



The magnitude of legal wildlife trade and implications for species survival

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The unsustainable use of wildlife is a primary driver of global biodiversity loss. No comprehensive global dataset exists on what species are in trade, their geographic origins, and trade's ultimate impacts, which limits our ability to sustainably manage trade. The United States is one of the world's largest importers of wildlife, with trade data compiled in the US Law Enforcement Management Information System (LEMIS). The LEMIS provides the most comprehensive publicly accessible wildlife trade database of non-the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) listed species. In total, 21,097 species and over 2.85 billion individuals were traded over the past 22 y (2000–2022). When LEMIS data are combined with CITES records, the United States imported over 29,445 wild species, including over 50% of all globally described species in some taxonomic groups. For most taxa, around half of the individuals are declared as sourced from the wild. Although the LEMIS provides the only means to assess trade volumes for many taxa, without any associated data on most wild populations, it is impossible to assess the impact on biodiversity, sustainability of trade, or any potential risk of pest or pathogen spread. These insights underscore the considerable underestimation of trade and the urgent need for other countries to adopt similar mechanisms to accurately record trade.

biodiversity | sustainability | trade | extinction | unsustainable

Wildlife Trade Data Remain Fragmented and Incomplete

The overexploitation of wildlife is one of the greatest global threats to species survival (1). Recent studies have revealed that the size and scope of the legal wildlife trade far exceed previous assessments, and misunderstanding of the trade's magnitude hampers decision-makers' ability to gauge the impacts of trade on species survival and tailor targeted policies (2–6). For the majority of legally traded species, we have no data to assess whether trade is sustainable at local, regional, or global scales (5). Much of our knowledge on global trade relies on the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which tracks and regulates international legal trade in certain species to reduce the risk of overexploitation for vulnerable species. Although a valuable data source, CITES only tracks a listed subset of species, and multiple analyses have identified key limitations of relying only on CITES data for decision-making. CITES does not catalog the majority of species across multiple key groups, including songbirds, reptiles, amphibians, fish, or arachnids, and consequently many traded species remain undocumented by CITES (2–4, 7, 8).

A lack of globally standardized legal trade data makes identifying trends and drawing inferences a time-intensive process fraught with uncertainty (9). Inconsistencies in wildlife trade datasets frequently lead to misinterpretations of trade data, which is a critical challenge in accurately assessing the impact of wildlife trade on biodiversity and conservation efforts (10, 11). The overreliance on taxonomically narrow data sources like the CITES database, or regional databases such as the EU's Trade Control and Expert System (TRACES (12)) or US Law Enforcement Management Information System (LEMIS), (13) limits our understanding of global wildlife trade and its role driving biodiversity loss. While some countries do record wildlife imports and exports and are responsible for the trade of wildlife through their countries, assessing sustainability of trade of non-CITES species is impossible without collation and sharing of such data. The essential data needed to inform trade regulation for conventions such as CITES simply do not exist for the majority of taxa potentially threatened by unsustainable trade (14).

Significance

The majority of wildlife in trade is traded legally, yet for most species, there are no data on their trade, meaning that we can only estimate how many species are traded. The United States is one of the world's greatest wildlife importers and the only country to collate and release comprehensive wildlife trade data. From the 22 y assessed almost 30,000 species, and over 2.85 billion individuals were recorded, with around half individuals in many taxa coming from the wild. This analysis assesses a wider array of taxa than previously considered, vastly exceeding former estimates of trade in many groups and highlighting the urgent need for standardized collation of trade data to provide the data essential for sustainably managing trade.

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Without more accurate and representative data, we have no way to reliably identify vulnerable wildlife populations that may be most susceptible to the impacts of high levels of international trade, no knowledge of where to most efficiently and effectively direct sustainability interventions, and no idea who to engage in the codesign of such interventions, especially around sourcing (15). Although particular industries, such as fisheries, now collate more comprehensive data to enable more sustainable management (and adhere to regulations and quotas), the majority of types of wildlife trade such as the exotic pet trade, medicinal trade, or even elements of fashion trade lack comprehensive and usable data (16). Understanding the sustainability of trade requires going beyond trade statistics to consider the provenance of species, which could allow researchers to establish a link between harvesting practices, the status of wild populations, and local socioeconomic benefits (17). Direct exploitation of wild populations (where such data exist) is estimated to drive average population declines of 62% in terrestrial mammals, birds, and reptiles, but only a tiny fraction of species in trade have any form of population assessment (18).

The United States is a major global market for wildlife and is one of the only countries that collates and releases wildlife import data across all taxa in trade, allowing unrivaled insights into global trade dynamics, given the lack of standard national collation of such data internationally (19). The US Fish and Wildlife Service's LEMIS records the volumes and origins of wild animals and plants imported into the United States for internal law enforcement purposes (6, 20). Although the LEMIS contains some inaccuracies, including the inevitable errors of a database of this size (21), and may underrepresent the number of species in trade due to aggregating some species data through harmonized codes (6, 22), it remains one of the most comprehensive wildlife trade databases. LEMIS data contain details on the declared provenance of wildlife (e.g., captive bred, taken from the wild), the quantity imported and exported, and more detailed trade purpose. US wildlife import and export regulations for non-CITES species are restrictive, especially compared to other markets, such as those in the European Union. The tighter restrictions within the United States are partially due to the Lacey Act, which prohibits the import of wildlife collected illegally (23), in addition to restrictions under the US Endangered Species Act, US Marine Mammal Protection Act, and the US Wild Bird Conservation Act (which largely lack equivalents elsewhere) (24).

Assessments of trade sustainability are impossible without comprehensive datasets. Knowledge of the quantities of species traded can, among other outcomes, inform conservation planning or evaluation and efforts to minimize the influence of unsustainable trade on biodiversity loss. We explore wildlife imported into the United States between 2000 and 2022 based on a recent release of LEMIS data. We describe what is traded, whether trade originates from captive or wild sources, the volumes of wildlife traded, and how these trends have shifted over the last two decades. To our knowledge, this represents the most comprehensive analysis ever made on wildlife trade and its dynamics in time, covering all taxonomic groups from across the world. This effort allows us to provide insights into global wildlife trade at an unprecedented level in terms of completeness, even if limited to the portion that crosses US borders.

Results

The LEMIS data from 2000-01-01 to 2022-06-30 included 8.7 million entries (i.e., representing a single entry line in the LEMIS database), of which we examined 3,479,466 entries (each representing a single row of import data). Of these, 93% of the 8.7 million entries, constituted whole individuals, and 52% was listed as a count (i.e., quantity of individuals, not mass, length, or

volume)(19). Nonwhole organisms are harder to quantify (as are those by weight); getting equivalent measures for other units, such as volume, area, and weight, is particularly challenging *SI Appendix, S2.4*. This is especially true in groups like fish, where weights can cover not only differing body sizes but also water (25). 99% of these entries were cleared for import, and 84% of 8.7 million entries were listed to a taxonomic level of genus or species. Once outliers were removed, these data record the import of 2,847,052,429 items that constituted a whole individual, 815,572,384 (29%) of which were vertebrates. Records included 21,135 species from 10,452 genera (*SI Appendix, Data_S22*), of which 6,689 species were invertebrates (4,496 genera), 11,243 were terrestrial vertebrates (3,968 genera), 2,885 were marine/aquatic vertebrates (1,664 genera), and 280 were plants. Small numbers of other taxa (such as fungi) were also noted (38; Fig. 1A and *SI Appendix, Data_S9*). All methods, code and data have been provided in Figshare repositories.

We merged LEMIS data with import data from CITES (2–4) into the United States over the same period and the number of species increased to 29,445 with the greatest increase being 8,116 plant species (in addition to 232 animal species) that were only recorded in CITES, not present in the LEMIS data. This difference is attributed to the jurisdiction of plant imports in the United States by the United States Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS). Likewise, animals inspected by the USDA (e.g., cattle, sheep, swine, goats, horses, mules, domesticated chickens, turkeys, ducks, geese, squabs) are not always included in the LEMIS even though some may come from the wild, and Siluriformes (e.g., catfish) and ratites may be declared to USFWS or USDA, and their records may not be reliable in terms of completeness due to the overlapping remits of these agencies (*SI Appendix, S2.4* for full details on agency remits).

Invertebrates tended to be traded the most in terms of numbers of whole individuals (both live and dead), four of the top five post hoc grouping were invertebrate groups. Arachnids had 863,988,333 individuals traded and represented the most traded of our post hoc groupings (30%; Fig. 2 and *SI Appendix, Data_S4*), followed by Fish at 599,575,055 (21%) and Insecta and Myriapoda 551,483,676 (19.4%).

By number of entries, Terrestrial Mammals dominated, with more than 1,349,701 entries (39%), followed by Echinoderms and Cnidaria 888,601 (26%; Fig. 1B and C). The differences between the numbers of individuals traded and the number of entries highlight differences in trade dynamics and/or recording (Text S1), where for some groups individuals are more likely to be imported in bulk shipments (potentially enabled by their size or form, e.g., eggs/slugs).

Dimensions of Trade: What Is Traded, What they Are Traded for, and Where Are they from?

Most species in trade, even if predominantly captive bred, will have some individuals from the wild (*SI Appendix, Table S1*), though the veracity of listings of source (wild or captive) may vary and is hard to assess as declarations may be false (11) (*SI Appendix, Data_S21*). Importantly we cannot guarantee the veracity of declarations on wild vs captive, but with increasing demand for captive bred individuals there is little motivations for false declarations of "wild", though it may be used as a default in some instances (11) (highlighting the need for more reliable recording).

Overall 24% of individuals were declared as wild-sourced, but this ranged dramatically depending on the group (Fig. 2 and *SI Appendix, S2.1*). For example, Marine Mammals show 95% (though these are not for commercial purposes) and Echinoderms and Cnidaria show 98% of individuals coming from the wild.

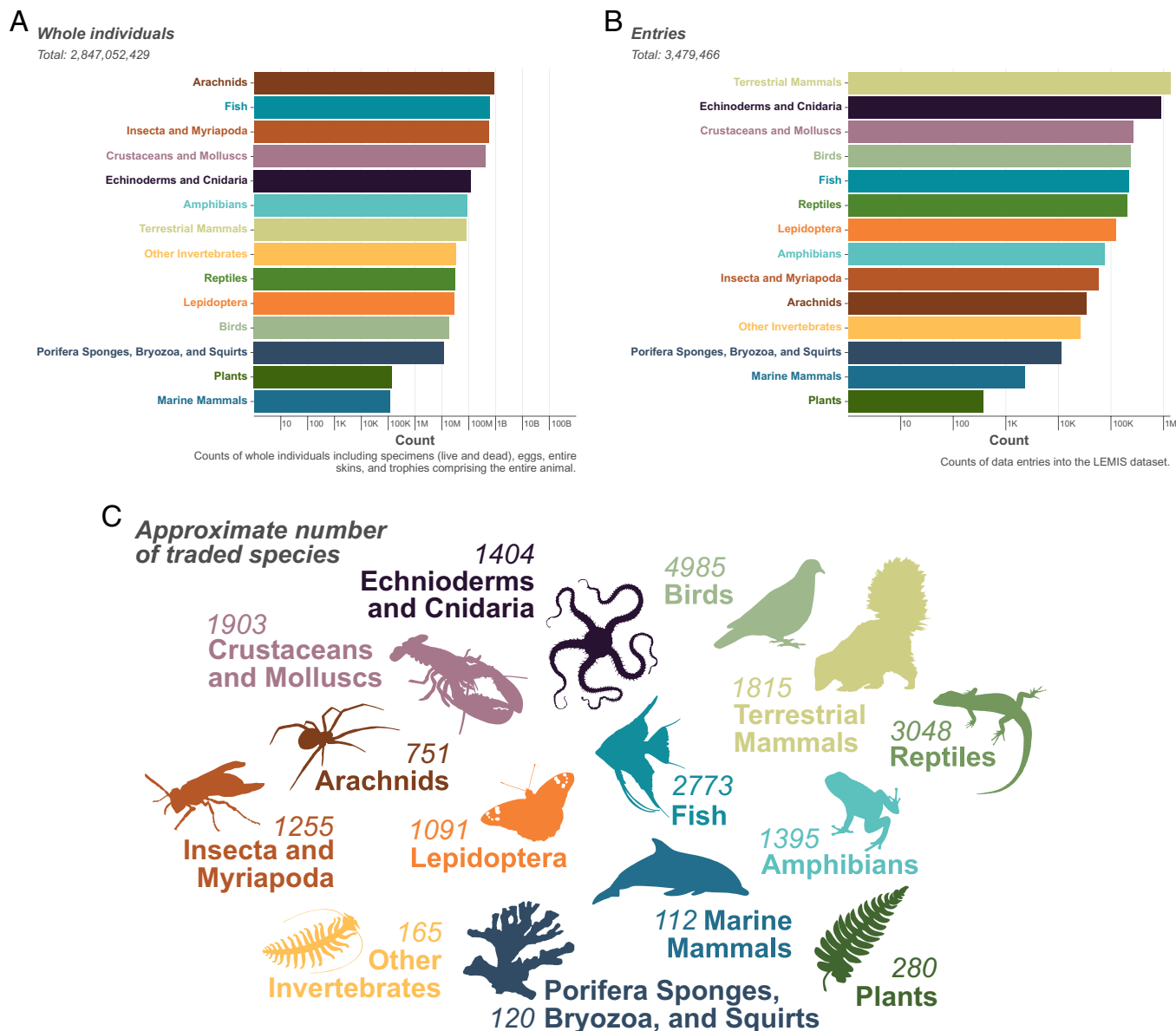


Fig. 1. Overview of species and quantities traded in the LEMIS. (A) Totals of whole individuals measured by count. (B) Total number of entries. (C) Approximate counts of species traded. Note that the x axis is logarithmic. Created using [SI Appendix, Data_S4](#), [Data_S3](#), and [Data_S9](#).

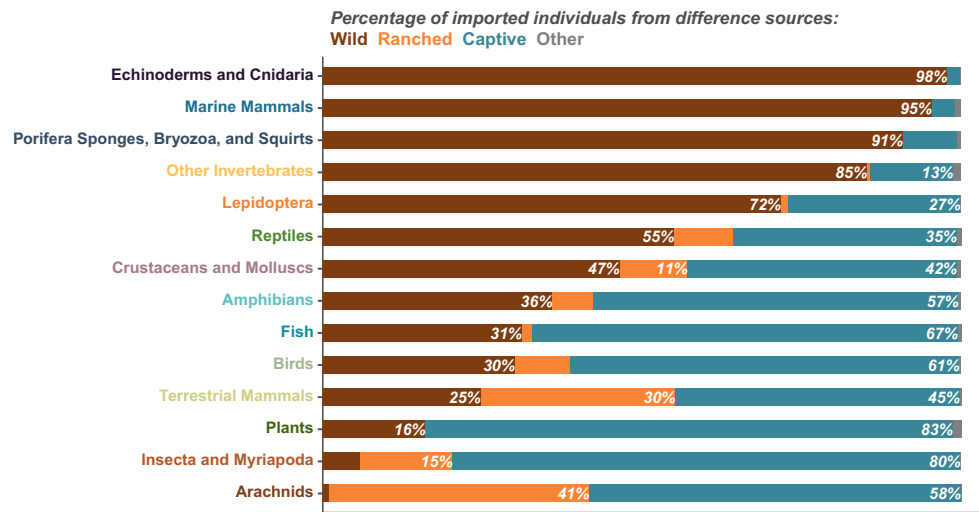
Insecta and Myriapoda and Arachnids are reported to fall below 15% wild-sourced individuals, thus skewing overall percentages (3). Terrestrial Mammals (30%) and Arachnids (41%) have higher rates of ranched individuals. Ranching refers to individuals collected from the wild as eggs or juveniles, then raised in captivity; however, the listing of some species (particularly certain invertebrates, as well as Terrestrial Mammals) as “ranching” suggests inconsistent use, as the collection of some of these species as juveniles or eggs from the wild seems improbable, especially in invertebrates. However, it should be noted that if weight was considered the percentage wild may increase for certain taxa such as fish, but inconsistent units, varying body sizes, and the inclusion of water in fish weights means it is not accurate (25) ([SI Appendix, S2.4](#)).

Mammals exhibit the most wild-sourced entries (94%), followed by Birds (89%) (Fig. 2). The wild sourcing of individuals is not evenly spread, but affects the vast majority of traded species to some extent ([SI Appendix, Fig S6](#)). All marine mammal species listed as traded have wild-sourced individuals, and every other group except Lepidoptera and Arachnids have over 80% of the species being wild-sourced at some point ([SI Appendix,](#)

[Data_S22](#)). The lower total percentage from the wild is influenced by a small number of captive bred species being traded in high volumes, while conversely the majority of other taxa are imported in smaller numbers, but largely from the wild ([SI Appendix, Fig. S6](#)). In vertebrates in particular, we find species traded in high quantities with most being wild-sourced. Similar patterns exist when examined by order, where many orders see high percentages of individuals wild-sourced ([SI Appendix, Fig. S7](#)). When looking by order, the skew is toward wild sourcing: over 64% of orders have over 90% of their individuals originating from the wild ([SI Appendix, Fig. S7](#)).

Changing Patterns of Trade Reflected in Data. For most vertebrate taxa, the number of species and genera traded annually increased until 2017 after which they declined and species counts fluctuated. Birds (at 1,876 species) and reptiles (at 1,249 species) reached peaks earlier, in 2015 (Fig. 3 and [SI Appendix, Data_S10](#) and [Data_S7](#)). Invertebrate groups show similar patterns, with a continued increase throughout the LEMIS data time frame; Crustaceans and Molluscs reached over 973 species in 2021, the most species traded in a single

A



B

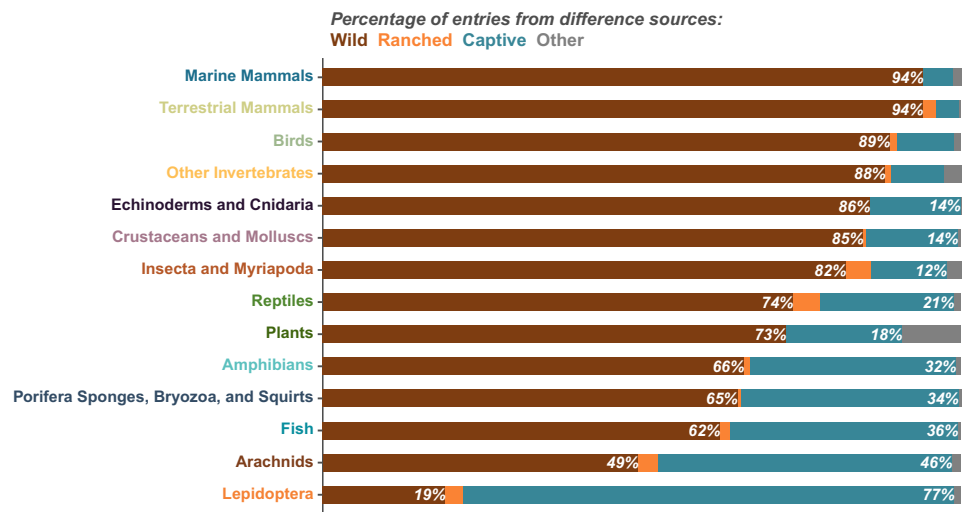


Fig. 2. Percentage of trade listed as originating from wild, ranched, captive, and other sources by group, (A) based on the number of entries, (B) based on entries that listed the count of whole individuals. Unlabeled sections contain percentages less than ten. Used [SI Appendix, Data_S12](#).

year for invertebrates (Fig. 3 and [SI Appendix, Fig. S1](#)). Increases in invertebrates during 2020 may relate to heightened trade during the pandemic (3). Declines in imports in recent years for some taxa may relate to more restrictive import regulations (26) and increased domestic trade from captive breeding. LEMIS recording methods also changed in 2016, which affected how data were split (records were split by purpose), which may be responsible for some of the rapid changes in trade. This may also reflect the implementation of Phase 5 of the Lacey act in 2015 (26). Notice of species that may be listed in upcoming CITES meetings could also increase trade in such groups prior to such meetings (such as 2019), and discussion forums of pet selling websites often do include mentions of “trading species now before potential uplisting in CITES” (2). Such increases have also been noted, for example, in the case of the Earless Monitor (*Lanthanotus borneensis*) (27). Part of the increase may also originate from changes in LEMIS methods, such as a single taxon that is then later split into multiple taxa, or creating notation to enable species to be more accurately listed (such as noting species individually rather than within aggregates such as “tropical fish”).

Cumulative sums of species over time similarly showed an increase in the number of species traded. Patterns largely follow the counts of species per group, with birds and fish showing the

steepest increases ([SI Appendix, Fig. S1 and Data_S5](#)). By contrast, marine mammals have remained stable over the past two decades. The higher species numbers of birds and fish appear largely due to high numbers of species traded in individual years, and possible changing popularity of particular species (28) ([SI Appendix, Fig. S1 and Data_S8](#)), while other groups (e.g., Terrestrial Mammals, Echinoderms, and Cnidaria) reveal a considerable number of species consistently traded over the entire period.

For some groups, the percentage of wild caught individuals decreased between 2020 and 2022 ([SI Appendix, Fig. S2 and Data_S13](#)), but this time period may include issues with harvesting and transport access during the COVID-19 pandemic, as well as lack of resources to protect areas in host countries (29). It should also be noted that Phase 6 of the Lacey act came into effect in 2021 and may also have impacted trade patterns (26). Patterns of ranching also varied over time, with increasing percentages of species listed as ranched for mammals, arachnids, and amphibians, especially in recent years. Other groups fluctuate, possibly marking changes in regulations, demand, and purpose, or other factors.

There are also differences between the number of individuals imported as whole vs. live. While all live individuals were obviously whole, whole specimens may also be imported dead for other

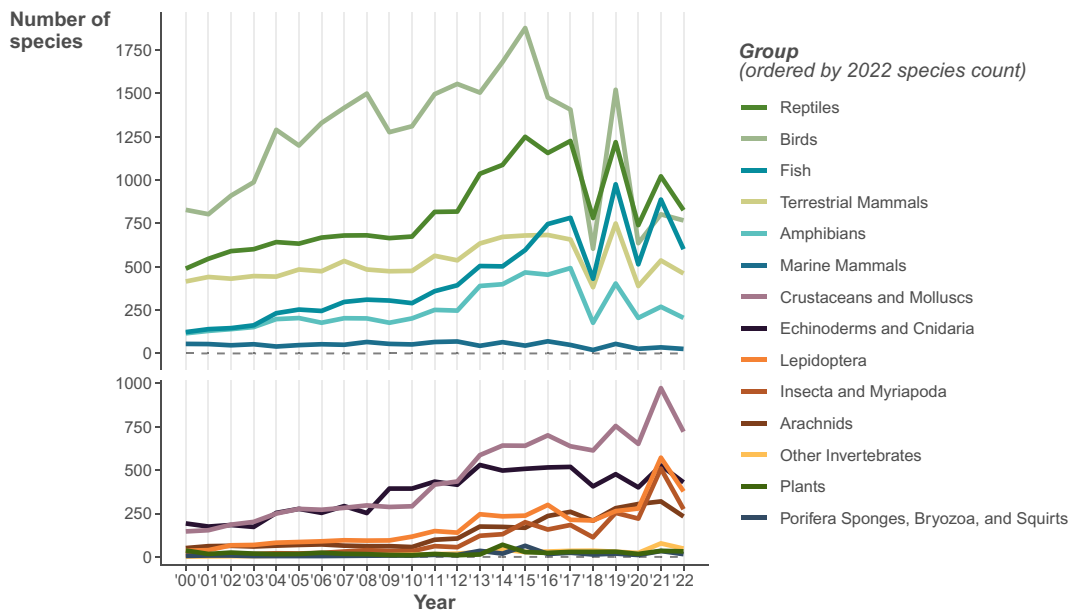


Fig. 3. Number of species traded per group through time, (Top) Vertebrate groups, (Lower) Invertebrate groups, and plants. Used *SI Appendix, Data_S10*.

purposes (compare numbers in *SI Appendix, Figs. S3 and S4 and Data_S11*). This highlights differences between likely trophies or specimens and animals imported live as pets or for research, education, and live exhibition. This difference is particularly noticeable in mammals, birds, and lepidopterans, who see large trade in dead whole individuals. For mammals and birds, this disparity is likely due to the import of hunting trophies (section 1.3). Live bird imports have decreased, whereas imports of live lepidopterans have increased. Conversely, Reptiles, Amphibians, Crustaceans, and Molluscs see little difference in the live versus whole individual trends, indicating the predominance of live trade in these groups.

Imported for What Purpose? Commercial trade was the dominant purpose stated for the trade of whole individuals (*SI Appendix, Fig. S5 and Data_S16*). All groups show over 77% of individuals are traded for commercial purposes (purpose code T), with the exception of marine mammals that are primarily imported for “scientific/research” purposes (purpose codes S and M). The focus on commercial purposes is particularly acute in 8 of 15 groups (Fig. 4A), with over 98% of individuals imported for commercial purposes. These numbers are likely even higher than reported by the LEMIS because noncommercial trade can still ultimately occur for commercial purposes, such as animals imported for pharmaceutical research.

Much of the wild sourcing of individuals is listed as being for commercial purposes (*SI Appendix, Fig. S5*). For example, 98% of species listed as wild-sourced within Echinoderms and Cnidaria are identified as being for commercial purposes, similarly over 90% of listed wild-sourced Porifera are labeled for commercial purposes; however, terrestrial invertebrates (at least those listed) are largely captive bred (Fig. 4). Reptiles show the greatest intersection for a vertebrate group, where 54% of wild-sourced individuals were for commercial purposes, likely for the pet trade (2). However, the reptile percentage (both live and whole) has likely declined over time due to an increase in the percentage of captive bred individuals imported, as well as a slight decrease in overall trade volumes (*SI Appendix, Fig. S2–S4*).

Much of the noncommercial trade is for scientific/research purposes, with a few notable exceptions (Fig. 4), for example, noncommercial trade of birds and mammals appears connected to hunting trophies. The primary noncommercial reason for amphibian import

is listed as education, and this appears linked to the live import of these individuals. Amphibians have the highest percentage of wild sourcing when looking at noncommercial live imports for vertebrate groups (*SI Appendix, Fig. S5 and Data_S19*), but the percentage of live reptiles and marine mammals is greater than amphibians when commercial trade is included. Live imports largely follow the trends of whole individuals when commercial trade is included. Notable exceptions are Terrestrial Mammals (25% wild dead or alive; 2% live only), Porifera Sponges, Bryozoa, and Squirts (91%; 62%), and Marine Mammals (95%; 78%) where we see less wild sourcing for live individuals.

Risks of Invasion from Wildlife Trade. Of the thousands of species listed in the LEMIS, many potentially pose a biological threat to native ecosystems by acting as invasive species. Of the world’s top 100 invasive species (30), 28 were recorded as imported live into the United States within the LEMIS. This includes continued (i.e., 2020–2022) trade of species like zebra mussels (*Dreissena polymorpha*) that have already led to detrimental ecological, environmental, and economic consequences in the United States (31). In total, 203 known invasive species were imported into the United States based on species listed as invasive in the United States by the IUCN invasive species database (*SI Appendix, S1*). In addition, the Lacey Act has a shortlist of injurious invasive species (32) that includes 57 genus-level listings and 34 species-level listings. Of these, at least 23 species were listed as being imported live into the United States on at least some occasions after regulatory changes. For example, 12 of the listed fish genera continue to be imported live, and of the 20 amphibian genera listed as injurious in 2016, seven were imported live after that date (and in addition to these imports, exports of all listed “injurious invasive” groups increased) (*SI Appendix, S2.2*). While this may have been for conservation or educational purposes, it underscores the need for further data in such systems.

Interpretations

Advancing Our Understanding of International Wildlife Trade. US wildlife trade covers a substantial proportion of global trade, and thus, the LEMIS data provide critical insight into worldwide wildlife trade. However, we know that the trade is undoubtedly

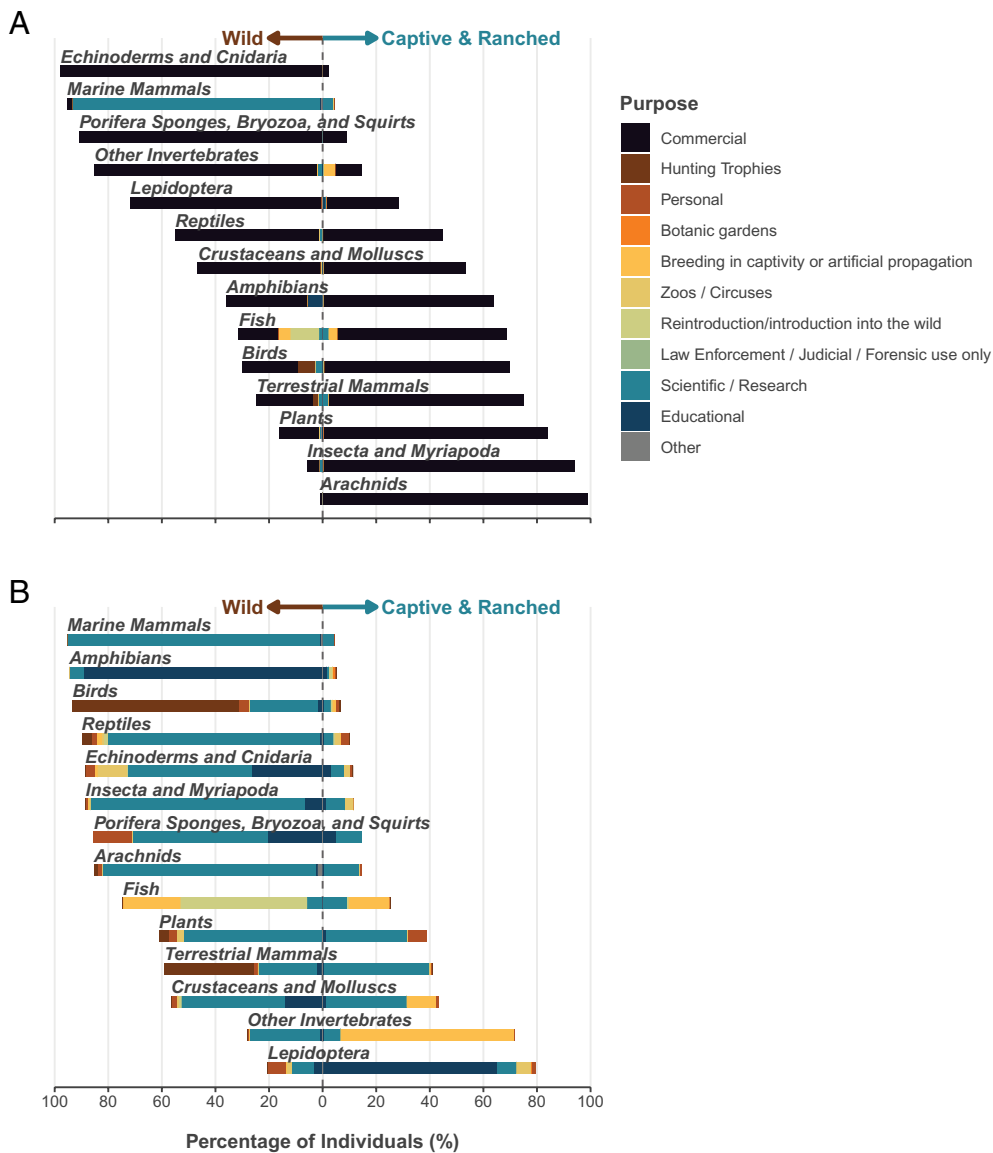


Fig. 4. Percentage of trade per purpose based on the number of whole individuals. (A) Breakdown of import purpose including commercial. (B) Breakdown of import purpose excluding commercial. Values to the left indicate wild sourcing, while those to the right indicate captive or ranched sourcing. Used *SI Appendix, Data_S16*.

much larger than what is included in the LEMIS. The United States has imported over 21,097 species between 2000-2022 based on LEMIS records, with over 11,243 terrestrial vertebrates, 2,885 marine vertebrates, and 14,128 invertebrates. When we add CITES records for the same time period, this number increases to 29,445 species, largely due to plants, which are not routinely recorded within the LEMIS.

This trade includes 46% of described birds, 28% of mammals, 26% of reptiles, and 16% of amphibians. Yet even these high percentages do not capture the trade's full magnitude, as many taxa in trade are underrecorded within the LEMIS (3, 33). Conversely, results from Rhyne et al. (2017) (22), indicated fewer individuals recorded on invoices than were recorded in the LEMIS, highlighting challenges in accurate quantification. Additionally, many listings within the LEMIS are denoted as "Exception 4" and hence do not provide species-specific taxonomic information. It is also important to define what "wildlife" might be considered [i.e., see ref. 34] as different species fall under the purview of different agencies, and this may obscure our understanding of trade. CITES data highlight further differences by indicating 8,139 more plant species than the 281 recorded in the LEMIS because plants

are inconsistently included in the LEMIS and fall under USDA not USFWS jurisdiction (*SI Appendix, S2.4*). There are likely thousands more plant species in trade going undetected and unmonitored. Though the United States records data for all declared wildlife imports (both CITES and non-CITES) in the LEMIS database, species may be missed owing to changing regulations and because particular agencies can be responsible for different taxa (e.g., USFWS, USDA, APHIS, and FDA) and often do not coordinate data collection or sharing. These gaps in monitoring further highlight that the US wildlife trade encompasses a broader swathe of global biodiversity than previously realized, and allowing these gaps to persist contributes to the continued exploitation of wildlife and reduces our ability to truly understand what is in trade (26).

Although the LEMIS has known gaps, it still provides a broad perspective on the wildlife trade, particularly when compared with other data sources, such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The IPBES sustainable use assessment was the most comprehensive global assessment of species in trade (1). Yet, that assessment cannot realistically estimate the degree of trade due to limited monitoring

of most taxa. For example, IPBES (1) stated 1,700 species of terrestrial arthropods are in trade globally. However, the LEMIS reports 751 species of arachnids (3) and over 1,091 lepidoptera imported into the United States alone. Further, a recent global analysis reported 3,767 traded lepidoptera species (33). The fact that the number of traded butterflies alone exceeds the global IPBES estimate of all traded terrestrial arthropods highlights the large data gaps in current global assessment of legal wildlife trade. Furthermore, the 3,097 invertebrate species imported into the United States within the LEMIS, highlights the scale of present difficulty in global assessments of legal wildlife trade and the risk of neglecting trade for many taxa. Additionally, while it is a major global importer (35–37), the United States is a single market for wildlife, and without comparable data from other regions, we cannot accurately quantify the global dimensions of trade. European Union (EU) imports may help to fill these data gaps and may contain information on many more species, particularly species with smaller body sizes like invertebrates, reptiles, and amphibians for pets. Almost no regulation exists for the majority of wildlife in trade in the EU, and while the EU 2005 ban on wild-bird trade caused major shifts in the global trade (38), most taxa are still imported into the EU with no specific regulations (2–4). Building on the EU Action Plan against Wildlife Trafficking (2022–2027), Cardoso et al. (39) proposed that the EU expand the EU-TWIX database to cover all trade following the (Findable, Accessible, Interoperable, Reusable) FAIR principles (40). Additional country- or region-specific trade databases comparable to the LEMIS are urgently needed to provide key baseline data to document and respond to the global dimensions of both legal and illegal wildlife trade. Furthermore, other regions, such as China are also known to be major, and potentially growing importers of wildlife, yet knowledge of the true dimensions of trade remains limited to species listed within CITES, and more research is clearly needed (41, 42).

Potential Negative Impacts for Importing Countries. The United States, along with other countries, faces ongoing challenges posed by numerous invasive species, and associated pathogens, that threaten native species, ecosystems, agriculture, and silviculture, with many of these introductions stemming from wildlife import (43–45). This threat is considerable, as invasive species have been identified as drivers of up to 60% of recent animal and plant extinctions and have an annual control cost of over \$423 billion (46). Our data reflect this scale: the legal wildlife trade into the United States carries substantial associated invasion risk: 203 of the species imported live are listed as invasive in the United States according to the IUCN ISSG, and 28 of these appear on the list of the world's 100 worst invasive species. Many of these species are listed as “injurious” under the Lacey Act (26), and these, as well as other potential invasive species, continue to be imported (47, 48). Given that these shipments were cleared into the country, they likely had sufficient permits, or were imported prior to regulation. The potential for species imported into the United States to become invasive, especially under a changing climate, is considerable (49, 50), yet many taxa are challenging to detect and identify within trade shipments. Better real-time analysis could help to validate the import of injurious species (13). Invasive invertebrates may be of particular concern given that many countries have limited resources for inspection and many invertebrates may have the capacity to become invasive (51). For example, the importation of millions of mites for biocontrol increases the chance that individuals of these species escape confinement and establish non-native populations in the United States (52, 53). At present, there appears to be relatively

little concern given to the potential risk of imported biocontrol agents, and more attention is likely needed (54–56). However, the risk of invasive species introduction exists beyond invertebrates, with the widespread invasion of pythons (originally imported for pets) across south Florida as one example of how wildlife trade can directly cause ecosystem disruption and wildlife declines within importing countries (57).

The potential for novel outbreaks of pathogens also presents a significant risk emanating from the largely unmonitored wildlife trade (58). For example, imported bees may have played a role in colony collapse disorder (59, 60), and the global wildlife trade has contributed to the spread of *Batrachochytrium* fungi species that are deadly pathogens of amphibians (61, 62). In the United States, the Lacey Act has been leveraged in forward-looking conservation policy that attempts to reduce the risk of pathogen import that could threaten native amphibians with disease, yet major concerns remain (63). Notably, even following the listing of some salamander genera as injurious under the Lacey Act to prevent the import of taxa known to host *Batrachochytrium salamandrivorans*, other amphibian species that could serve as disease carriers continue to be imported (64). In addition, already established non-native populations can contribute to pathogen spread (i.e., “bridgeheading”), further amplifying the risk posed by wildlife import, invasive species, and their pathogens (65). Wildlife trade also carries a risk of spread of various zoonoses with epidemic potential, and risks of pathogen spread associated with wildlife trade were a major motivation for the development of both the EU Birds Directive and the US Wild Bird Conservation Act (66, 67).

Understanding Origins: Do we have the Data to Understand the Impact of Trade? Mirroring patterns previously reported in the recent literature (2, 3, 4, 66), the LEMIS data indicate that wild sourcing of traded individuals for some taxa continues at high rates. While the LEMIS has shown a trend toward listing more species as captive and ranched within Amphibians, Arachnids, Fish, Insecta and Myriapoda, and Reptiles (*SI Appendix, Fig. S2*), a majority of species have at least some individuals coming from the wild, and for less voluminous groups, most individuals are wild sourced. Understanding the sustainability of wildlife trade requires both the volumes of taxa in trade and the impacts on wild populations. Yet in most countries, there is virtually no monitoring for the impact of wild sourcing or ranching for terrestrial animals (18), despite indications it comprises a large portion of the trade. Wild sourcing impacts thousands of species yet we have virtually no data on wild populations, nor adequately reliable data on the level of imports or their sources; thus we have no means to assess the sustainability of wildlife trade of most species. Furthermore, it is known that while freshwater aquaria trade has largely transitioned to documented captive breeding, up to 95% marine species still largely come from the wild (68) and our results show this trend has continued through recent years. In fisheries, trade data are an important component within productivity-susceptibility analyses used to prioritize species requiring additional wild stock monitoring and recent PSAs (69) rely on trade data derived outside of the LEMIS (6, 22). Although the LEMIS supplies an unprecedented insight in terms of scale, the reliability of import data cannot be interpreted unquestionably. Examples of wild-caught individuals sold as captive-bred and misidentification of species are well documented and often require targeted effort to reveal (70). By contrast, captive bred (cultured) individuals may be listed in importation records as wild, but the lack of oversight precludes the ability to verify captive cultivation

(17). Legality and lack of evidence of harm cannot be used to assume trade is sustainable (71) (*SI Appendix, Fig. S7*).

Recent years have seen an increase in the number of species traded in many groups, with the percentage of individuals and species coming from the wild often staying approximately similar, though declining in some instances (*SI Appendix, Fig. S3*). This persistent collection of wild animals undoubtedly poses a risk to the survival of wild species. For some taxa (largely vertebrates) the number of species within LEMIS records peaked around 2016-2018, whereas many invertebrates show a peak during the COVID-19 pandemic, which may be continuing.

Moving Forward: Improving Inventory of Wildlife Trade to Inform Management? The Kunming-Montreal Global Biodiversity Framework in December 2022 presents two targets devoted to “sustainable wildlife trade” [Targets 5 and 9; (4, 72)]. While the United States trades almost 30,000 species, there are insufficient data to unequivocally demonstrate sustainability for the majority of these species. Given that the data collated by the United States remain some of the best at a National level globally, these targets are unlikely to be achieved without renewed effort to monitor what is in trade more widely and connect that trade to impacts on wild populations to evaluate the impact and sustainability. While the LEMIS is considered one of the better contemporary systems for collecting wildlife trade data, it was not developed to collect biodiversity information but rather to track the volume of commerce at each port of entry to guide staffing and resource allocations. To gather better data through systems such as the LEMIS, and to better gauge the impacts of wildlife trade, a number of improvements are needed, including (but not limited to): (1) ensuring that correct and up-to-date taxonomic identification is entered, (2) units are standardized with the default being counts of items, and that protocols included standardized unit recording to accurately detail the number of individuals of each species within each assignment, (3) automated processes that ensure declaration and invoice data match, and (4) a commitment to making the data publicly available in real or near-real time (13, 73). In addition, as declarations of provenance (wild or captive) are not verified, additional mechanisms for verification or checking, as well as assessments of accuracy of species identification could be added where possible, especially for species of concern.

It is reasonable to expect that accurate trade data accounting be the minimum requirement of any country for wildlife import or export. CITES provides the only overarching mechanism for regulating international wildlife trade given that other global trade databases, such as COMTRADE, do not record species information and harmonized codes are largely not species specific (unlike those used and developed by the LEMIS). However, CITES includes only a fraction of species in trade (74). The limited availability of such trade data undermines efforts to list species potentially threatened by trade. Major importing regions, such as the EU, should mandate better data collation to improve understanding of what is in trade. While the EU-TWIX (www.eu-twix.org) focuses on illegal wildlife trade, and TRACES (https://food.ec.europa.eu/animals/traces_en) provides data for some species, when imported for food, their focus on biosecurity has not been optimized to provide the detail needed to understand legal wildlife trade or gauge the sustainability. Yet exporter regions require both capacity and resources to develop and implement such approaches, and the development of these should be supported by major import regions (35). Having a clearer understanding of the dimensions of wildlife trade in a major market such as the EU could dramatically improve our ability to assess species at risk for conventions such as CITES. These data are instrumental to enumerate

the risk to biodiversity that wildlife trade poses, which is an important step toward ensuring that international wildlife trade does not compound efforts to reduce accelerating rates of biodiversity loss.

Here, we show that almost 30,000 wild species are declared as being imported into the United States, largely with no data to assess the risk these species pose as invasive species or the sustainability of trade on populations of the species in their native ranges. For the majority of species in trade, most individuals are wild-sourced, most plants and invertebrates are not assessed by the IUCN, and there is no requirement for nondetriment findings, demonstrating trade on a scale that cannot be assumed to be sustainable. Globally, the number of species in trade is unknown, and the LEMIS estimates we produce here likely dramatically underestimate the number of species in international trade globally, especially given that undescribed and threatened species may be traded under other species names and newly described species can be freely traded (a situation which would not occur under a reverse listing approach) (2, 375). Further, implementing regulations to propagate the principle of “do no harm” should be applied to all trade in wildlife, including the collation of better data to enable a more accurate assessment of potential risk. At present the lack of data on trade is often stated as a reason to preclude the listing of species within CITES, yet current mechanisms dictate that such data not be routinely collected unless a species is listed within CITES. This represents a data “chicken and egg” situation. Better databasing could be a minimum to allow CITES to access the key data needed for its current function, and approaches such as a reverse listing approach (*SI Appendix, S2.3*) could generate a small list of species which could be traded and therefore may be easier to verify. Furthermore, resources for “nondetriment findings” could be made available for species where a desire to trade has been stated and funded by importers of the species through independent scientific bodies (for example, in conjunction with National CITES focal points), creating a more self-contained and sustainable system.

This paper helps demonstrate the immense value of holistic datasets for advancing our understanding of what is in trade. More complete data of species in trade could highlight species for up-listing, flagging what species may be at risk, and highlighting where monitoring data for wild populations is clearly needed given the risk of unsustainable trade, and which species most urgently need nondetriment findings to be assessed. Such approaches are challenging, as they require both data on wild populations and data on offtake; but monitoring of international trade provides key data to attempt to assess levels of offtake (5). Without such efforts, and without clear understanding of what is in trade, we cannot hope to reach these targets (such as targets 5 and 9 of the GBF) or prevent unsustainable trade. We collectively observe that globally, national authorities continue to lack the necessary resources and capacity to accurately and reliably collect and report data for monitoring trade. Given the gap in funding noted within the Global Biodiversity Framework (GBF), and the lack of appropriate data for Targets 5 and 9 on Wildlife trade (72), taxing importers of wildlife to cover the costs of species verification, and the generation of nondetriment findings could also provide a mechanism to ensure trade is sustainable. Yet even in the absence of such approaches, creating global standards for the collation of wildlife trade data, based on the standards set by the LEMIS and with issues such as higher-level taxonomic listing addressed, would be beneficial (*SI Appendix, S2.3*). To do so would require careful planning and collaboration, and to assess means of exchange to promote improved standards to enable constructive policy diffusion and create global best practice in collation of international

wildlife trade data (76). We believe that such planning and collaboration are possible, and by creating appropriate enabling conditions (as for organic farming), the benefits of complying with new standards can make compliance desirable and provide diverse benefits. With the enactment of such standards, we could collate the data needed to understand and monitor global dimensions of trade and provide the data needed to assess species vulnerability to unsustainable trade.

Materials and Methods

LEMIS data were released online in November 2022, which included wildlife trade data from the period 2000-01-01 to 2022-06-30. Data were first downloaded, consolidated (SI Appendix, section S1.1), and cleaned (SI Appendix, section S2.1) so that it was standardized, and fit for use. Data were partitioned by year, and by use, and all major taxonomic groups were split into different groups (SI Appendix, sections S1.2 and S1.3). First, the data were collated for each year, split by group, (including fourteen taxonomic groupings), and species names corrected to ensure they were standardized and consistent (SI Appendix, section S1.2). Many different taxonomic references were needed to correct all species names, clean synonyms and create a full taxonomic backbone. The LEMIS also uses a system of harmonized codes to denote species; however, these may merge multiple species under a single code, so both species names and harmonized code needed to be considered in generating a corrected species name. Grouping assessments were verified to ensure that species were listed consistently within a group (for example, fish, amphibians, and reptiles were often in the wrong category according to LEMIS categorization, and insects were listed in multiple inappropriate groupings). After correction, the data were compiled for summary (SI Appendix, section S1.3), and unit types filtered to analyze quantitative patterns. The results were broken down by year, purpose, and to understand the source of individuals, these dimensions were also plotted over time (SI Appendix, section S1.4). The import of species defined as injurious and invasive was also analyzed to understand other risks associated with wildlife

trade (SI Appendix, section S1.6). Full methods, codes, and processed data are available in supplements, and codes are referenced through text to allow replicability of analysis shown here.

Data, Materials, and Software Availability. Codes and data have been deposited in Figshare (<https://figshare.com/s/960af99373aba13791be>) (77). Code used to compile data, create summaries, and figures is available: <https://figshare.com/s/afe281866edefe334a5c?file=48911671> (78). Main data files detailing the correction and filtering process is available: <https://figshare.com/s/43a5aa6f7fc171508439> (79). All other data are included in the manuscript and/or SI Appendix.

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