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RESEARCH ARTICLE

The dark web trades wildlife, but mostly for use as drugs

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Abstract

1. Contemporary wildlife trade is massively facilitated by the Internet. By design, the dark web is one layer of the Internet that is difficult to monitor and continues to lack thorough investigation.
2. Here, we accessed a comprehensive database of dark web marketplaces to search across *c.* 2 million dark web advertisements over 5 years using *c.* 7 k wildlife trade-related search terms.
3. We found 153 species traded in 3332 advertisements (*c.* 600 advertisements per year). We characterized a highly specialized wildlife trade market, where *c.* 90% of dark-web wildlife advertisements were for recreational drugs.
4. We verified that 68 species contained chemicals with drug properties. Species advertised as drugs mostly comprised of plant species, however, fungi and animals were also traded as drugs. Most species with drug properties were psychedelics (45 species), including one genera of fungi, *Psilocybe*, with 19 species traded on the dark web. The native distribution of plants with drug properties were clustered in Central and South America. A smaller proportion of trade was for purported medicinal properties of wildlife, clothing, decoration, and as pets.
5. *Synthesis and applications*. Our results greatly expand on what wildlife species are currently traded on the dark web and provide a baseline to track future changes. Given the low number of advertisements, we assume current conservation and biosecurity risks of the dark web are low. While wildlife trade is rampant on other layers of the Internet, particularly on e-commerce and social media sites, trade on the dark web may still increase if these popular platforms are rendered less accessible to traders (e.g., via an increase in enforcement). We recommend focussing on surveillance of e-commerce and social media sites, but we encourage continued monitoring of the dark web periodically to evaluate potential shifts in wildlife trade across this more occluded layer of the Internet.

KEYWORDS
biological use, biosecurity, conservation, drugs, exotic species, illegal wildlife trade, internet, traditional medicine

1 | INTRODUCTION

We are amidst a human-driven mass extinction event, where the direct harvesting of wildlife constitutes one of the greatest threats to biodiversity and species survival (IPBES, 2019). The trade in wildlife presents severe conservation, biosecurity and ethical problems (Cardoso et al., 2021; Fukushima et al., 2020; 't Sas-Rolfes et al., 2019). Specifically, unsustainable harvesting for the wildlife trade is a major driver of the decline in the populations of thousands of species (Di Minin et al., 2019). At the same time, transporting harvested individuals beyond their native distributions to locations they have never occurred can result in the establishment of invasive alien species and the emergence of new diseases (Jiang & Wang, 2022; Lockwood et al., 2019). The economic and ecological consequences of invasive alien species and novel diseases are grave, resulting in damages of at least 1 trillion dollars, to date, and representing one of the leading causes of native species extinctions (Bellard et al., 2016; Woinarski et al., 2019; Zenni et al., 2021). In turn, both the loss of native species from unsustainable harvesting and the introduction of alien species contributes to the degradation of natural systems, which ultimately threatens the wellbeing of humanity (Cardinale et al., 2012).

Given the risks associated with wildlife trade, many traded taxa are regulated to prevent population declines and extinctions, where the primary regulatory body for international wildlife trade is the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES, 2023). While individual countries have their own domestic policies for wildlife trade occurring within their borders, not all wildlife trade is regulated (Romero-Vidal et al., 2022). In terms of international trade, less than 10% of all known plant and terrestrial vertebrate species, and less than 1% of all known fish and invertebrate species, are listed on CITES. Further, since there is no international regulatory framework in place to monitor the trade of species not listed in CITES, the true diversity of species involved in trade is unknown (Fukushima et al., 2020; Scheffers et al., 2019). According to recent estimates, the diversity of unregulated trade outnumbers the regulated trade by a factor of >3 (Watters et al., 2022). Notably, the trade of these unregulated species remains largely untracked by most countries, and the conservation status of many species remains undetermined (Watters et al., 2022). Ideally, the level of trade permitted by regulations should result in sustainable harvesting of species (i.e., populations do not decline; IPBES, 2022). Furthermore, species subjected to unsustainable levels of unregulated trade should, in principle, be protected to ensure their conservation. However, obtaining trade protections is not automatic and can involve a lengthy process, spanning several years or even decades before implementation can be achieved (Frank & Wilcove, 2019).

Wildlife trade will always be a physical occurrence because of the requisite to harvest or breed individuals and transport them (Sinclair et al., 2021). However, at the level of the consumer, the mode of purchasing wildlife is rapidly shifting from in person to virtual transactions (Chng & Bouhuys, 2015; Marshall et al., 2022; Siriwat & Nijman, 2020). Increasingly, the Internet facilitates wildlife trade in ways that were not previously possible (Lavorgna, 2014; Siriwat & Nijman, 2020). Thus, monitoring the Internet for wildlife trade is a conservation and biosecurity priority (Fukushima et al., 2021; Stringham, Toomes, et al., 2021; Whitehead et al., 2021). Most Internet wildlife trade occurs on publicly viewable websites, known as the *open web* (e.g. e-commerce sites; Heinrich et al., 2019; Ye et al., 2020); but increasingly, wildlife trade also occurs on the *deep web*, which consists of social media and private messaging apps (e.g. Facebook Van et al., 2019 and WhatsApp Sánchez-Mercado et al., 2020). Prior research has found very small amounts of wildlife traded on the *dark web*, which remains the most obscure section of the Internet (Harrison et al., 2016; Roberts & Hernandez-Castro, 2017). In light of the emerging impact of the Internet on wildlife trade, CITES has recommended that all internet trade should be tracked and reported, including the dark web (CITES Resolution Conf. 11.3, Rev. CoP18). The legality of online trade is complicated and depends on many factors including the taxon traded, the laws of the country or countries involved, and whether the final transaction occurred (Fukushima et al., 2021). Thus, the location on the Internet (i.e. the open, deep, and dark web) does not directly signify legality, where illegal trade is known to occur at all levels of the Internet (TRAFFIC, 2019). Considering illegal trade occurs frequently on the open web, which is easily findable, the main cited driver of illegal trade on the Internet is lack of enforcement (Morgan & Chng, 2018; Siriwat & Nijman, 2018).

The dark web is different from other layers of the Internet in several ways (Stringham, Toomes, et al., 2021). First, the dark web requires special software to access, making it more obscured and difficult to navigate compared to the open and deep web. Further, no search engine exists for the dark web and thus, users must know a website address (i.e., URL) beforehand to be able to visit a site. The purpose of the dark web is to provide anonymity to users; although several successful law enforcement operations suggest that anonymity is not guaranteed (Décary-Hétu & Giommoni, 2017; Hiramoto & Tsuchiya, 2020; Zhuang et al., 2021). Some of the most well-known and "popular" dark-web sites are marketplaces that sell drugs and other illicit items (Aldridge & Décary-Hétu, 2014; Cunliffe et al., 2017; Soska & Christin, 2015).

Due to the level of obscurity and difficulty to access, the full extent of wildlife trade on the dark web has not been fully explored. There are currently no known marketplaces specifically dedicated to wildlife trade on the dark web, unlike the open and deep web where wildlife marketplaces are plentiful (e.g. 151 websites trading reptiles Marshall et al., 2020). Preliminary investigations indicate wildlife trade does occur on the dark web. Specifically, two prior studies found several wildlife species traded across a handful of dark-web drug marketplaces; finding cacti (sold as drugs for their hallucinogenic properties), reptile-skin handbags and a few advertisements for ivory and rhino horns (Harrison et al., 2016; Roberts & Hernandez-Castro, 2017). The wildlife trade on the dark web warrants an in-depth investigation into the extent of trade and any conservation or biosecurity implications. Given the growing evidence of the impact of the open and deep web on wildlife trade, the dark web should not be ignored (Chaber et al., 2021; Wong & Liu, 2019; Xu et al., 2020).

Here, our research objective was to provide an extensive examination of wildlife trade on the dark web. We accessed the most comprehensive dark-web database available to academic research, consisting of nearly 2 million advertisements from 51 marketplaces spanning from 2014 to 2020. We identified advertisements that traded wildlife and analysed which taxa are traded and for what purposes. Our study sets out to answer the questions: (i) what wildlife is currently being traded on the dark web? And, (ii) what are the biosecurity and conservation risks of this trade? Our results further serve as baseline to compare future monitoring on internet enabled wildlife trade (CITES REF) and particularly to investigate the influence of new policies or changes in enforcement levels, which may cause traders to move from the open or deep web to the dark web.

2 | METHODS

We accessed a dark-web database collected by the DATACRYPTO software (described in Décary-Hétu & Aldridge, 2015). At the time we accessed DATACRYPTO (May 2021), the database spanned *c.* 5.6 years (2014 July 29 to 2020 March 6) and contained *c.* 1.94 million advertisements across 51 marketplaces (i.e. dark-web websites). Each advertisement contained the following information: a unique identifier, a marketplace identifier, a seller identifier, the date, the title of advertisement and the text description taken directly from the advertisement. The names of the marketplaces and the identities of the sellers were de-identified by DATACRYPTO prior to us obtaining the data.

We generated 6959 keywords related to the scientific names, common names and use-types involved in the illegal wildlife trade (derived from Stringham, Moncayo, et al., 2021; a full list of search terms is provided in Appendix S1). These keywords are derived from seizure records of wildlife on three global wildlife trade databases, which encompass over 3000 species. We composed our keywords to be in English to correspond with the knowledge that most dark web marketplaces on DATACRYPTO are predominately in English (Décary-Hétu et al., 2016). We searched the dark web database for these keywords, returning advertisements that 'fuzzy' matched to our keywords (i.e. words within a Levenshtein distance of 2 or less, see Appendix S2). This search returned 1,232,462 advertisements.

We used a variety of semi-automated and manual methods to identify if advertisements were selling wildlife (Appendix S2). Ultimately, we identified 3332 advertisements that traded wildlife. We excluded taxa that are used in common agricultural, aquaculture or farming operations (see Appendix S3 for a list of excluded species). The list of excluded taxa included: 16 plant genera, 42 plant species, one animal family, two animal genera and five animal species. We did not analyse the quantity traded within an advertisement (e.g. mass, volume, number of products, or number of individuals), which were hugely inconsistent both within and across taxa; instead, we measured the number of advertisements, as a measure of relative frequency.

We identified advertised taxa to the most specific rank possible (e.g. species, genus, family). We used the Global Biodiversity Information Facility database (GBIF, 2022) to standardize taxonomy and to obtain upstream taxonomic information. For each taxon in each advertisement (i.e. taxon-advertisement combination), we identified the category of wildlife traded: live, dead/raw, or processed/derived (see Appendix S4 for definitions) and the purpose the taxon was being traded for (e.g. drugs, medicinal, pets, decorative), which we called the 'use-type' (see Appendix S5 for full list and definitions of use-types). For some taxon-advertisement combinations, we assigned more than one use-type. For instance, several plants were advertised both for their use as drugs and for their medicinal properties. For species advertised as drugs, we conducted a structured literature search to identify the category of drug (e.g. stimulant, hallucinogen) and the chemical(s) responsible for producing the drug effect (e.g., DMT, psilocybin; Appendix S6). We did not verify the accuracy of claimed medicinal properties, but simply reported this use-type as (purported) medicinal.

We obtained the IUCN Red List status for each species (IUCN, 2021). We determined if the species or taxa was listed in the Appendices of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES; UNEP-WCMC, 2022). We used the Global Invasive Species Database (GISD) to designate if a species is invasive (Invasive Species Specialist Group, 2015). For each taxon-advertisement combination, we recorded if the seller specified that the specimen was harvested from the wild. For plant species, we obtained their native distributions using the World Geographical Scheme for Recording Plant Distributions (WGSRPD; see Appendix S7 for more details; Brummit, 2001).

We performed exploratory summary analyses on wildlife advertisements, describing taxonomic trends, use-type trends, number and identity of species, and number of advertisements. We examined species that were of potential conservation concern (i.e. IUCN status, CITES-listed, wild harvested) or invasive (i.e. listed in GISD). We quantified geographic hotspots for traded plants using geographic level three of WGSRPD (Appendix S7). Finally, we performed exploratory summaries on the markets and sellers that traded wildlife.

We conducted data analysis and data visualization using R (version 4.1.0; R Core Team, 2022) and used the following packages: TIDYVERSE (version 1.3.1; Wickham et al., 2019); SF (version 1.0–7; Pebesma, 2018); JANITOR (version 2.1.0; Firke, 2021); GSHEET (version 0.4.5; Conway, 2020); GLUE (version 1.6.2; Hester & Bryan, 2022);

LUBRIDATE (version 1.7.10; Grolemund & Wickham, 2011); GGALLUVIAL (version 0.12.3; Brunson, 2020); PATCHWORK (version 1.1.1; Pedersen, 2020); NETWORKD3 (version 0.4; Allaire et al., 2017); HTMLWIDGETS (version 1.5.4; Vaidyanathan et al., 2021); FLEXTABLE (version 0.6.6; Gohel, 2021a); and OFFICER (version 0.3.18; Gohel, 2021b). To obtain upstream taxonomic information, we used the TAXIZE package (version 0.9.99; Chamberlain & Szöcs, 2013).

3 | RESULTS

3.1 | Overall characteristics

We identified 153 species traded from 3332 advertisements of wildlife, at an average rate of 595 advertisements per year (Figure 1a; Appendix S8). Most advertised taxa were identifiable to the species level (82% of taxa, 90% of advertisements; Appendix S9). In total, we detected 188 unique taxa (i.e. including the upper-level taxa of five orders, 11 families and five genera; see Appendix S10 for a full list of species and taxa) and 4368 taxon-advertisement combinations (Figure 1b). The most common use-type of wildlife was drugs, consisting of 90% of all advertisements and 96 species (62% of the recorded species). However, we could only verify that 68 species actually contained chemicals with known drug properties (of the 96 advised as drugs; Appendix S10).

Psychedelics were the most common class of drugs measured by number of advertisements ($n=2403$) and species ($n=41$ species). The next most common use-type was for purported medicinal use, consisting of 8% of advertisements and 60 species (39% of species). Half of all traded species (excluding Bacteria) have not been assessed by the IUCN (74 species), while 55 species were categorized as Least Concern and 19 species are threatened (Vulnerable, Endangered or Critically Endangered). There were 17 species and three upper-level taxa (one genus and two families) listed in CITES Appendix I or II. Nine traded species were categorized as invasive by the GISD; although none of those species were traded live.

3.2 | Taxa-use trends

The majority of species traded were plants (Plantae; $n=101$ species), followed by fungi (Fungi, $n=28$), and animals (Animalia; $n=18$; Figure 1). Plants were the most commonly traded kingdom, with 2513 taxon-advertisements (58% of total), followed closely by fungi with 1721 taxon-advertisements (39%), while animals made up only 126 taxon-advertisements (3%; Figure 1).

Plant species were the most taxonomically diverse kingdom, represented by 55 families and 94 genera (Appendices S10 and S11). Overall, most plants were advertised for their use as drugs (88% of plant advertisements; Figure 2). Of the 70 plant species advertised as drugs, we verified that 45 of them contained chemicals with known drug properties. Psychedelics were the most common class of drugs with 21 plant species and 947 advertisements (Appendix S12). Likewise, the most commonly traded plant species contained chemicals with known drug properties (Table 1). For example, *Mimosa tenuiflora*, the most commonly traded plant ($n=551$ advertisements), contains the psychedelic methyltryptamine (DMT; Table 1). Three plant species were drug facilitators, meaning they contain a chemical that enables a different drug to become chemically active when ingested (Brito-da-Costa et al., 2020). Other plants were traded for their purported medicinal properties (10% of species; 46 species).

Most plants were traded as processed/derived (61% of plant advertisements; 72 species), followed by dead/raw (i.e. dead parts: 30% plant advertisements; 58 species), and few were living plants (9% of advertisements; 15 species; Appendix S13). Five of the traded plant species are at risk of extinction, including peyote *Lophophora williamsii*, goldenseal *Hydrastis canadensis* and catuaba *Erythroxylum vaccinifolium*; each listed as Vulnerable by the IUCN. Seven plant species and one genus (*Dalbergia*) are listed in CITES Appendix I or II, including one orchid species (*Dendrobium nobile*), four cacti (*L. williamsii* and three species in *Echinopsis*), *H. canadensis* and *Panax quinquefolius*. According to the GSID, seven traded plant species are invasive, including coltsfoot *Tussilago farfara* and Formosan koa *Acacia confusa*. The native distributions of traded plants were geographically diverse, spanning every continent except Antarctica (Figure 3). Traded plant species with drug properties had native distributions mostly in Central and South America, while other plant species had native distributions mostly in Europe and parts of Western and Southern Asia (Figure 3; Appendix S14).

The most common fungi species were from the *Psilocybe* genus (83% of fungi advertisements; 1381 advertisements; 17 species), where *P. cubensis* (commonly referred to as 'magic mushroom') was the most popular species in this study, with 1189 advertisements (Table 1). Almost all fungi were sold as drugs (96% of listings;

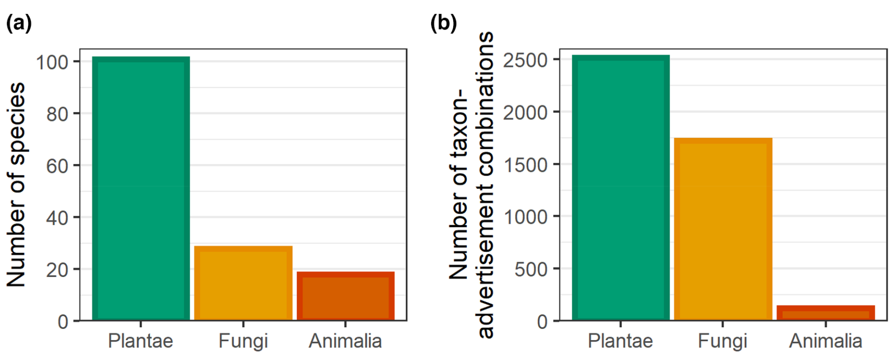

FIGURE 1 (a) The number of species traded on the dark web and (b) the number of taxon-advertisement combinations (i.e. some advertisements listed more than one taxon), stratified by taxonomic kingdom.

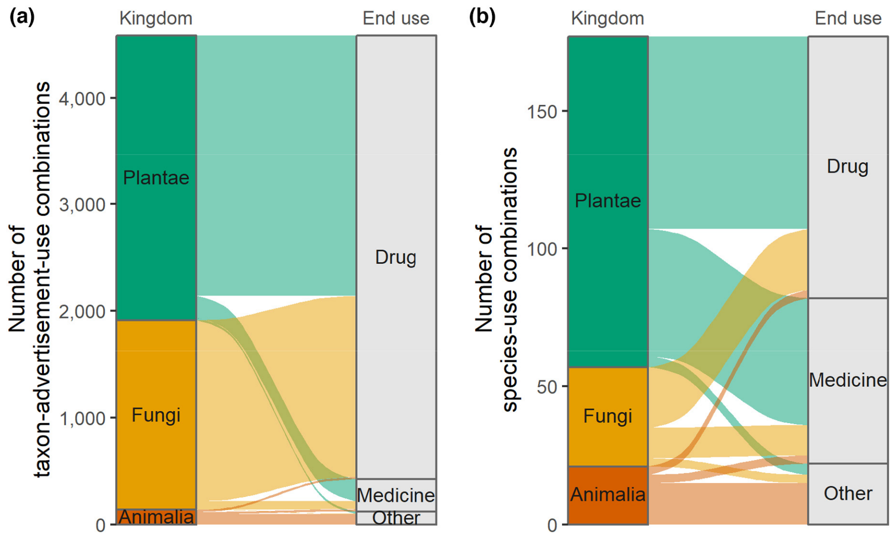

FIGURE 2 End use characteristics of wildlife traded on the dark web. (a) Number of taxon-advertisement combinations stratified by end use and (b) number of species stratified by end use. Note that some taxon-advertisement and species had more than one end use. End use definitions can be found in Appendix S5. Advertisements and species of Bacteria are not shown (4 advertisements; 6 species).

TABLE 1 The twenty most commonly traded species on dark web marketplaces by number of advertisements. Sixteen of the top twenty species contain chemicals with known drug properties or chemicals that facilitate (i.e. activate) the intake of another chemical with drug properties. For one species, *Mitragyna speciosa*, the drug class depends on the dosage of the active chemical ingested (mitragynine). Four of the twenty species were not found to be drugs but have medicinal properties (labelled as Medicinal in Drug Class). See Appendix S6 for our methods on identifying the drug class and active chemical of each species.

Species	Common name	Kingdom	Drug class	Number of ads
Psilocybe cubensis	Magic mushroom	Fungi	Psychedelic	1189
Mimosa tenuiflora	Jurema	Plantae	Psychedelic	551
Mitragyna speciosa	Kratom	Plantae	Stimulant, Depressant	237
Banisteriopsis caapi	Yage	Plantae	Facilitator	233
Peganum harmala	Syrian rue	Plantae	Facilitator	151
Nymphaea nouchali	Blue lotus	Plantae	Depressant	101
Salvia divinorum	Salvia	Plantae	Dissociative	100
Passiflora incarnata	Passion flower	Plantae	Medicinal	87
Echinopsis pachanoi	San Pedro cactus	Plantae	Psychedelic	66
Acacia confusa	Formosan koa	Plantae	Psychedelic	63
Calea ternifolia	Dream herb	Plantae	Medicinal	61
Verbascum thapsus	Mullein	Plantae	Medicinal	58
Turnera diffusa	Damiana	Plantae	Anxiolytic	54
Lophophora williamsii	Peyote	Plantae	Psychedelic	52
Psilocybe tampanensis	Magic truffles	Fungi	Psychedelic	50
Diplopterys cabrerana	Chaliponga	Plantae	Psychedelic	43
Psychotria viridis	Chacruna	Plantae	Psychedelic	38
Psilocybe subaeruginosa	Gold tops	Fungi	Psychedelic	33
Erythroxylum coca	Coca plant	Plantae	Stimulant	32
Handroanthus impetiginosum	Pau d'arco	Plantae	Medicinal	31

Figure 2). Of the 22 species advertised as drugs, we verified that 21 of them contained chemicals with known drug properties. The most common drug class for fungi was psychedelics, found in 19 species and 1400 advertisements (Appendix S12). The active chemical psilocybin is a psychedelic found in every traded species of *Psilocybe*. There were 11 species advertised for their purported medicinal properties and three species traded as food, including the black truffle *Tuber melanosporum*.

Most fungi were traded as dead/raw (54% of fungi advertisements; 23 species), followed by processed/derived (31% fungi advertisements; 14 species), then live (15% fungi advertisements; 16 species; Appendix S13). One fungus species, the caterpillar fungus *Ophiocordyceps sinensis*, is categorized as Vulnerable by the IUCN as it is used and traded for medicinal purposes locally, nationally and internationally. No other traded fungi species were evaluated by the IUCN (except for *Hericium erinaceus*; Least Concern). No fungi were listed in CITES appendices and no traded fungi were classified as invasive.

Animals were more taxonomically diverse than fungi, having 14 families represented (10 families in the phylum Chordata, three

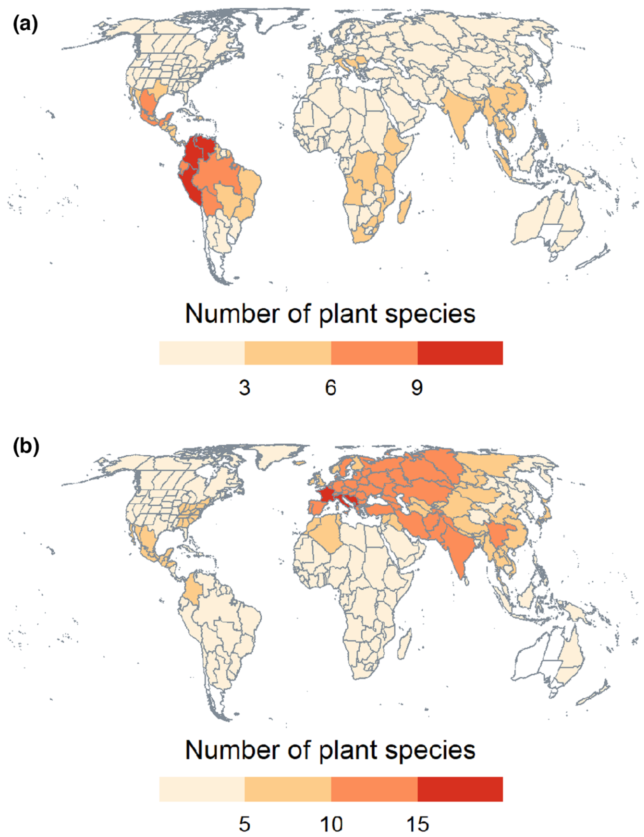

FIGURE 3 The native distribution of plant species traded on the dark web stratified by (a) if the plant has verified drug properties ($n=45$) and (b) all other traded plants species ($n=56$). The number and colours correspond to the number of species in each geographic area. Geographic area borders mostly correspond to either country or country subdivisions (see Appendix S7 for details). White indicates no species having native distributions. There were no traded plant species native to Antarctica. Note this map only shows traded plant species, not fungi or animals.

in Arthropoda, one in Echinodermata). Animals were traded for a range of use-types, including clothing (i.e. furs, skins), drugs, decorative purposes, pets, medicine and food. Of the 18 mammal species traded, the two most common species were the racoon *Procyon lotor*, traded for clothing (i.e. racoon fur), and the Sonoran Desert toad *Incilius alvarius*, traded because its secretions contain psychoactive properties (i.e. psychedelic).

There were three live species advertised as pets (12 advertisements): the African grey parrot *Psittacus erithacus*, hyacinth macaw *Anodorhynchus hyacinthinus* and goliath beetle *Goliathus goliatus*. Nine traded animal species were listed as threatened by the IUCN and one traded animal was categorized as Extinct (western black rhinoceros *Diceros bicornis longipes*). The nine threatened species included two parrots (*A. hyacinthinus* and *P. erithacus*), six mammals (*Panthera leo*, *Panthera tigris*, *Acinonyx jubatus*, *Loxodonta africana*, *Hippopotamus amphibius* and *Rangifer tarandus*), and *Apostichopus japonicus* (Japanese spiky sea cucumber). All traded mammals (except for *P. lotor* and *R. tarandus*) and the two threatened parrots were also listed in CITES Appendix I or II. Further, three animal taxa traded at the family level are listed in CITES Appendix I or II: Elephantidae, Rhinocerotidae and Pythonidae. Two traded animal species were classified as invasive (*P. lotor* and *R. tarandus*), although neither were traded as live specimens.

We recorded 17 traded species that were specified by sellers as being harvested from the wild, in 52 advertisements (median 3 wild-harvested advertisements per species; Appendix S15). Three wild-harvested species were listed as at risk of extinction by the IUCN: *A. japonicus* (Japanese spiky sea cucumber; Endangered), *L. williamsii* (peyote; Vulnerable) and *Ophiocordyceps sinensis* (caterpillar fungus; Vulnerable).

We observed some animals traditionally implicated in the illegal wildlife trade being advertised in low quantities. This included the tusks of species in the elephant family (Elephantidae) (i.e. ivory; $n=22$ advertisements), horns of species in the rhinoceros family (Rhinocerotidae; $n=13$), and the teeth and skins of tigers (*P. tigris*; $n=4$) and lions (*P. leo*; $n=3$).

We found several traded taxa that did not fit the traditional definition of wildlife trade. Specifically, there were five species of bacteria traded as potential bioweapons, including *Corynebacterium diphtheriae* (causes diphtheria), *Staphylococcus aureus* (causes a variety of infections) and *Clostridium botulinum* (causes botulism).

3.3 | General market & seller characteristics

Wildlife advertisements constituted a small proportion (0.2%) of all dark web advertisements. Advertisements of wildlife were found in 47 of the 51 marketplaces searched (92%), although the majority of marketplaces (>50%) contained less than 30 wildlife advertisements (Appendix S16). The number of species traded in a given marketplace generally increased as the number of wildlife advertisements in a marketplace increased (Appendix S17). Less than 1% of all dark-web sellers advertised wildlife (1222 of 155,094 sellers). The majority of sellers listed only a single advertisement of wildlife and thus, a single taxon (>50% of sellers, Appendix S16). The number of wildlife advertisements remained relatively stable over time (Appendix S18).

4 | DISCUSSION

Our results greatly expand on the number of wildlife species known to be traded on the dark web (Harrison et al., 2016; Roberts & Hernandez-Castro, 2017). At the same time, our findings confirm that the dark web is a highly specialized wildlife trade market, consisting primarily of plants, fungi and animals traded for their properties as recreational drugs. We speculate that other species which meet this criteria may become ensnared in future wildlife trade on the dark web, such as plants that contain methyltryptamines (i.e. DMT containing plants; Bussmann, 2016), *Psilocybe* fungi, plants with drug properties in Central and South America, or frogs that contain bufotoxin (de Greef, 2022; Figure 4). Further, we observed other types of wildlife trade occurring in much smaller amounts, for

FIGURE 4 A sample of species traded on the dark web for their properties as drugs. (a) Sonoran Desert toad *Incilius alvarius*, whose poison in the parotoid glands contains 5-MeO-DMT, a known psychedelic. (b) A preparation of Ayahuasca containing *Psychotria viridis*, a source of DMT, and *Banisteriopsis caapi*, a liana that contains monoamine oxidase inhibiting alkaliods (MAOIs). (c) *Psilocybe cubensis* contains the psychedelic compound psilocybin. (d) *Mitragyna speciosa* can have stimulant effects in low doses or opioid-like effects in higher doses. Photo credits: (a) Wildfeuer; (b) Awkipuma; (c) Alan Rockefeller; (d) Uomo vitruviano.

use as medicine, clothing, rituals and pets. While the conservation risks of this trade (through biodiversity loss and the introduction of new invasive alien species and novel diseases) are currently minimal, there is always the possibility of this trade expanding in the future.

The number of advertisements of wildlife, and the number of species traded on the dark web, appears to be vastly lower than the growth in trade on the open and deep web (Lavorgna, 2014; Sajeva et al., 2013; Stringham, Toomes, et al., 2021). We observed *c*. 600 advertisements of wildlife per year on the dark web across 47 marketplaces. While not directly comparable, other studies with different wildlife-trade contexts (i.e. public e-commerce sites) had a rate of three to over 300 times as many advertisements for a *single* website (i.e. from 2 to 67k advertisements per year: Olden et al., 2021; Xu et al., 2020; Ye et al., 2020). Further, while we found 154 species traded on the dark web, other non-dark-web online-trade studies have observed over 2600 species from one taxonomic kingdom or class (e.g. plants Humair et al., 2015 and reptiles Marshall et al., 2020, respectively). This comparison reinforces the notion of the dark web as a highly specialized and small niche market for wildlife as drugs. However, we note that we did not capture the volume of wildlife in a given advertisement and some advertisements may contain tens to hundreds of a given species/product or may represent an ongoing supply of the wildlife. For example, we observed the sale of 200kg of powered *Mimosa tenuiflora* root bark (DMT containing) in one advertisement. Thus, we note that the number of advisements we measured is a conservative measure of any given taxa traded on the dark web.

Given the small number of advertisements, and low species diversity, we assume that the current trade on the dark web is unlikely to be a major conservation threat. Nevertheless, we identified trade of three threatened species that were harvested from the wild (*Apostichopus japonicus*, *Lophophora williamsii* and *Ophiocordyceps sinensis*), which is of potential conservation concern and warrants further investigation. We note that not all sellers will explicitly mention if a specimen is harvested, thus, our numbers (52 advertisements mentioning wildlife was harvested) and interpretation may be conservative. Further, around half the species we found traded on the dark web (74 species) have not been evaluated by the IUCN, representing a serious gap in determining the conservation risk of these species. Also, the trade we uncovered of elephants, rhinos, tigers and lions likely originated from wild animals and demands further investigation. In terms of biosecurity, the dark web is unlikely to be a concern currently or is at most of low concern for invasive species. We found nine species traded that are known invasive species (seven plants, two animals); however, none were traded alive (i.e. only dead or derived products) and therefore of low biosecurity concern. We note that the database we used for categorizing invasive species (GISD) does not include many regionally invasive species. Thus, we may have missed categorizing some invasive species traded on the dark web. Yet, of the live specimens traded (31 species), most occurred in limited numbers (i.e. the median number of advertisements was three), which is why we consider this trade to be a low concern for invasive species (Cassey et al., 2018). We did not evaluate the disease risk of traded taxa, which can potentially be hosts or reservoirs for wildlife or human pathogens (Calisher et al., 2006; Fu & Waldman, 2022; Liebhold et al., 2012).

In terms of legality, we were unable to quantify if traded species were illegal because we did not know what jurisdictions the trades occurred in (Fukushima et al., 2021). Thus, it is possible that some of this trade may be illegal from an environmental (i.e. conservation/biosecurity) legislative standpoint. In particular, species listed in CITES Appendices ($n=17$) are illegal to trade between international borders (assuming dark web sellers do not have a permit and CITES and/or national legislation requires one). However, it is more likely that many of these species are regulated for their drug properties. For example, the most common species on the dark web, the magic mushroom *Psilocybe cubensis*, is currently illegal to sell or possess in most of the United States (Pollan, 2019).

We did not attempt to verify the validity of dark web advertisements. In general, the validity of any online wildlife advertisement is difficult to verify (i.e. determine if the advertisement is genuine or fraudulent). This is especially true in the case of the dark web, particularly without the help of law enforcement agencies (Stringham, Toomes, et al., 2021). Specifically, sellers may either obscure what wildlife is being traded (i.e. use vague or coded descriptions) or falsely advertise wildlife, even if they do not actually possess the species being sold (i.e. scams). Prior studies of wildlife trade on the dark web have attempted to verify advertisements (Harrison et al., 2016; Roberts & Hernandez-Castro, 2017); however, since we identified substantially more advertisements, this was not feasible during our study. Therefore, it is possible that some advertisements we found were falsified (e.g. fake rhinoceros horns have been found in advertisements in prior studies; Harrison et al., 2016; Roberts & Hernandez-Castro, 2017).

Due to the nature of the dark web, we cannot rule out the possibility that there are other sites (marketplaces or forums) where wildlife is traded. This is a serious limitation of monitoring the dark web where unlike on the open and deep web, either a search engine can find relevant websites, or a company keeps records of what is being sold (e.g. eBay), the dark web keeps no such records. Thus, we very likely did not capture the entirety of wildlife trade on the dark web, although we used the most comprehensive dataset of the dark web available, DATACRYPTO (Décary-Hétu & Aldridge, 2015). Further, the sites monitored by DATACRYPTO are the most accessed dark web sites on the Internet. Therefore, if there are other sites on the dark web where wildlife trade is occurring, then we speculate that trade volume is even lower than what we observed on the general illicit marketplaces covered by DATACRYPTO. Finally, the search terms we used to search through DATACRYPTO were not as targeted as we initially assumed because *c.* 1.2 out of *c.* 1.9 million advertisements (*c.* 60% of the entire database) were returned. Thus, we suspect that we did not miss many advertisements in DATACRYPTO that traded wildlife.

Current wildlife trade is thriving on the open (e-commerce) and deep web (social media, messaging apps; Hinsley et al., 2016; Sánchez-Mercado et al., 2020; Sung et al., 2021), and an increasing number of species are directly threatened by this trade (Fukushima et al., 2021). Thus, in the limited resource landscape of conservation and biosecurity efforts (World Bank Group, 2016), we recommend that the majority of monitoring and enforcement resources for wildlife crime linked to the internet be focused on the open and deep web; especially considering the massive amount of trade occurring on social media sites, such as Facebook (Xu et al., 2020). This recommendation is especially relevant given the continuing efforts from CITES to implement monitoring to track all online wildlife trade (CITES Resolution Conf. 11.3, Rev. CoP18). If future wildlife trade increases on the dark web we have provided a baseline to compare the composition and frequency of trade against. We strongly encourage continued regular surveillance of the dark web as well as new efforts to find any dark-web marketplaces or websites that trade wildlife, but which are not currently known.

AUTHOR CONTRIBUTIONS

Oliver C. Stringham: conceptualization, methodology, formal analysis, data curation, writing—original draft, writing—review & editing, visualization, supervision, project administration; **Jacob Maher**: methodology, investigation, data curation, writing—original draft, writing—review & editing, visualization; **Charlotte R. Lassaline**: data curation, writing—original draft, writing—review & editing; **Lisa Wood**: data curation, writing—original draft, writing—review & editing; **Stephanie Moncayo**: data curation, writing—review & editing; **Adam Toomes**: data curation, writing—review & editing; **Sarah Heinrich**: writing—review & editing; **Freyja Watters**: writing—review & editing; **Charlotte Drake**: data curation, writing—review & editing; **Sebastian Chekunov**: data curation, writing—review & editing; **Katherine G. W. Hill**: writing—review & editing; **David Decary-Hetu**: software, data acquisition, writing—review & editing; **Lewis Mitchell**: data curation, writing—review & editing, supervision, funding acquisition; **Joshua V. Ross**: writing—review & editing, supervision, funding acquisition; **Phillip Cassey**: conceptualization, resources, data curation, writing—review & editing, supervision, funding acquisition.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to state.

DATA AVAILABILITY STATEMENT

The data used in this paper can be downloaded at https://doi.org/10.6084/m9.figshare.20063726.v2.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Full list of search terms.

Appendix S2. Semi-automated and manual methods to detect if advertisements were trading wildlife.

Appendix S3. Taxa found traded on the dark web but were excluded from analysis.

Appendix S4. Wildlife advertisement category definitions.

Appendix S5. Wildlife advertisement end use definitions.

Appendix S6. Methods for drug verification and classification.

Appendix S7. Methods to obtain native plant distributions.

Appendix S8. Dataset of taxon-advertisement combinations.

Appendix S9. Detailed results of number of taxa and advertisements by taxonomic rank.

Appendix S10. Dataset of taxa traded on the dark web and their characteristics.

Appendix S11. Detailed results of taxonomic diversity.

Appendix S12. Detailed results of species with known drug properties.

Appendix S13. Detailed results of advertisement category by taxonomic kingdom.

Appendix S14. Dataset of plant species richness by geographic areas.

Appendix S15. Detailed results on species advertised as wild harvested.

Appendix S16. Detailed results on market and seller characteristics.

Appendix S17. Detailed results on marketplace and species relationships.

Appendix S18. Detailed results of taxonomic trends over time

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