kurtmuelleri Balkan frog	AL, GR	LC (2008, **outdated**)	⇨	-	• Nationally and internationally utilized for consumption • in northern parts of its native range > significantly threatened through commercial overexploitation for consumption (Uzzell et al. 2009) • another threat is considered in the unintentional introduction of commercially traded non-native water frogs
Pelophylax ridibundus Eurasian marsh frog	Western Europe across the Arabian Peninsula, Central Asia to Russia	LC (2008, **outdated**)	⇧	-	• harvested for educational & medical research, and food • populations extensively collected for food in Turkey (~ 1,000 t/yr) (Alkaya et al. 2018); • trade for frog legs may detrimentally impact populations in Turkey*(Çiçek et al. 2020; Şereflişan and Alkaya 2016) • frog-leg trade has led to declines in populations in eastern Asia, former Yugoslavia and possibly in Romania* • *Rana (Pelophylax) kl. esculenta* considered a synonym
Pelophylax shqipericus Albanian water frog	AL, ME, introduced to IT & HR	VU (2019)	⇩	D	• Nationally and internationally utilized for consumption

	• No management plan in Albania; significantly threatened by overexploitation • Potentially threatened by unintentional introduction of commercially traded non-native water frogs

Threat status, population trends and sustainability

Among the 30 species consumed and traded locally, nationally, and/or internationally (relevant for the European frogs' legs trade), uncertainties persist in several species regarding the level of exploitation (Table 3, Suppl. Inf. 2). Of all amphibian species that are consumed for food and assessed in the IUCN Red List, 20 have been evaluated "Least Concern", one "Data Deficient", five "Near Threatened (NT)", one "Vulnerable (VU)", one "Endangered (EN)", one "Critically Endangered (CR)", and nine not assessed or "Data Deficient (DD)" (Suppl. Inf. 4). Importantly, most Red List assessments for these species are outdated. For example, the years of assessments are 2004 (11 species), 2008 (five species), 2015 (one species), 2017 (four species), 2018 (three species), 2019 (five species) and 2020 (one species), leaving more than half of these species with assessments more than 10 years old (Table 3, Suppl. Inf. 2). IUCN Red List population trends indicate 18 species "decreasing", six species "stable", three species "increasing", and three species with an "unknown" population trend (though little data exists on these populations), indicating that many species may need to be carefully reviewed, especially given the possibility of misidentification (Table 3, Suppl. Inf. 2). Of considerable concern are those species that were last assessed in 2004, most notably *Limnonectes blythii*, and. *L. malesianus*. These outdated assessments are further exacerbated by the fact that the species are regionally overharvested for consumption as well as being involved in the international trade at uncertain levels. However, of all 30 species known to be consumed, 16 species have special mention of harvest that might influence their conservation status. Of these, 12 species (*Leptodactylus fallax, Limnonectes blythii, L. leporinus, L. macrodon, L. malesianus, Lithobates pipiens, Pelophylax caralitanus, P. kurtmuelleri, P. ridibundus, P. shqipericus, Rana amurensis,* and *R. chensinensis*), have either "regional overexploitation-collection", or "harvest leading to declines" explicitly stated in their IUCN assessments. Another four species (*Fejervarya cancrivora, Hoplobatrachus rugulosus, Limnonectes kuhlii, L. microtympanum*), have these same parameters as 'presumed' within their Red List assessments (Table 3, Suppl. Inf. 2). A detrimental harvest impact is indicated for *Rana dybowskii* for the medicinal trade

(Kuzmin et al. 2004) and in *Limnonectes grunniens* and *Pelophylax bedriagae*, harvest for the food trade is considered a significant threat. In *Limnonectes ibanorum* and *L. ingeri*, harvest is considered detrimental due to the species' unfavourable life history traits (Table 3, Suppl. Inf. 2). Of the 187 species filtered from the IUCN Red List that are collected for either local, national, or international consumption (Suppl. Inf. 4), assessments of population trends since 2004 to 2020 clearly show population declines as well as the upgrading of threat categories over the study period (cf. Figs. 5, 6). Uncertainties outlined in this review remain unevaluated, and a resolution of these for individual species assessments would likely influence the categorisation of the threat status and population trends.

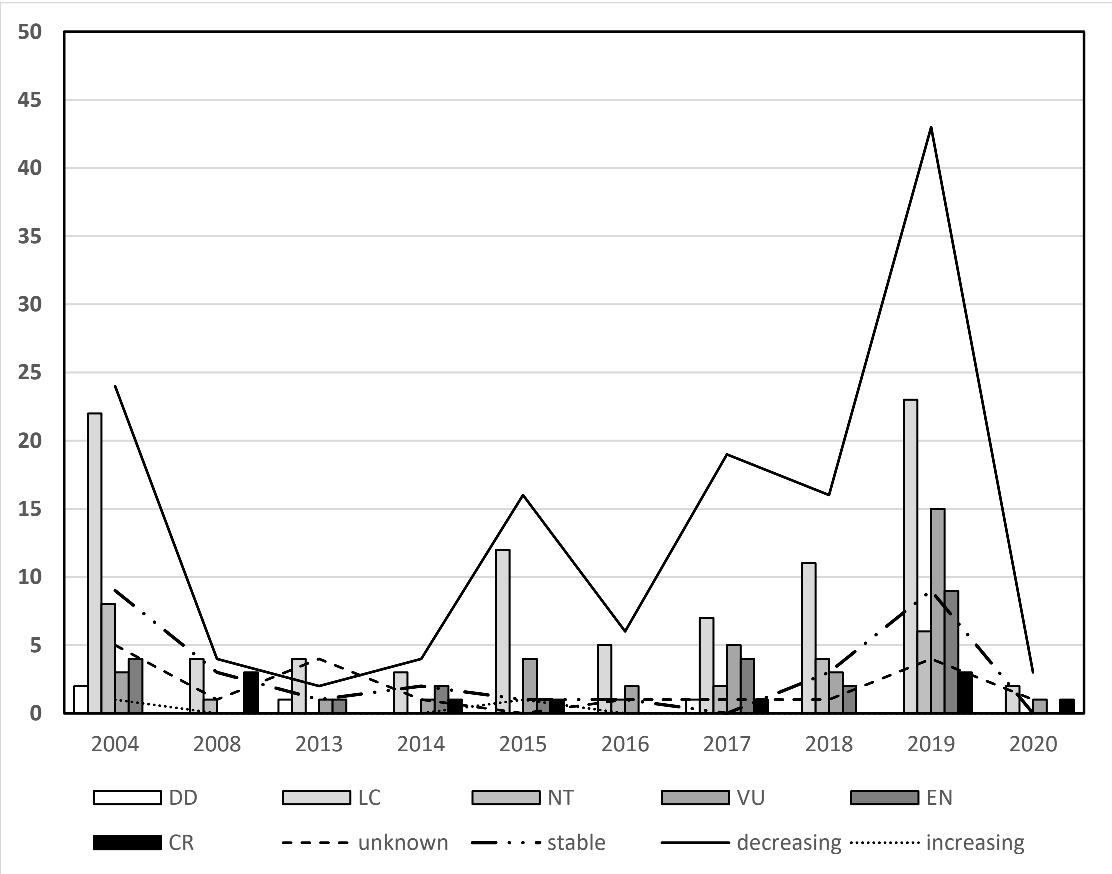

Figure 5. Relationship of Red List status (bars) and population trend (lines) of 187 amphibian species globally utilized for consumption that have been assessed between 2004 and 2020. Source: IUCN (2021); cf. Suppl. Inf. 4).

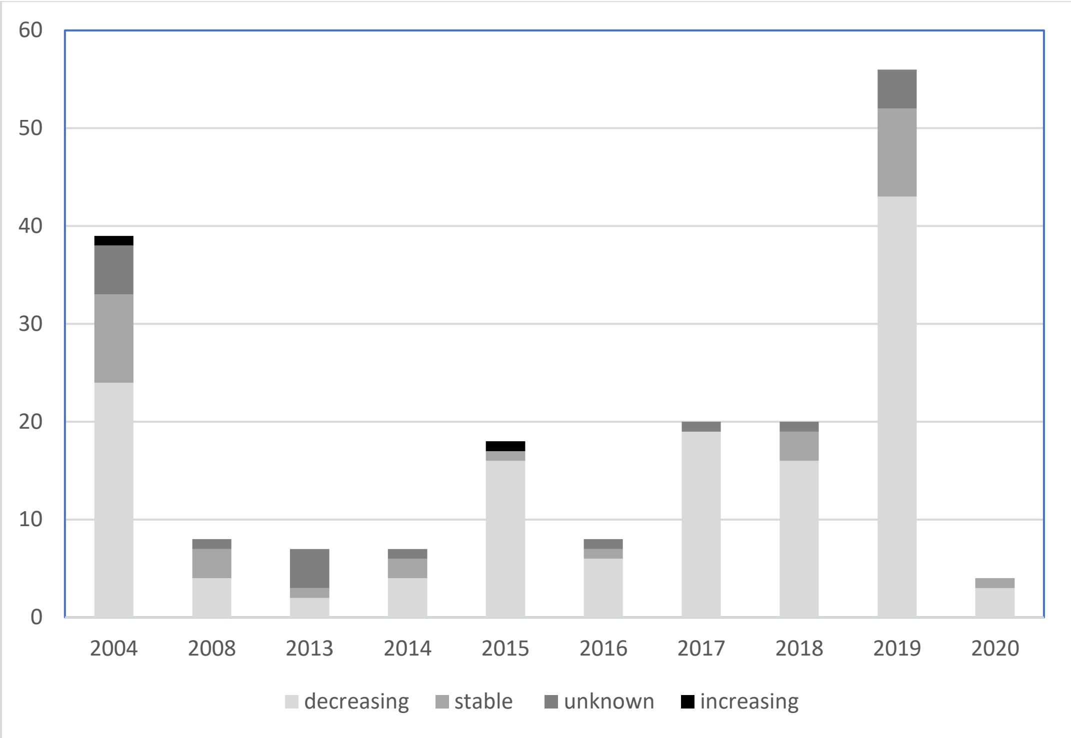

Figure 6. Population trends assessed in 187 amphibian species, consumed for food, in 10 assessment periods between 2004-2020 (cf. Suppl. Inf. 4).

CITES species and their trade

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) currently lists 220 amphibian species in their appendices, equating to ca. 2.6% of all amphibian species (8,386 spp.; Frost 2021) recognized by science. The CITES trade database (https://trade.cites.org/, accessed January 2022, see Suppl. Inf. 3) merely lists seven anuran species that are traded for the purpose of consumption (Table 3). Nonetheless, the majority of species involved in the frogs' legs trade are not listed in the appendices of CITES (cf. Table 3, Suppl. Inf. 2, 4), and cannot refer to CITES trade data in order to obtain approximate information on species volumes traded per annum or query specific trends.

All seven CITES listed anuran species are utilized on a local/national scale and three (i.e., *Pelophylax shqipericus*, *Limnonectes macrodon* and *Hoplobatrachus tigerinus),* are involved in the international frogs' legs trade (cf. Table 4) as well. All seven species have been evaluated in the IUCN Red List and three other species, (i.e., *Conraua goliath*, *Laotriton laonensis* and *P. shqipericus)* are not listed in the appendices of CITES but appear in the annexes of the European Wildlife Trade Regulations (EU WTR). All but two of these species have a decreasing population trend and two species were last assessed in 2004 and 2008.

Table 4. Seven anuran species listed on the appendices of CITES (I-III) and annexes of the European Wildlife Trade Regulations (A-D) that are currently known to be consumed locally/nationally and those utilized within the international frogs' legs industry. Country codes follow acronyms provided in the CITES Trade Database (https://trade.cites.org/cites_trade_guidelines/en-CITES_Trade_Database_Guide.pdf); RLA: Red List Assessment and year, when the species was assessed, LC: Least Concern, VU: vulnerable, EN: endangered, CR: critically endangered; Pop. trend: population trend (⇨: stable; ⇩: decreasing). CITES: listed in either the appendices I-III, or in the annexes of the European Union Wildlife Trade Regulations (EU-WTR) A-D; Sources: IUCN (2021) and therein published Red List assessments of the species concerned (https://www.speciesplus.net).

Species	Distribution	RLA (year)	Pop. Trend	CITES & EU-WTR (year when listed)	Consumption & Trade
Calyptocephalella gayi Helmeted water toad	CL	VU (2018)	⇩	III (2011) C (2012)	National, international (likely only pet trade)
Conraua goliath Goliath frog	CM, GQ, GA?	EN (2018)	⇩	B (1997)	National
Euphlyctis hexadactylus Indian green frog	BD, IN, NP?, LK	LC (2004)	⇨	II (1985) B (1997)	National
Hoplobatrachus tigerinus Asian bull frog	AF, BD, BT?, CN?, IN, MM, NP, PK	LC (2008)	⇨	II (1985) B (1997)	National, international
Limnonectes macrodon Giant Javan frog	ID (Sumatra, Java)	LC (2017)	⇩	D (2009)	National, international
Pelophylax shqipericus Albanian water frog	AL, ME	VU (2019)	⇩	D (2009)	National, international
Telmatobius culeus Titicaca water frog	BO, PE	EN (2019)	⇩	I (2017) A (2017)	National, international

Four species are listed in CITES App. II, and one in CITES App. III that are consumed either locally/nationally and/or internationally traded for consumption, while another four species are only listed in the annexes of the EU-WTR (Table 4, Suppl. Inf. 4).

1. *Calyptocephalella gayi*. - Since 2011, the species is listed on CITES App. III in Chile. In 2012-2016, reported exports of 114 live individuals were recorded at the same time that 550 live individuals were imported. In 2012, 14 live individuals were seized in Japan, and the 550 animals were sourced from captivity in Chile and imported by the US and Japan. International trade for the purpose of consumption is not explicitly documented, despite the fact that the species is nationally and internationally involved in the food trade (IUCN SSC Amphibian Specialist Group 2019a).

2. *Conraua goliath*. - This species is not listed in the appendices of CITES but in Annex B of the EU-WTR. However, eight transactions 1998 - 2019 of wild sourced individuals were documented in the CITES trade database. All exports were from Cameroon, with 19 live

individuals commercially exported by Cameroon and 65 individuals claimed as commercial imports by EU importing countries. In 2004, Cameroon exported 199 specimens to the United States for scientific purposes. International trade for the purpose of consumption is not documented despite the species being locally/nationally consumed (IUCN SSC Amphibian Specialist Group 2019b).

3. *Euphlyctis hexadactylus*. – International trade has been documented since 1985 (date of CITES listing), with India as the major supplying country until 2006, documenting the export of roughly 1,215 tonnes of meat, while importing countries documented the import of ca. 2,588 tonnes meat (https://trade.cites.org, see Suppl. Inf. 3). Within the same period, Belgium and the United States imported another ~0,7 tonnes meat indicating India as the country of origin. As of March 2018, India banned the commercial export of wild harvested specimens (https://www.speciesplus.net/species#/taxon_concepts/4945/legal, see Suppl. Inf. 3).

4. *Hoplobatrachus tigerinus*. – Exports are documented since 1985 (date of CITES listing) and transactions have been reported until 2019. However, the largest quantities were shipped in 2007. Analysis of trade data of this species is particularly challenging because quantities are misleadingly indicated and non-range States of the species export large quantities, including meat of wild sourced individuals (e.g., from Vietnam and Madagascar, documented in the CITES trade database).

5. *Limnonectes macrodon*. - This species is not listed in the appendices of CITES but in Annex D of the EU-WTR. However, a single transaction was documented in the CITES trade database. In 2016, Germany reported the import of two live individuals from Indonesia, sourced from the wild. The species is intensively involved in the local, national, and international food trade (IUCN SSC Amphibian Specialist Group 2018a). It is remarkable that the Annex D records do not reflect an intense EU import of frogs' legs officially labelled as "*Limnonectes macrodon*", as noted by Dittrich et al. (2017), since this is almost a certainty.

6. *Pelophylax shqipericus*. - This species is not listed in the appendices of CITES but is in Annex D of the EU-WTR since 2009 because there was concern regarding the numbers imported into the EU, with monitoring of this trade warranted, and a distinct lack of a rigorous non-detriment finding (https://www.speciesplus.net/species#/taxon_concepts/5193/legal, see Suppl. Inf. 3).

7. *Telmatobius culeus*. - Commercial trade of the species was suspended in 2017, with listing in CITES Appendix I and EU-WTR Annex A. In the period 2010-2022, the CITES trade database indicates only two transactions: the import of 20 live individuals to Canada, and 150 live animals to the UK. In both cases, the animals were destined for zoos and sourced as

“farmed” from the USA. According to the IUCN SSC Amphibian Specialist Group (2020j), it is estimated that >15,000 animals/year are used to prepare frogs' legs.

Disease, pesticides and veterinary drug residues, genetic pollution

The farming and regional/international trade activities involving amphibian species for consumption purposes is associated with numerous risks. Here, we outline these more specifically.

Disease. - Evidence clearly demonstrates that the commercial trade of amphibians infected with pathogens contributes to the spread of diseases within and between countries, on a global scale, and involves species traded for food (Fisher and Garner 2007; Miller et al. 2011; Rodgers et al. 2011; Olson et al. 2013; O’Hanlon et al. 2018).

The intercontinental spread of two fungal diseases, *Batrachochytrium dendrobatidis* (*Bd*) and *B. salamandrivorans* (*Bsal*), has led to the decline of more than 500 amphibian species and currently more than 1000 species are known to be infected by one of these two emergent infectious diseases (Scheele et al. 2019; Monzon et al. 2020). The spread of infectious diseases may also be exacerbated by global warming (e.g., Lampo et al. 2006; Bosch et al. 2007; Seimon et al. 2007). With new climate projections, models predict expansion of *Bd* into new areas both in higher altitudes and elevations (Xie et al. 2016) which might impact with current farms in those areas. Other pathogens (e.g., ranaviruses) also could expand their range as a consequence of climate change (cf. Price et al. 2019), highlighting the need for better biosecurity measures in the commercial trade.

Interactions between ecological factors and amphibian-pathogen dynamics are extremely complex and pose major challenges for management decisions (Lips 2016; Bienentreu and Lesbarrères 2020). The commercial farming of anuran species poses challenges in terms of hygiene and proactive biosecurity and disease prevention measures. In the past (Kanchanakhan 1998; Zhang et al. 2001; Mauel et al. 2002; Weng et al. 2002), as well as more recently (Gilbert et al. 2013; Aktaş et al. 2019), many bacterial, viral, and fungal pathogenic diseases have been reported affecting mass-produced farmed frogs. A Mycobacterium-associated disease has been detected in *Hoplobatrachus rugolosus* animals in Vietnam that may pose a public health risk and highlights the need for improved biosecurity measures in the breeding and trade of frogs (Gilbert et al. 2013). Already in the 1970s (Andrews et al. 1977) and 1980s, *Salmonella* was detected in samples of frozen frogs' legs. Out of 304 samples, *Salmonella* was detected in 121 samples (39.8%), with 25.4% from India and 51.5% of the positive samples from Indonesia. In

France, frogs' legs are a significant source of *Salmonella* and are undoubtedly a source of multiplication (Catsaras 1984). In a long-term study 1990-1998, *Salmonella* of the serotype C1 was isolated of domestically available frogs’ legs from New York State previously imported from Indonesia (Heinitz et al. 2000).

Exports of *Pelophylax [Rana] esculentus* from Albania for consumption to foreign markets also revealed *Salmonella*, *Vibrio cholerae*, *Listeria* spp. and *Aeromonas* spp., the latter two being clearly more common (Vergara et al. 1999).

One internationally commercialised species for consumption is particularly striking: the North American bullfrog (*Lithobates catesbeianus*), a known vector of ranavirus detected in cultured specimens in South American exports to the USA (Galli et al. 2006; Miller et al. 2007; Schloegel et al. 2009), and the fungal disease *Bd* (Garner et al. 2006) translocated within farming operations in South America (Mazzoni et al. 2003) and in China and Singapore, where cross-infections from farmed individuals to native amphibians have been suggested (Bai et al. 2010; Gilbert et al. 2013). The danger that *L. catesbeianus*, as a carrier of *Bd*, can threaten naïve populations of other amphibian species has been emphasised by Rödder et al. (2013) who clearly highlight the link between the spread of *Bd* and bullfrogs. Also, novel chytrid genotypes have been identified and linked to the trade with *L.catesbeianus* (Schloegel et al. 2012). However, with regard to live imports of *L. catesbeianus* into the EU since 2016, the species is subject to a stricter legal regime, and has therefore been deleted from Annex B (http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R2029&from=EN, accessed March 2022, see Suppl. Inf. 3); in 2013 and 2014 *L. catesbeianus* listing in Annex B referred to the import of live specimens.

Two more species involved in the food trade (see Table 3, Suppl. Inf. 2) have tested *Bd*+: *Lithobates megapoda* (Frías-Alvarez et al. 2008) and Albanian populations of *Pelophylax epeiroticus* (Vojar et al. 2017; IUCN SSC Amphibian Specialist Group 2020g).

Challenges with regard to the spread of diseases with live animals intended for the food trade are multi-layered. On one hand, trade of live amphibians poses a potential risk of cross-infection into naïve wild populations via escape and contamination through waste water disposal. On the other hand, commercial breeding farms also pose risks of escaped animals and disposal of water and housing materials that can be carriers of pathogenic diseases. This demonstrates two predominant pathways for spreading pathogenic diseases: translocation and commercial farming operations (cf. Jaÿ et al. 2019; Travis et al. 2011). To what extent processed frogs' legs pose a hygiene risk (see issues described above) appears to be a largely understudied topic. However, skinned and frozen meat seems to present less risk with regard to the spread of infectious diseases such as *Bd* (Gratwicke et al. 2010). In the case of *Salmonella*, however, more care is needed to avoid contamination (Grano 2020) in any substrate, individual, or tissue, frozen or fresh.

Pesticide and veterinary drug residues in wild and farmed frogs. - We cannot provide comprehensive information on residues and effects (on the end consumer) of toxins used in regional agriculture and ingested indirectly (via the nutrient cycle) by frog species. Nor are we able to tease apart the effects of ingestion of veterinary cocktails of commonly used antibiotics, i.e., oxytetracycline and doxycycline (see Nguyen and Tran 2021) used in commercially farmed frog species for international consumption. Instead, we would like to illustrate existing health risks for humans as end consumers with a collection of circumstantial evidence. Many of the studies mentioned provide initial results of research projects, but many more follow-on studies do not exist due to the lack of interdisciplinary studies, opacity of supply chains, and distances and conditions of transportation of fully or partially processed frogs' legs.

Here we address the questions: (1) What are the most common habitat types and species that are captured for the international consumption trade?, (2) How are these habitats managed with regard to the use of pesticides, herbicides, and other agricultural chemicals?, (3) Do these agrochemicals negatively affect faunal assemblages and their ecosystems?, (4) Are these chemicals detectable in imported frogs' legs?, (5) Have veterinary drug residues been detected in aqua-cultured frog legs?, and finally, (6) Is there evidence that the consumption of frog legs contaminated with medicinal or pesticide residues can be hazardous to human health?

Probably the most common frog involved in the global frogs’ legs industry is Indonesian *F. cancrivora* (75% of reported species). This species is considered the most abundant frog species inhabiting rice fields in Indonesia (see Kusrini 2006, and references therein).

It appears that Javan populations of *F. cancrivora* are predominantly harvested for the international frog leg trade (cf. Kurniati and Sulistyadi 2017). The intense use of pesticides is prominent in Indonesia, and according to Ardiwinata et al. (2018), highest pesticide residues are found in Central Java. Quality of freshwater in terms of pesticide input and hence the contamination of semi-aquatic communities (e.g., amphibians), in rice plantations on Java, is problematic (Iskandar 2014). Disruption of the food web has led to an increase in populations and population densities of the brown locust (*Nilaparvata lugens*) which damages rice plantations and causes significant crop losses. West and Central Java farmers therefore feel compelled to use more pesticides and create their own mixtures of these chemicals (Prihandiani et al. 2021). The use of pesticides in various agro-ecosystems (incl. freshwater ecosystems) negatively affects food webs (see Relyea and Hoverman 2008), shifts species composition and abundance, and leads to severe declines of some species in these systems (cf. Pingali and Roger 1995 and references therein). Furthermore, exposure of frogs to pesticides also leads to an increased risk of infection due to the weakening of the immune system (Kiesecker 2011). According to Quaranta et al. (2009), absorption of herbicides such as atrazine through the skin of amphibians is "300 times higher than in mammals". Herbicides were found to negatively affect larval stages of *F. limnocharis* populations in Taiwan (Liu et al. 2011) and health status was likewise reduced in populations of *F. limnocharis* in pesticide-contaminated rice fields (as residues in soil and direct exposure) in the Western Ghats and Kerala (India) (Hedge and Krishnamurthy 2014; Kittusamy et al. 2014). A study by Kittusamy et al. (2014) also found pesticide residues in *F. limnocharis* and *H. crassus* that led to malformations in some individuals. However, other pathogenic influences besides pesticides as well as synergistic effects of pesticides are also considered to be causing these malformations (also see Wijesinghe 2012). The harmful effects of pesticides on anuran species have been confirmed in populations of *Pelophylax perezi* in France as well (Mesléard et al. 2016).

The question now arises whether pesticide residues or other toxins have been detected in traded animals or parts thereof for commercial consumption by humans. Information on the potential of bioaccumulation has rarely been analysed and more work is needed (Mani et al. 2021). It was found that some populations of pig frogs (*Lithobates* [*Rana*] *grylio*) harvested in south-eastern United States (for local consumption) contain a high level of mercury (Ugarte et al. 2005). According to a study performed by Turnipseed et al. (2012), drug residues could be detected in aqua-cultured samples of frogs' legs. The combination of different residues in the examined frogs' legs was striking, and lead to the conclusion that varying chemotherapeutic agents (including those harmful to human, e.g., chloramphenicol; Turnipseed et al. 2012) are apparently used indiscriminately in frog aquaculture. More recently, a study highlighted a variety of antibiotics applied at commercial frog aquaculture facilities in Viet Nam and uncontrolled dosage of drugs (Nguyen and Tran 2021).

The question of whether pesticide residues and other potentially toxic substances in frogs that are imported into the EU have been monitored could not be determined in the course of this work. This in itself is shocking, and in view of the situation in exporting countries and the lack of transparency and management in the application of agrochemicals and veterinary medicinal substances within commercial farms, we strongly recommend that this monitoring become an urgent near-future task for importing countries.

Genetic pollution. - In 2010, Holsbeek and Jooris reported that in the preceeding decade, humans translocated individuals of *Pelophylax* spp. either unintentionally (e.g., escaped animals from nurseries and markets) or intentionally (e.g., for stocking garden ponds and for local culinary harvest) almost everywhere they exist. A study conducted by Duresnes et al. (2018) showed that the presence of individuals of the *Pelophylax ridibundus* species complex derive from varying genetic lineages that correlate with registered frog leg industry imports in Switzerland, implying that individuals were also released/translocated for commercial purposes (regionally and internationally), revealing hybridisation events in several cases. Thus, the harvest of East European frog species involved in the frog-leg industry and subsequent introduction into western Europe has led to genetic pollution and threatens to damage their native congeners (Dubey et al. 2014; Dufresnes et al. 2018). It has also been suggested that the introduction of the invasive *P. kurtmuelleri* from the southwestern Balkans to southern Italy was also due to the frogs' legs trade (Bisconti et al. 2019).

Another example that does not explicitly address commercial trade of frogs' legs in the EU, but names taxa that are traded regionally for this purpose (see also Table 3), is the unregulated trade of frogs for ornamental ponds in Belgium. This has led to non-native *Pelophylax* spp. displacing native species or hybridising with them and is due to inefficient legislation at national and EU level, lacking regulation for the import of potentially invasive species (Holsbeek et al. 2010).

Furthermore, the commercial frog leg industry already contributes to the unintentional release of specimens into naïve habitats and displacing native species (e.g., Ribeiro et al. 2019 and references cited therein). Amongst these myriad species are American bullfrogs (*L. catesbeianus*), which, including their larval stages, detrimentally impact many other anuran species (cf. Kiesecker et al. 2011). Escapes of *Hoplobatrachus rugulosus* (originating from Thailand, referred to as "Thailand tiger frogs") have been reported, and are kept in Chinese frog farms and may lead to hybridisation with Chinese populations of *H. rugulosus* (referred to as "Chinese tiger frogs") (Yu et al. 2015). The authors suggest improving management of these farms to avoid further release of Thailand tiger frogs because a cryptic species complex is suspected, and thus species may unwittingly be driven extinct because they have not been recognised. These issues are also pertinent for other amphibian species complexes. For example, in the case of the Chinese Giant salamander, recent assessments show that multiple species exist across China, but farming and release of one of these species outside its range has virtually eliminated other Chinese Giant salamander species (Turvey et al. 2018; Yan et al. 2018; Lu et al. 2020).

Taxa traded with uncertain taxonomic status

The use and trade of species in their country of origin and whose taxonomic status is uncertain affects at least four species involved in the international frogs' legs industry as well. Among these, three are designated as species complexes (i.e., more than one species under one current scientific name) and species with unresolved taxonomy in IUCN Red List assessments. They are: *Fejervarya cancrivora*, *Hoplobatrachus tigerinus* and *Limnonectes blythii*. There are many other species complexes, wherein the taxonomy is extremely complex, and uncertainties are even more fraught with problems. In *Fejervarya moodiei*, for example, it remains unclear exactly to what free-living population this species should be assigned. In another two species (*Limnonectes grunniens* and *L. kuhlii*), where impact of international trade for frog legs has not been explicitly ascertained within their assessments (but is very high), taxonomy remains unresolved. In these species of *Limnonectes*, both their geographic range and number of cryptic species 'hiding' under one scientific name are still unclear (IUCN SSC Amphibian Specialist Group 2020e; van Dijk et al. 2004b). To what extent populations assigned to *L. kuhlii* are involved in the international frog leg industry is not indicated in the species' Red List assessment. Since all but two assessments are from 2004, *H. tigerinus* in 2008 and *L. grunniens* in 2019 (Table 3, Suppl. Inf. 2), recent research findings sometimes provide more clarity regarding the unsettled taxonomy of aforementioned species/taxa.

Of the three "species" that clearly represent complexes of many different species, we highlight what is known here, but reiterate that the dearth of data is staggering, considering that these are the most economically valuable species in terms of the known trade in commercial frogs' legs.

Fejervarya cancrivora. - An initial molecular analysis, six years after *F. cancrivora* was evaluated in the IUCN Red List (Yuan et al. 2004), revealed three geographically distinct clades/subclades: one confined to Bangladesh, Thailand, and the Philippines; another representing Malaysia and Indonesia (Greater Sundas); and the remaining one from Sulawesi (incl. one population in southern West Java, as a result of human introduction) (Kurniawan et al. 2010). A second study by Kurniawan et al. (2011) examined the species' morphological traits and crossing experiments through artificial insemination that resulted in three distinct taxa: 1) populations of West Java, peninsular Malaysia, and Bangladesh assigned to *F. cancrivora*, 2) populations from the Philippines and China previously referred to as *F. moodiei*, and 3) a new species endemic to Sulawesi. However, findings of a more recent study delimit *F. cancrivora* to Thailand, peninsular Malaysia, and Indonesia (Sumatra, Kalimantan, western and central Java, Bali), with introduced populations occurring in Papua New Guinea and Guam (Yodthong et al. 2019; and refs therein). According to Dubois and Ohler (2000) *F. moodiei* was not allocated to any known natural population. However, almost 20 years later, the species was validated and confirmed from mainly coastal areas of South Asia (eastern India, Andaman, and Nicobar Isl.,), East Asia (southern China), and Southeast Asia (Vietnam, Thailand, Myanmar, Malaysia, and the Philippines [Luzon Isl.]) (Yodthong et al. 2019; and references therein).

Clear taxonomy is the foundation of efficient and sustainable species conservation, and so is the naming of the species or parts thereof that are to be traded. Examination of 209 frozen frogs' legs sold in supermarkets in France listed exclusively as *Limnonectes [Rana] macrodon* (based on product labelling), revealed that almost all (206 of the 209 or 98.6%) were in fact legs of *F. cancrivora*, and only 2 (0.96%) could be attributed to *L. macrodon*, while one sample was revealed to be *F. moodiei* (Ohler and Nicolas 2017). Such forensic studies clearly highlight the importance of competent species identification, especially when it comes to evaluating current use in terms of sustainability, as the lack of such information precludes accurate monitoring of trade as a consequence of misidentification. Many more members of both the Dicroglossidae and Ranidae families are commercially involved in the frogs' legs industry, and their taxonomic status remains blurry at best.

Hoplobatrachus tigerinus. - in their Red List assessment, the authors indicate *H. tigerinus* reflects a species complex including an unknown number of morphologically very similar (cryptic) species (Padhye et al. 2008). This was confirmed by Hasan et al. (2012). Most recent research identified populations of *H. tigerinus* from Pakistan and Bangladesh as genetically identical to those from Nepal (Khatiwada et al. 2017), but genetically different from Indian populations (Akram et al. 2021). Clearly, this is a complex issue with much more clarity needed before the trade becomes sustainable.

Limnonectes kuhlii. - the taxonomic status of *L. kuhlii* associated with the species' currently known distribution range has been described as particularly uncertain within the Red List assessment (van Dijk et al. 2004b), and many more new taxa have been assumed with some revealing range-restricted distributions. Following genetic research, this complex now includes a minimum of 22 "distinct evolutionary lineages" (McCleod 2010). Again, the real biological entities that are involved in the commercial frogs' legs trade clearly are not well understood, much less studied to the degree to which we can provide realistic plans or guidelines for sustainable trade.

Ecological impact of trade

Sixteen of the 30 anuran species listed in Table 3 and Suppl. Inf. 2, (i.e., *Fejervarya cancrivora*, *Limnonectes blythii*, *L. grunniens*, *L. kuhlii*, *L. leporinus*, *L. macrodon*, *L. malesianus*, *L. microtympanum*, *Lithobates pipiens*, *Pelophylax bedriagae*, *P. caralitanus*, *P. kurtmuelleri*, *P. ridibundus*, *P. shqipericus*, *Rana amurensis*, and *R. chensinensis*) have commercial (regional) overharvest/overexploitation as a significant/main threat (both for food) indicated as assumed or known threat in their respective Red List Assessments. Species that were previously intensively exploited were not included (i.e., *Hoplobatrachus tigerinus* and *Leptodactylus fallax*), as former legal trade was banned in the mid-1990s (Padhye et al. 2008), and other utilization was banned since the 2000s (IUCN SSC Amphibian Specialist Group 2017). It is important to note that the conservation status of most species involved in the food trade (Table 3; Suppl. Inf. 2) is not up to date (53% or 16 species last assessed 2004-08), and reassessments of some species might indicate overexploitation, adding more species where commercial exploitation for international consumption is considered unsustainable.

Prior to export for international trade, a considerable number of live animals die on arrival to the processing facilities. For Indian exports, this loss has been estimated at 10-20%, in Indonesia it is 40-50 % because quality is not sufficient for export and some frogs are killed prior to being exported (Niekisch 1986, and references therein). Information on pre-export mortality rates in countries of origin were not easy to obtain within the scope of our study. These figures are also relevant when it comes to evaluating the ecological impact of harvest, and more clear understanding of how these losses could be lowered would benefit both the people involved in the trade and the frog populations.

Initial reports on the sustainability of this trade were published more than 20 years ago, however large-scale ecological studies to assess offtake rates and their sustainability appear severely lacking. Here, we highlight studies that indicate amphibian declines associated with harvest for the food trade both regionally and internationally. Historically, overharvest was detected in Californian populations of *Rana aurora draytonii* (Jennings and Hayes 1985). In Florida, harvest regimes of *Lithobates [Rana] grylio* affect population structure and survival rates (Ugarte 2004). The increasingly intense regional harvest of frogs in West Africa, particularly in Nigeria where trade has moved across borders (e.g., Benin), clearly demonstrates overexploited species and populations (Mohneke 2011). The harvest of populations of *Quasipaa spinosa* in Hong Kong is also detrimental to populations in the long-term (Chan et al. 2014). Below, we highlight case studies that report on overexploitation of species/populations from Indonesia and Turkey involved in the international commercial trade.

Indonesia. – In 2005, Kusrini noted that current harvest levels of *Fejervarya cancrivora* and members of the *F. limnocharis-iskandari* complex (*F. iskandari* was separated from the *F. limnocharis* complex through allozyme data; Veith et al. 2001) appear to be sustainable, however offtake of *Limnonectes macrodon* may detrimentally affect populations more than those of *F. cancrivora*.
The majority of frog hunters in East Java reported that the number of harvested frogs has decreased and this was also perceived by middlemen (in West and East Java), and exporters, who argued that depending on the season, supplies were sometimes scarce (Kusrini and Alford 2006). To explain declines in frog populations, hunters reported a combination of three reasons, *"1) increasing numbers of harvesters; 2) increasing numbers of middlemen, allowing harvesters to go to other middle-men; and, 3) habitat change, as more rice fields have been developed for other uses"* (Kusrini and Alford 2006). However, overharvest synergistically promotes decline of amphibian populations happening simultaneously from habitat loss and degradation, pollution, disease, and invasive exotic species (Kusrini 2007).
Several regional field studies have been conducted in Indonesia to assess population densities of frog species involved in the food trade, and these clearly show these synergistic effects. In a 20x20m paddy field in West Kalimantan, the density of *F. cancrivora* was measured at 1.01 individuals/m^2 (Saputra et al. 2014). According to Iskandar (2014), populations of *Limnonectes blythii* in West Sumatra have largely been decimated by export of frogs' legs (though once again monitoring is absent) and hence the harvest of populations has shifted to other provinces like Riau, Jambi, and South Sumatra. The Karawang district, on the other hand, is the largest producer of frog meat in West Java. In order to determine the sustainability of hunted populations of *F. cancrivora*, in May 2016 an approximately 10-day population survey was conducted in a rice field in eastern Karawang. Average density for juveniles was 0.33 individuals/m^2, 0.04 for subadults, and 0.005 for adults. In contrast, average density in watered paddy fields was 0.89 individuals/m^2 for juveniles, 0.08 for subadults, and 0.01 for adults (Kurniati and Sulistyadi 2017). Depending on the season and the status of the rice fields (state of cultivation, amount of water), an average of 3-10 kg of adult frogs can be caught per night since frog hunters have an agreement not to capture juveniles and subadults to maintain viable breeding populations (Kurniati and Sulityadi 2017). Populations of *F. cancrivora* in the rice fields of the Karawang region are considered unhealthy, most likely due to unsustainable exploitation, and setting export quotas for frogs' legs should be done with care (Kurniati and

Sulityadi 2017). The main threat to *F. cancrivora* is the large-scale harvest for trade and consumption, although habitat destruction and degradation also play a role and further impair population recovery following collection of individuals from the wild (Amin 2020).

Limnonectes macrodon is also regionally impacted and preferred for their better taste (compared to *F. cancrivora*; Kusrini and Alford 2006). In addition, *L. macrodon* has slower reproduction rates, [~1000 eggs per clutch (Iskandar 1998) as opposed to >18,000 eggs in one spawning for *F. cancrivora* (Saputra et al. 2014)], and is therefore more vulnerable to overharvest. According to Ohler and Nicolas (2017), populations of *L. macrodon* are in rapid decline.

Turkey. – Overharvest of frog populations in Turkey (intended for export to France, Italy, Greece, Spain, Switzerland, and Lebanon) has been reported by Şereflişan and Alkaya (2016), who note that individual frogs had a reduced weight due to overharvest, and that had a negative effect on the export value. Regional overharvest in Turkey has been shown for *Pelophylax caralitanus* populations in southwestern Anatolia (Erismis 2018).

A very recent study, by Çiçek and others in 2021, on the sustainability of Anatolian water frogs, is by far one of the most comprehensive studies to analyse commercial trade in frogs' legs for the EU market. In 2013-2015, >13,000 *Pelophylax* spp. (cf. Red List assessments of *Pelophylax bedriagae, P. caralitanus,* and *P. ridibundus*) from two regions were tagged for population and density estimation. A population viability analyses was conducted over a 50-year period based on catch and export data from Turkey. If this trade were to continue at the same harvest rate, extinction risk would be 90% in 50 years, affecting two to five species of the *Pelophylax* species complex (Çiçek et al. 2021, and references therein). Accordingly, a reduction of harvest rates would be advisable in order to be able to ensure the viability of these frog populations and a long-term source of income for the harvesters/frog catchers (Çiçek et al. 2021).

DISCUSSION

During the course of this study, it became clear just how difficult it is to obtain concrete data on the current international trade in frog legs. Specifically, relevant data are scattered across different unconnected databases (e.g., national databases, FAO, EUROSTAT, or information/services that can only be obtained/provided via payment, e.g., Infofish International (http://infofish.org/v3/, Suppl. Inf. 3). Another problem is data reliability with the competence of sourcing agencies and institutions having conflicts of interest and little expertise in frog identification. While the USA primarily imports live frogs and frog products for human consumption originating from frog farms, frogs and their processed legs imported into the EU are mostly sourced from the wild. The EU trade also includes far more species than are officially declared, potentially including many cryptic species of conservation concern.

Our findings highlight the central role of the European Union as the main importer of frogs' legs derived from wild individual anuran populations, the urgent need for stricter trade regulations, better monitoring and data integrity to prevent further declines of wild frog populations, and help create a more sustainable commercial trade.

A long road to EU accountability

The high uncertainty of the assumed number of individual frogs within total imports throughout the study period impressively illustrates the opacity of the trade. Actual harvest numbers imported into the EU for annual consumption remain unknown and very difficult to quantify. This is undoubtedly due to the fact that they are non-CITES species and thus international trade data (species/volumes) remain undocumented. Listing species in the appendices of CITES is justified when international trade poses a severe threat to the conservation status of a species. The scientific authority of a CITES member state must review the harvest/export for Appendix II in terms of compatible offtake numbers/quotas in order to maintain the species' ecological function in its native habitat (https://cites.org/eng/disc/text.php#IV, accessed May 2022, see Suppl. Inf. 3). Complete transparency of annual quotas and the quantification of numbers of individual frogs per kilo must be ensured if a kilo value is to represent the number of affected individuals. It remains unclear for what reasons the calculations of the number of individuals per kilo have been reduced by seven animals as of 2018 (Table 2), and we remain skeptical of these numbers.

Anurans involved in the international frogs' legs trade are all r-strategists, which means that they have large numbers of offspring, a rapid developmental rate, and a high reproductive output. This also makes these species more amenable to regular (monitored) harvest while remaining viable. However, r-strategists also define themselves in having highly variable population sizes over time and mortalities may be density-independent or even catastrophic (Pianka 1970). Despite relatively high individual densities of some species in agroecosystems, regular removal of thousands of individuals still raises questions about the extent that the ecosystems can compensate for this intervention. For example, negative ecological shifts may have already occurred (e.g., can ecologically more flexible species outcompete more specialised species? and how have populations of insect pests been affected by fluctuations in frog populations?). There is also no doubt that trophic interactions in certain agro-ecosystems such as rice fields are very complex, and we still do not have a grasp at the main drives of the complexities. For example, type of cultivation and human impact can have strong impacts on biodiversity. Abrupt regular removal of rice plants in a wet paddy, for instance, results in a considerable sudden loss of energy for the entire biotic community (cf. Bambaradeniya et al. 2004). A decline in pond frogs (*Pelophylax nigormaculatus*) in rice field-dominated landscapes in Japan has been noted as a result of the modernisation of drainage systems which also led to the decline of the grey-faced buzzard (*Butastur indicus*) (Fujita et al. 2015). It is clear that human impacts on nutrient supply and food web structure have strong and interdependent effects on biodiversity and ecosystem functioning, and it is therefore essential to monitor/ these both (see Worm et al. 2002).

These considerations may, however, be too complex to be actively explored within the framework of the EU. We highlighted that there are many internationally traded species/species groups with sales in the EU where unsustainable trade has been detected (cf. Symes et al. 2018), that could be regulated more easily. Governmental priorities within transnational cooperation projects should develop common methodological approaches that include genetics (species identification and origin) and biosecurity measures to prevent the spread of disease.
But in the context of amphibians that are e.g., imported live into the EU for the exotic pet trade industry among which many are traded that are also known to be infected with *Bd/Bsal*, (see Wombwell et al. 2016; Nguyen et al. 2017; Fitzpatrick et al. 2018) even here biosecurity measures prior to the import into the EU (incl. non-EU- European States) have not been implemented to prevent cross-infections, despite the fact that *Bd* was listed as a notifiable disease by the World Organization for Animal Health (OIE) in 2008 (Schloegel et al. 2010), and *Bsal* in 2017 (https://www.oie.int/app/uploads/2021/03/a-bsal-disease-card.pdf, see Suppl. Inf. 3).

IUCN Red List assessments

Required data for the IUCN Red List are crucial for assessing the conservation status of species. In Red List assessments, trade in a species can either (1) be mentioned at the national/ international level, (2) go unmentioned (despite the fact that trade occurs) or, (3) if mentioned, in some cases be designated as an acute threat to a species/population. In such cases, it is particular problematic when Red List assessments are up to 18 years old (Table 3, Suppl. Inf. 2, 4), and for species utilized domestically or traded internationally where overexploitation was already identified in 2004, but the impact on the local populations have not been well assessed (e.g., *Limnonectes blythii*, *L. kuhlii* or *L. malesianus;* see Table 3).

Taxonomic uncertainties, interbreeding

Several *Pelophylax*, *Limnonectes*, and *Fejervarya* spp. are morphologically very difficult to distinguish and many taxa are taxonomically treated as cryptic species complexes (see Bickford et al. 2007) within their genera (Kurniawan et al. 2011; Dufresnes et al. 2018; Yodthong et al. 2019). Therefore, challenges of quantifying actual harvest of each species are substantial if these taxa are harvested in the hundreds of thousands to millions of individuals per year. Accurate identification of species is the foundation for any management plan, and trade and conservation need to go hand in hand. Disregard of this basic knowledge and trading activity can cause fundamental damage to the species and, in the worst case, to respective ecosystems (Estes et al. 2011). Unfortunately, it is precisely this taxonomic uncertainty that is exploited by companies, for example, as done in Turkey, labelling frogs as the hybrid *Pelophylax esculentus* which does not occur in Turkey but does in other parts of Europe (Çiçek et al. 2020). Evidence provided by genetic methods could reveal incorrect labelling in Indonesian exports of frozen frog's legs destined for European markets with packages indicating *Limnonectes [Rana] macrodon* rather than as *Fejervarya cancrivora*, but rigorous assessments of accuracy of species identification have not been conducted (Dittrich et al. 2017; Ohler and Nicolas 2017). In 2001, Veith and colleagues could separate *F. iskandari* as a valid species from the *F. limnocharis*-complex through allozyme data. Another clear example is *F. iskandari* (restricted to the island of Java) which was previously traded undetected within the *F. limnocharis*-complex (Kusrini 2005) and could be negatively impacted by overharvest. Apart from these examples of harvested taxa included in species-complexes with uncertainty in their taxonomic status (e.g., Holsbeek et al. 2008; McLeod 2010; McLeod et al. 2011; Dehling and Dehling 2017; Yodthong et al. 2019; Stuart et al. 2020), introduction of exotic species that interbreed with closely related species or crossbreeding incidences of farm escapees into other ecosystems (Yu et al. 2015), may lead to a replacement of formerly native species (cf. Leuenberger et al. 2014). In addition to these concerns is the potential for an invasive species (e.g., *Lithobates catesbianus*) to become a driver of ecological trophic cascades in naive ecosystems (e.g., Gobel et al. 2019). Such issues are well known from other taxa, yet the lack of monitoring and the number of cryptic species underscores the under-appreciated risks associated with hybridization of these as yet unrecognized frog species. Species identification of skinned or frozen frogs' legs is impossible without genetic techniques, thus mislabeling may not have been strategic, but an indication that processors and exporters in Indonesia are not trained in frog species identification. This knowledge was not considered a prerequisite for the export of frogs' legs, and as there are no strict checks, the trade of potentially misidentified species has been allowed to continue. More concerningly, it may also be that maintaining consistent supplies would not be possible if adequate scrutiny of what is in the trade, where it is from, and how availability fluctuates, are taken into account. In fact, it must be clearly emphasized that the prerequisite, "we only use/trade what we know", has not yet been met and relevant stakeholders (including government agencies) have not made an adequate effort to address this issue.

Ecological impact and economic uncertainties

Sustainable international trade can only be ensured if the use and movement of species within national borders is managed in such a way that species or populations maintain their viability and do not show shifts in physical traits due to bias in selection of key traits (cf. Leader-Williams 2002). In fact, differences in body size in intensely harvested populations of *Lithobates [Rana] grylio* are probably due to selective harvesting pressure on larger size classes (Ugarte 2004). Kusrini (2005) found that body sizes of captured adults are smaller than those of the same species in other un-harvested regions, and capturing larger adults may lead to lower recruitment rates. Similarly, the pronounced sexual dimorphism in species attractive to hunters (e.g., *F. cancrivora* and *L. macrodon)*, leads to reduction in the number of those larger individuals. According to Kusrini (2005), one important criterion for monitoring is the recording of body size. These worrying but prescient data from 17 years ago do not seem to have been properly considered until now, and viability of harvested frog populations has largely been overlooked.

In this context, governments are called upon to use resources in an adaptive and sustainable manner. Furthermore, EU commitments to Environmental impact Assessments (EIAs) of imported wildlife mean that the EU is obligated to monitor what is in trade as well as the impact it is likely to have on source populations. As soon as the species triggers international demand and sales, importing countries are equally held accountable to take responsibility, whereby relevant stakeholders must ensure that their consumption of exotic species does not lead to population declines. Clearly, this will entail other anthropogenically induced threats affecting these species/populations (e.g., Chen et al. 2019). It is worrying to note that there are very few studies reviewing current trade in terms of sustainability and the little information that is published, implies very strongly that current harvest /trade is unsustainable. For example, populations of *Pelophylax caralitanus* are still locally widespread in Turkey, but the species is considered endangered (Ǒz et al. 2009), not only because of habitat loss, but also because of local overexploitation for trade with the EU (Erismis 2018; Çiçek et al. 2021). Further, overharvest of *P. shqipericus* has been noted in the species' Red List assessment (IUCN SSC Amphibian Specialist Group 2020h), and the unsustainable trade of this species has been highlighted (Gratwicke et al. 2010). However, populations of *P. shqipericus* in Albania (core distribution of the species) have not yet been considered within a conservation management plan (Eco Albania 2019).

Numerous examples of overexploited species assessed in the IUCN Red List assessments are detailed (see Table 3, Suppl. Inf. 2, 4) and examples of unsustainable trade at the regional level (e.g., in western Africa and that of species and species complexes in Southeast Asia) have also been presented. However, there is a severe shortage of established field studies (cf. Auliya et al. 2016; Morton et al. 2021) over longer periods of time to provide not only snapshots of single localities, populations, and their harvest status, but also long-term studies (e.g., use of pesticides and potential residues on populations in trade, impact of local population declines, if populations can maintain their role as pest control, etc.).

According to Raghavendra et al. (2008) comprehensive ecological field studies in India investigating the function of anuran communities and their control of pests such as mosquitos are still in their infancy. Local knowledge in West Java (Indonesia) reveals that at least *Fejervarya limnocharis* is perceived in functioning as pest control (Partasasmita et al. 2016).

A two-year field study in the Philippines compared prey items of the native Luzon wartfrog (*Fejervarya vittigera*) with that of the introduced cane toad (*Rhinella marina*) to determine the proportion of rice pests in their diets, and which of the two species was more efficient feeding on rice pests. It turned out that the proportion of pests eaten by *F. vittigera* was significantly larger than that of *R. marina*, which mainly preyed on beneficial arthropods in the rice-ecosystems. The authors conclude that adult *F. vittigera* may provide effective pest control services and suggest protecting and promoting *F. vittigera* populations (as opposed to reducing *R. marina* populations) to minimize the use of insecticides (Shuman-Goodier et al. 2019).

Is frog farming a sustainable alternative?

Due to problems of sustainability caused by the removal of species from their ecosystems (see Table 3), various authors suggest a focus on commercial frog farming (e.g., Şereflişan and Alkaya 2016; Nguyen 2017; Ribeiro et al. 2019). Indeed, commercialisation of frog farming appeared to be the way forward for a promising industry in many countries (first attempts breeding *Lithobates catesbeianus* in the US and Canada are dated before 1900), but continuing efforts to implement these plans have proved less successful (Helfrich et al. 2009; Dodd and Jennings 2021). Such ventures have been discouraged since the 1930s and many problems (e.g., live food and water quality availability, risk of spreading disease, slow mass increase or growth, and economic start-up constraints) were known to the early proponents of such ventures. However, because investments are relatively low and profits can be many times higher, this branch of business creation continues.

Globally, *Lithobates catesbeianus* is the most widespread species involved in farming operations and has been introduced for the purpose of commercial farming into more than 40 countries (FAO 2021).

In other parts of the world, initiatives to commercialize frog farming are also being publicized as a result of increased demand. For example, under EU funding, the CaPFish Capture and Aquaculture programmes were launched to promote aquaculture in 10 provinces of Cambodia, primarily to promote food security in line with national government plans for fisheries development. Specifically, the Minister of Agriculture, Forestry, and Fisheries, "Veng Sakhon", encouraged farmers to raise frogs due to an increased market demand (https://en.khmerpostasia.com/2020/10/16/frog-farming-encouraged-as-market-demand-rising/, accessed, June 2022, see Suppl. Inf. 3). However, this programme is explicitly designed for national needs, not international export.

Likewise in Thailand, establishment of commercial frog breeding families has been described, and limited for national consumption (Pariyanonth and Daorerk 1995).

A major problem underlying establishment of commercial frog farming facilities is that there are no international standards or hygiene guidelines (see Dittrich et al. 2017). In some of EU's major supplying countries, i.e., Vietnam, frog farms remain being insufficiently controlled (Nguyen 2014; Nguyen and Tran 2021) implying that no health controls are imposed on farms and processing into frogs' legs, as well as testing for disease. As a result, the risk of international trade spreading diseases such as ranavirus and *Bd* into naive amphibian populations is ever-present (cf. Gratwicke et al. 2010; Gilbert et al. 2013). However, unfavourable conditions are present, e.g., the lack of appropriate management measures, resulting in the (unintentional) release of disease-infected *L. catesbeianus* into the environment of supplier countries (cf.

Ribeiro et al. 2019). Species escaping from breeding farms may also hybridize with congeners, and here the problem of genetic pollution needs to be addressed.

An additional complicating factor for international control is that species harvested for frogs' legs are exclusively non-CITES species, implying that there is no documentation across international borders.

Conclusions and Recommendations

The complexity of issues underlying the frogs' legs trade is not a priority policy item for the EU, despite several important issues reviewed herein. This strongly suggests that the EU, as the main consumer of wild harvested frogs' legs, has deliberately shirked responsibility in addressing the many issues facing the frog's leg trade. The important precondition for such trade must be that consumers in the EU can have a guarantee that their actions will not contribute to the decline of species they consume or cause the spread of pathogens to native species. However, to achieve this goal, all stakeholders have to work together to remove existing loopholes and implement new regulations to control the trade in the foreseeable future. Full transparency of current supply chains, including information on sourced populations or commercial breeding farms, is also critically needed. Otherwise, we suggest temporarily suspending trade in certain species until such data are available and assurances made by all stakeholders. These measures result from the uncertainties highlighted here and are to ensure maintenance of viable populations in the countries of origin. Accompanying these should be awareness campaigns and education to help foster information for consumers to help them make decisions. The role of the EU should therefore be guided by the problematic conditions of this trade (unclear taxonomy, unsustainable offtakes, no disease control/biosecurity measures, reintroduction of exotic and invasive species and lack of a centrally established checkpoint for imports into the EU) in order to develop a more responsible and sustainable framework of the frogs' legs trade. The only measure the EU has in place for non-CITES species at present is TRACES, and it generally fails to list species. In addition, the World Trade Organization (WTO) does not require that amphibian species be clearly listed in trade, making it almost impossible to monitor.

One fact in particular became clear in this review: the lack of knowledge about species conservation and factors to promote implementation of sustainable harvest. The establishment of strictly supervised commercial farming according to industry-set protocols and hygiene measures, (especially in the main supplier countries), and the difficulty in implementing these, is ignored by the EU. On both sides of the trade, short-term economic benefit is more important than long-term sustainability of the trade itself. Unsustainable trade prevents continued harvest and therefor, long-term economic viability, and ultimately ecological costs will also mount unrealized until severe non-linear results accrue (e.g., crop failure due to pest outbreaks because predators are gone, as in India in the 1970s). This observation is particularly sobering because the international trade in frogs' legs has been ongoing for decades (Le Serrec 1988; Warkentin et al. 2009; Altherr et al. 2011).

It is irrefutable that the international frogs' legs trade into the EU is riddled with uncertainties (no biosecurity measures, species identity is opaque, reported source is absent or doubtful, etc.). The EU, as the main consumer of frog's legs, does not assume any obligation to responsibly solve problems listed in this review, but herein is challenged to address the problems identified. We can only presume that many departments and agencies within the EU are aware of the extreme complexity of this trade with its diffuse network and various databases, but clearly put economics before the conservation of natural resources or the long-term benefits and livelihoods of people involved in the trade internationally.

Gratwicke et al. stated in 2010 that additional CITES listings could help reduce negative impact of international commercial trade. As stated earlier, IUCN Red List assessments of several trade-relevant anurans highlight the need for improved monitoring and creating a more regulated trade. Intensively traded species should also be re-evaluated for IUCN Red List status at more frequent time intervals in order to add up-to-date information on the conservation status of vulnerable species. More specifically, we propose that the IUCN SSC Amphibian Specialist Group designate a new working group that monitors and evaluates the conservation/threat status of particularly intensively harvested/traded species involved in the frogs' legs trade at regular annual intervals. This information is critical to be implemented into CITES for timely decisions.

The increasing incidence of infectious diseases (both within a species as well as zoonotic spillovers) via the wildlife trade correlates closely with the loss of biodiversity in source countries and is considered a worrying environmental problem that must be counteracted as a matter of urgency (see Kiesecker 2011).

More science required

Modern innovative scientific methods are required to ensure a fully transparent, legal, traceable, and sustainable trade. We will need to implement scientific methodologies to distinguish farmed vs. wild individuals (cf. Dittrich et al., 2017) and to obtain sufficient data on all source populations to ensure that harvest levels fall below annual population replacement levels. Basically, taxonomic uncertainties need to be clarified and the formation of specific research groups (e.g., taxonomists, field ecologists, experts of current legal frameworks, etc.) is highly recommended.

To prevent the spread of infectious diseases, biosecurity measures need to be established at distinct points along the trade chain. Interestingly, such measures were already proposed at the 37th Standing Committee of the Convention on the Conservation of European Wildlife and Natural Habitats, in December 2017 (https://rm.coe.int/recommendation-on-biosafety-measures-for-the-prevention-of-the-spread-/168075a4b0, accessed May 2022, see Suppl. Inf. 3), but never implemented. Therein, recommendation No. 197 refers to "biosafety measures for the prevention of the spread of amphibian and reptile species diseases". This document lists 10 recommendations for contracting parties, none of which include information on species traded either alive or processed for the frogs' legs trade. The majority of recommendations encourage support for increased research. However, recommendation 5, "*Using the most appropriate legal framework, and at the earliest opportunity implement immediate restrictions on the amphibian and reptile species trade when an emerging pathogen spread with significant impact on wild populations has been identified until necessary preventive and management measures are designed, based on evidence, throughout the entire commercial chain*", does not reflect an expansion of the regulatory framework but describes a direct suspension of trade in an infected species. With regard to the prevention and spread of known diseases identified by OIE (such as *Bd*), we reference a document from 2015 by the Standing Committee to the Convention on the Conservation of European Wildlife and Natural Habitats on the Recommendation on the Prevention and Control of the *Bsal* fungus (https://rm.coe.int/1680746acf, accessed May 2022, see Suppl. Inf. 3). The implementation of these recommendations, however, cannot be verified. The need for supervision of hygiene and veterinary inspections for edible frogs (also those farmed and are non-native) in the Asian region has been indicated (Grano 2020; Borzée et al. 2021), given the tight links observed between market locations and detection of *Bd* in wild amphibian populations.

Hardouin (1997) indicated that authorities in countries that import frogs' legs should be encouraged to regulate international trade more closely by banning products that cannot be sourced from farms where they are subject to official controls. He further notes that Europe cannot ignore risk of wild harvests that may lead to declines in local frog populations as a result of overexploitation. We also recommend the listing of some if not all species in trade on CITES

App. II. International trade should be regulated for those species that are already documented in an IUCN Red List threat category and those for which there is published evidence that trade has depleted local or regional populations. Taxa in species complexes whose morphological differentiation is not readily possible or are processed only as frogs' legs are particularly vulnerable, so standardised use of molecular approaches to verify and monitor trade would be particularly useful.

Results outlined in this review provide strong clear recommendations for both source and consuming countries. Promptly counteracting abuses in the international trade of frogs' legs by adapting existing legislation and applying the precautionary principle to prevent irreversible damage to populations or species will help to promote the sustainability of the trade in the long-term. Recommendations for source and consuming countries are listed separately below.

We recommend that source countries should:

- conduct field surveys at comparative study areas to estimate size and trends of wild frog populations and of the impact of harvest for both national consumption and international trade.
- validate species identity through centralised authorities to check and certify trade exports through the use of genetic tools
- include analyses of trade data and standardize documentation of volumes (number of individuals must be considered, not an estimate of the number of individuals by means of weight).
- establish long-term field studies in selected areas (where regular harvest takes place) to assess biotic communities in relation to the application of pesticides.
- make non-detriment findings (NDFs) a result of CITES listings at regular time intervals
- examine the domestic/national use of frogs' legs versus exports to decipher the complexity of this resource use and improve equity and fairness within each source country.
- study mortality rates of frogs in transport and processing prior to export. When identifiable loopholes exist, source countries should make every effort to minimize mortality and economic loss.
- accurately and regularly verify harvest rates, including both local as well as harvest for international trade. As highlighted earlier, it has been estimated that offtakes of edible

frogs on a national level can be seven times as much as that of annual exports (Kusrini 2005).

- establish conservative but reasonable harvest and export quotas based on high quality data for targeted species/populations and taking into account other threats that affect species/populations.
- ban harvest during the mating season. Specific management measures have been highlighted for the harvest of *Pelophylax* spp. in Turkey and claim, "that further harvest restrictions are essential for the sustainability of Anatolian water frog populations" (Çicek et al. 2020).
- evaluate and implement adaptive management measures for all harvested species, i.e., the ban of certain size classes for a given period/season as a default to help insure sustainability.
- define and implement stricter regulations for farming operations to ensure closed systems, prevent re-stocking from the wild, release of farmed animals back into the environment, as well as avoid farming of non-native species when possible.
- register and monitor all export companies and their suppliers, and require that exporters identify processed frog products by DNA analysis.

Consumer countries have the obligation to take appropriate responsibility for the consumption of a resource. Accordingly, it would be obligatory to transparently inform relevant societies on which information basis trade is permitted.

We recommend that consumer countries should:

- implement a centralized database to document all imports of all wildlife and list species and quantities in the Annexes of the EU Wildlife Trade Regulation, using the LEMIS database as a model.
- list all species in trade in CITES to regulate international trade and enforce restrictions.
- implement NDF's for the import of species from the wild, regardless of CITES status.
- provide captive breeding guarantees for species claimed to be of captive origin.
- push for improved standards (based on revised guidelines), such as import bans on wild harvested species that have been evaluated in one of the IUCN Red List threat categories.
- impose trade suspensions if trade data are not provided in full transparency.

- check all imports for pesticides and other pollutant residues.
- assist range states in conducting surveys of wild frog populations and to create a biobank with references samples from species/populations of major harvest regions to cross-check genetic identities of shipments imported.
- conduct random DNA analysis of frogs' legs shipments to determine if shipment labelling is correct and ban imports for persistent mislabelling.
- allow only positively identified, skinned, processed, and frozen frogs' legs to be imported to avoid the introduction and spreading of diseases and invasive species.
- rigorously catalogue all imported species with standards parallel to those implemented under LEMIS.
- improve regional monitoring schemes with joint-efforts between stakeholders and governments to bolster the sustainability of the trade along multiple facets.

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