The dark web trades wildlife, but mostly as drugs

Oliver C. Stringham[1,2], Jacob Maher[1], Charlotte R. Lassaline[1], Lisa Wood[1], Stephanie Moncayo[1], Adam Toomes[1], Sarah Heinrich[1], Charlotte Drake[1], Sebastian Chekunov[1], Katherine G.W. Hill[1], David Decary-Hetu[3], Lewis Mitchell[2], Joshua V. Ross[2], Phillip Cassey[1]

1. Invasion Science & Wildlife Ecology Lab, University of Adelaide, SA 5005, Australia
2. School of Mathematical Sciences, University of Adelaide, SA 5005, Australia
3. School of Criminology, Université de Montréal. 2900 Boul., Edouard-Montpetit, C.P. 6128, succursale Centre-ville, Montréal, Québec, Canada, H3C 3J7

Corresponding Author: Phillip Cassey, The University of Adelaide, North Terrace Campus, Adelaide, SA, 5000, Australia. phill.cassey@adelaide.edu.au

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

Palabras Clave: uso biológico, bioseguridad, conservación, drogas, especies exóticas, comercio ilegal de vida silvestre, medicina tradicional

Abstract

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 lacks thorough investigation. Here, we accessed a comprehensive database of dark web marketplaces to search across c. 2 million dark web advertisements over 5 years using c. 7k wildlife trade-related search terms. We found 153 species traded in 3,332 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. 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. Our results greatly expand on what 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 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.

Resumen

La web oscura comercializa vida silvestre, pero principalmente como drogas

El internet facilita enormemente el comercio contemporáneo de vida silvestre. Por diseño, la web oscura es una capa de Internet que es difícil de monitorear y carece de una investigación exhaustiva. Aquí, accedimos a una base de datos completa de mercados de la web oscura y buscamos a través c. 2 millones de anuncios web oscuros durante 5 años utilizando c. 7k términos de búsqueda relacionados con el comercio de vida silvestre. Encontramos 153 especies comercializadas en 3332 anuncios (c. 600 anuncios por año). Caracterizamos un mercado de comercio de vida silvestre altamente especializado, donde c. el 90% de los anuncios de vida silvestre en la web oscura eran de drogas recreativas. Verificamos que 68 especies contenían químicos con propiedades farmacológicas. Las especies anunciadas como medicamentos se componen principalmente de especies de plantas, sin embargo, los hongos y los animales también se comercializaron como medicamentos. La mayoría de las especies con propiedades farmacológicas eran psicodélicos (45 especies), incluido un género de hongos, *Psilocybe*, con 19 especies comercializadas en la web oscura. La distribución nativa de plantas con propiedades farmacológicas se agruparon en América Central y del Sur. Una proporción más pequeña del comercio fue para las supuestas propiedades medicinales de la vida silvestre, la ropa, la decoración y como mascotas. Nuestros resultados amplían en gran medida qué especies se comercializan actualmente en la web oscura y proporcionan una línea de base para rastrear cambios futuros. Dada la baja cantidad de anuncios, asumimos que los riesgos actuales de conservación y bioseguridad de la dark web son bajos. Si bien el comercio de vida silvestre prolifera en otras capas de Internet, particularmente en el comercio electrónico y los sitios de redes sociales, el comercio en la web oscura puede aumentar si estas plataformas populares se vuelven menos accesibles para los comerciantes (por ejemplo, a través de

un aumento en la aplicación). Recomendamos enfocarse en la vigilancia de los sitios de comercio electrónico y redes sociales, pero alentamos el monitoreo continuo de la web oscura periódicamente, para evaluar los posibles cambios en el comercio de vida silvestre a través de esta capa más ocluida de Internet.

Introduction

Wildlife trade can present severe conservation, biosecurity, and ethical problems (‘t Sas-Rolfes et al. 2019; Fukushima et al. 2020; Cardoso et al. 2021). 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 (Stringham et al. 2021b; Fukushima 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).

The dark web is different from other layers of the Internet in several ways (Stringham et al. 2021b). First, the dark web requires special software to access, making it more obscured and difficult to access 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; Soska & Christin 2015; Cunliffe et al. 2017).

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)). However, some wildlife has been traded on dark-web drug marketplaces and prior studies monitored 5 marketplaces from 2014 to 2017; finding cacti (sold as drugs for their hallucinogenic properties), reptile-skin handbags, and a handful of advertisements for ivory and rhino horns (Harrison et al. 2016; Roberts & Hernandez-Castro 2017).

Here, we provide an extensive examination of wildlife trade on high-traffic portions of 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 what wildlife is being traded on the dark web.

Methods

We accessed a dark-web database collected by the DATACRYPTO software (described in (Décary-Hétu & Aldridge 2015)). At the time we accessed the database (May 2021), it 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 6,959 keywords related to the scientific names, common names, and use-types involved in the illegal wildlife trade (derived from (Stringham et al. 2021a); a full list of search terms is provided in Appendix S1). 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 3,332 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). 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.

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 underwent 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 used the Global Invasive Species Database to designate if a species is invasive (GISD) (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 conservation concern (i.e., IUCN status, 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 performed 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).

Results

Overall characteristics

We identified 153 species traded from 3,332 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 (Appendix S10 for full list of species and taxa) and 4,368 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 (Appendix S10). Psychedelics were the most common class of drugs measured by number of advertisements (n = 2,403) 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 are categorized as Least Concern and 19 species are threatened (Vulnerable, Endangered, or Critically Endangered). Nine traded species are categorized as invasive by the Global Invasive Species Database (GISD); although none of those species were traded live.

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 2,513 taxon-advertisements (58% of total), followed closely by fungi with 1,721 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 (Appendix S10; Appendix 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 common plant traded (n=551 advertisements), contains methyltryptamine (DMT), a psychedelic (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. 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, 1,381 advertisements, 17 species), where *P. cubensis* (commonly referred to as 'magic mushroom') was the most popular species in this study, with 1,189 advertisements (Table 1). Almost all fungi were sold as drugs (96% of listings; 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 1,400 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) and no traded fungi were classified as invasive.

Animals were more taxonomically diverse than fungi, having 14 families represented. Animals were traded for a range of use-types, including clothing (i.e., furs, skins), drugs, decorative purposes, pets, medicine, and food. The two most common animal 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 are listed as Threatened by the IUCN and one traded animal was categorized as Extinct (western black rhinoceros, *Diceros bicornis longipes*). Two traded animal species were classified as invasive (*Procyon lotor* and *Rangifer tarandus*), although neither were traded as live specimens.

We recorded 17 traded species that were specified by sellers to be wild harvested, in 52 advertisements (median 3 wild-harvested advertisements per species; Appendix S15). Three wild-harvested species are listed as at risk of extinction by the IUCN: *Apostichopus japonicus* (Japanese spiky sea cucumber; Endangered), *Lophophora 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 ads), horns of species in the rhinoceros family (Rhinocerotidae, n=13), and the teeth and skins of tigers (*Panthera tigris*, n=4) and lions (*Panthera 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).

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 (1,222 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).

Discussion

Our results greatly expand on the number of wildlife species known to be traded on the dark web. At the same time, our findings suggest 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 3). Our findings are consistent with prior research that found the dark web to mostly trade wildlife as drugs (Harrison et al. 2016; Roberts & Hernandez-Castro 2017). However, we did observe other types of wildlife trade occurring in much smaller amounts, for use as medicine, clothing, decor, rituals, and pets. While this trade is currently minimal, there is always the possibility of this trade expanding in the future.

The quantity of wildlife and number of species traded on the dark web appears to be vastly lower than the open and deep web. 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 2k to 67k advertisements per year: (Xu et al. 2020; Ye et al. 2020; Olden et al. 2021)). Further, while we found 154 species traded on the dark web, other non-dark-web online-trade studies have observed over 2,600 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 and wild harvested species, which is of potential conservation concern for those species and warrants further investigation. For the same reason, the dark web is unlikely to be a biosecurity concern currently, or is at most of low concern for invasive species. We found nine species traded that are known invasive species (7 plants, 2 animals); however, none were traded alive (i.e., only dead or derived products) and therefore cannot become invasive. 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; Liebhold et al. 2012; Fu & Waldman 2022). 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. 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 illegal to sell or possess in 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 et al. 2021b). 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 found in advertisements in prior studies (Harrison et al. 2016; Roberts & Hernandez-Castro 2017)).

A serious limitation of monitoring the dark web is that it is not possible to know every location (e.g., website) where wildlife is traded. Specifically, 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. Unlike the open and deep web, where 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.

We provide a baseline of wildlife trade to be compared against future trade on the dark web. If wildlife trade increases on the dark web in the future, we should turn our collective efforts to reporting illegal trade and enforcing trade regulations. Nevertheless, 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). Thus, in the limited resource landscape of conservation and biosecurity efforts related to wildlife trade (World Bank Group 2016), we recommend most monitoring and enforcement resources 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). At the same time, we recommend continued regular surveillance of the dark web and encourage new efforts to find any dark-web marketplaces or websites that trade wildlife, but which are not currently known.

Data Availability

The data used in this paper can be downloaded at https://figshare.com/articles/dataset/The_dark_web_trades_wildlife_but_mostly_as_drugs/20063726.

Acknowledgements

The authors acknowledge the Kaurna people as the Traditional Owners of the land where we live and work. We acknowledge the Kaurna people as the custodians of the Adelaide region and we respect and value their past, present and ongoing connection to the land and cultural beliefs. This work was supported by funding from the Centre for Invasive Species Solutions (PO1-I-002: 'Understanding and intervening in illegal trade in non-native species'), and an Australian Research Council Discovery Grant (DP210103050: 'Drivers of the live pet trade in Australian reptiles').

References

Aldridge J, Décary-Hétu D. 2014. Not an “Ebay for Drugs”: The Cryptomarket “Silk Road” as a Paradigm Shifting Criminal Innovation. SSRN Scholarly Paper ID 2436643. Social Science Research Network, Rochester, NY. Available from https://papers.ssrn.com/abstract=2436643 (accessed January 5, 2022).

Allaire JJ, Gandrud C, Russell K, Yetman CJ. 2017. networkD3: D3 JavaScript Network Graphs from R. R package version 0.4. Available from https://CRAN.R-project.org/package=networkD3.

Brito-da-Costa AM, Dias-da-Silva D, Gomes NGM, Dinis-Oliveira RJ, Madureira-Carvalho Á. 2020. Toxicokinetics and Toxicodynamics of Ayahuasca Alkaloids N,N-Dimethyltryptamine (DMT), Harmine, Harmaline and Tetrahydroharmine: Clinical and Forensic Impact. Pharmaceuticals **13**:334. Multidisciplinary Digital Publishing Institute.

Brummit RK. 2001. World Geographical Scheme for Recording Plant Distributions., 2nd edition. Hunt Institute for Botanical Documentation, Carnegie Mellon University, Pittsburgh. Available from https://github.com/tdwg/wgsrpd.

Brunson JC. 2020. ggalluvial: Layered Grammar for Alluvial Plots. Journal of Open Source Software **5**:2017.

Bussmann RW. 2016. Magic Plants. Pages 163–169 in Albuquerque UP, Nóbrega Alves RR, editors. Introduction to Ethnobiology. Springer International Publishing, Cham. Available from https://doi.org/10.1007/978-3-319-28155-1_24 (accessed January 27, 2022).

Calisher CH, Childs JE, Field HE, Holmes KV, Schountz T. 2006. Bats: Important Reservoir Hosts of Emerging Viruses. Clinical Microbiology Reviews **19**:531–545. American Society for Microbiology.

Cardoso P et al. 2021. Scientists’ warning to humanity on illegal or unsustainable wildlife trade. Biological Conservation **263**:109341.

Cassey P, Delean S, Lockwood JL, Sadowski JS, Blackburn TM. 2018. Dissecting the null model for biological invasions: A meta-analysis of the propagule pressure effect. PLOS Biology **16**:e2005987.

Chamberlain SA, Szöcs E. 2013. taxize: taxonomic search and retrieval in R. F1000Research **2**:191.

Conway M. 2020. gsheet: Download Google Sheets Using Just the URL. R package version 0.4.5. Available from https://CRAN.R-project.org/package=gsheet.

Cunliffe J, Martin J, Décary-Hétu D, Aldridge J. 2017. An island apart? Risks and prices in the Australian cryptomarket drug trade. International Journal of Drug Policy **50**:64–73.

de Greef K. 2022, March 21. The Pied Piper of Psychedelic Toads. The New Yorker. Available from https://www.newyorker.com/magazine/2022/03/28/the-pied-piper-of-psychedelic-toads (accessed March 23, 2022).

Décary-Hétu D, Aldridge J. 2015. Sifting through the net: Monitoring of online offenders by researchers. European Review of Organised Crime **2**:122–141.

Décary-Hétu D, Giommoni L. 2017. Do police crackdowns disrupt drug cryptomarkets? A longitudinal analysis of the effects of Operation Onymous. Crime, Law and Social Change **67**:55–75.

Firke S. 2021. janitor: Simple Tools for Examining and Cleaning Dirty Data. R package version 2.1.0. Available from https://CRAN.R-project.org/package=janitor.

Fu M, Waldman B. 2022. Novel chytrid pathogen variants and the global amphibian pet trade. Conservation BiologyDOI: 10.1111/cobi.13938. Available from https://onlinelibrary.wiley.com/doi/abs/10.1111/cobi.13938 (accessed June 2, 2022).

Fukushima CS et al. 2021. Challenges and perspectives on tackling illegal or unsustainable wildlife trade. Biological Conservation **263**:109342.

Fukushima CS, Mammola S, Cardoso P. 2020. Global wildlife trade permeates the Tree of Life. Biological Conservation **247**:108503.

GBIF. 2022. GBIF: The Global Biodiversity Information Facility. Available from https://www.gbif.org/what-is-gbif.

Gohel D. 2021a. flextable: Functions for Tabular Reporting. R package version 0.6.6. Available from https://CRAN.R-project.org/package=flextable.
Gohel D. 2021b. officer: Manipulation of Microsoft Word and PowerPoint Documents. R package version 0.3.18. Available from https://CRAN.R-project.org/package=officer.
Grolemund G, Wickham H. 2011. Dates and Times Made Easy with lubridate. Journal of Statistical Software **40**:1–25.
Harrison JR, Roberts DL, Hernandez-Castro J. 2016. Assessing the extent and nature of wildlife trade on the dark web. Conservation Biology **30**:900–904.
Heinrich S, Ross JV, Cassey P. 2019. Of cowboys, fish, and pangolins: US trade in exotic leather. Conservation Science and Practice **1**:e75.
Hester J, Bryan J. 2022. Interpreted String Literals. R package version 1.6.2. Available from https://CRAN.R-project.org/package=glue.
Hinsley A, Lee TE, Harrison JR, Roberts DL. 2016. Estimating the extent and structure of trade in horticultural orchids via social media. Conservation Biology **30**:1038–1047.
Hiramoto N, Tsuchiya Y. 2020. Measuring dark web marketplaces via Bitcoin transactions: From birth to independence. Forensic Science International: Digital Investigation **35**:301086.
Humair F, Humair L, Kuhn F, Kueffer C. 2015. E-commerce trade in invasive plants. Conservation Biology **29**:1658–1665.
Invasive Species Specialist Group. 2015. The Global Invasive Species Database. Available from http://www.iucngisd.org/gisd/.
IUCN. 2021. The IUCN Red List of Threatened Species. Available from https://www.iucnredlist.org.
Lavorgna A. 2014. Wildlife trafficking in the Internet age. Crime Science **3**:5.
Liebhold AM, Brockerhoff EG, Garrett LJ, Parke JL, Britton KO. 2012. Live plant imports: the major pathway for forest insect and pathogen invasions of the US. Frontiers in Ecology and the Environment **10**:135–143.
Marshall BM, Strine C, Hughes AC. 2020. Thousands of reptile species threatened by under-regulated global trade. Nature Communications **11**:4738. Nature Publishing Group.
Olden JD, Whattam E, Wood SA. 2021. Online auction marketplaces as a global pathway for aquatic invasive species. Hydrobiologia **848**:1967–1979.
Pebesma E. 2018. Simple Features for R: Standardized Support for Spatial Vector Data. The R Journal **10**:439–446.
Pedersen TL. 2020. patchwork: The Composer of Plots. R package version 1.1.1. Available from https://CRAN.R-project.org/package=patchwork.
Pollan M. 2019, May 10. Opinion | Michael Pollan: Not So Fast on Psychedelic Mushrooms. The New York Times. Available from https://www.nytimes.com/2019/05/10/opinion/denver-mushrooms-psilocybin.html (accessed March 21, 2022).
R Core Team. 2022. R Foundation for Statistical Computing, Vienna, Austria. Available from https://www.R-project.org/.
Roberts DL, Hernandez-Castro J. 2017. Bycatch and illegal wildlife trade on the dark web. Oryx **51**:393–394. Cambridge University Press.
Sánchez-Mercado A, Cardozo-Urdaneta A, Moran L, Ovalle L, Arvelo MÁ, Morales-Campos J, Coyle B, Braun MJ, Rodríguez-Clark KM. 2020. Social network analysis reveals specialized trade in an Endangered songbird. Animal Conservation **23**:132–144.
Siriwat P, Nijman V. 2020. Wildlife trade shifts from brick-and-mortar markets to virtual marketplaces: A case study of birds of prey trade in Thailand. Journal of Asia-Pacific Biodiversity **13**:454–461.
Soska K, Christin N. 2015. Measuring the Longitudinal Evolution of the Online Anonymous Marketplace Ecosystem. Pages 33–48. Available from https://www.usenix.org/conference/usenixsecurity15/technical-sessions/presentation/soska (accessed January 5, 2022).

Stringham OC et al. 2021a. Dataset of seized wildlife and their intended uses. Data in Brief **39**:107531.
Stringham OC, Toomes A, Kanishka AM, Mitchell L, Heinrich S, Ross JV, Cassey P. 2021b. A guide to using the internet to monitor and quantify the wildlife trade. Conservation Biology **35**:1130–1139.
Sung Y-H, Lee W-H, Leung FK-W, Fong JJ. 2021. Prevalence of illegal turtle trade on social media and implications for wildlife trade monitoring. Biological Conservation **261**:109245.
‘t Sas-Rolfes M, Challender DWS, Hinsley A, Veríssimo D, Milner-Gulland EJ. 2019. Illegal Wildlife Trade: Scale, Processes, and Governance. Annual Review of Environment and Resources **44**:201–228.
Vaidyanathan R, Xie Y, Allaire JJ, Cheng J, Sievert C, Russell K. 2021. htmlwidgets: HTML Widgets for R. R package version 1.5.4. Available from https://CRAN.R-project.org/package=htmlwidgets.
Van TP, Luu VQ, Tien TV, Leprince B, Khanh LTT, Luiselli L. 2019. Longitudinal monitoring of turtle trade through Facebook in Vietnam. Herpetological Journal **29**:48–56.
Whitehead D, Cowell CR, Lavorgna A, Middleton SE. 2021. Countering plant crime online: Cross-disciplinary collaboration in the FloraGuard study. Forensic Science International: Animals and Environments **1**:100007.
Wickham H et al. 2019. Welcome to the Tidyverse. Journal of Open Source Software **4**:1686. The Open Journal.
World Bank Group. 2016. Analysis of International Funding to Tackle Illegal Wildlife Trade. World Bank. Available from https://elibrary.worldbank.org/doi/abs/10.1596/25340 (accessed May 20, 2022).
Xu Q, Cai M, Mackey TK. 2020. The illegal wildlife digital market: an analysis of Chinese wildlife marketing and sale on Facebook. Environmental Conservation:1–7. Cambridge University Press.
Ye Y-C, Yu W-H, Newman C, Buesching CD, Xu Y, Xiao X, Macdonald DW, Zhou Z-M. 2020. Effects of regional economics on the online sale of protected parrots and turtles in China. Conservation Science and Practice:e161.
Zhuang Y, Peltier E, Feuer A. 2021, June 8. The Criminals Thought the Devices Were Secure. But the Seller Was the F.B.I. The New York Times. Available from https://www.nytimes.com/2021/06/08/world/australia/operation-trojan-horse-anom.html (accessed January 5, 2022).

Tables

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	1,189
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

Species	Common name	Kingdom	Drug Class	Number of ads
Handroanthus impetiginosum	Pau d'arco	Plantae	Medicinal	31

Figures

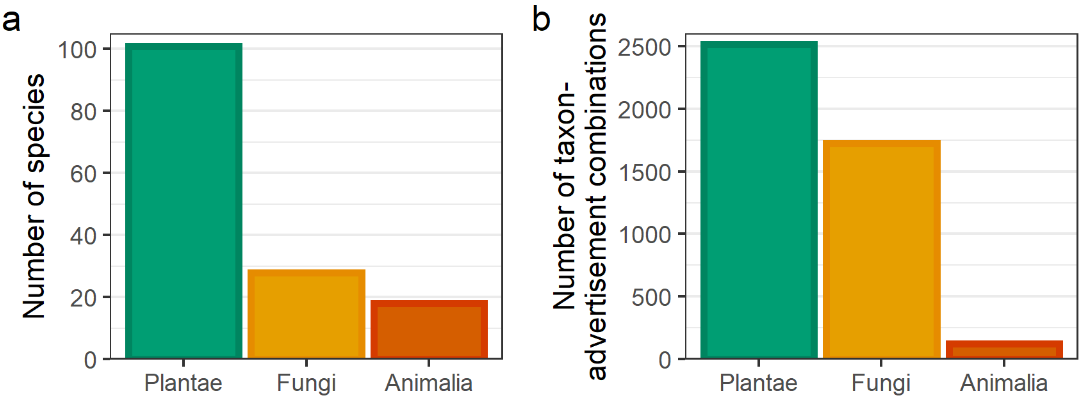

Figure 1.

(a) The number of species traded on the dark web and (b) the number of taxon-advertisement combinations, stratified by taxonomic kingdom.

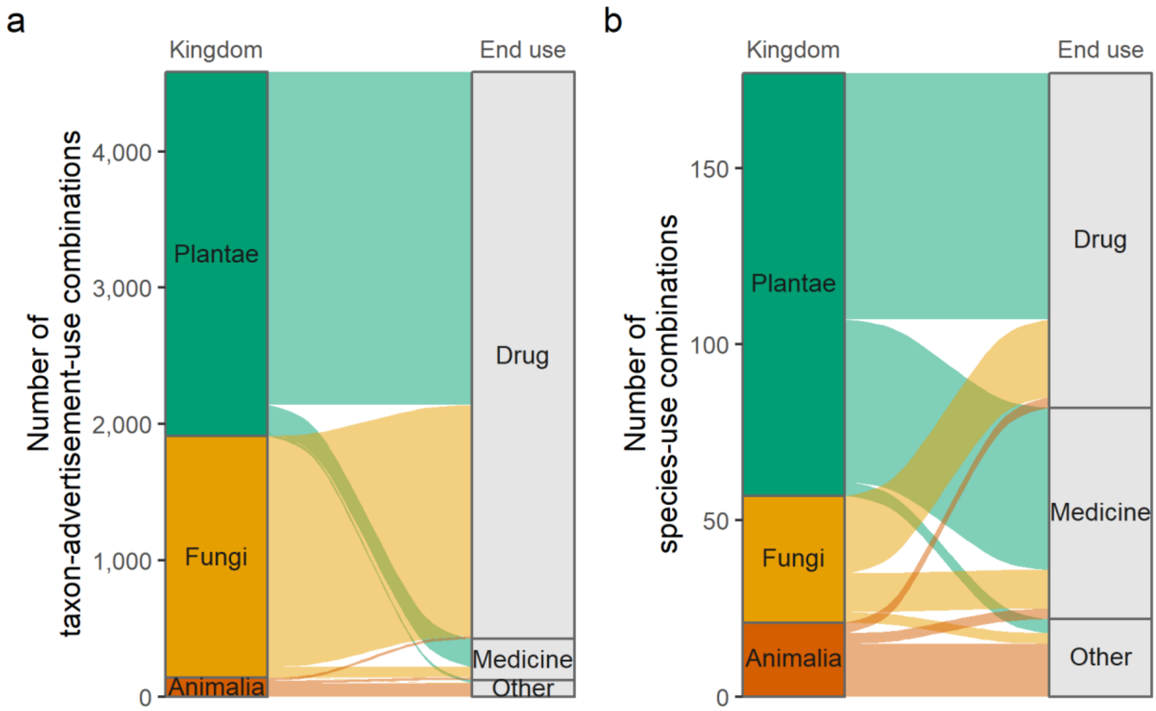

Figure 2.

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).

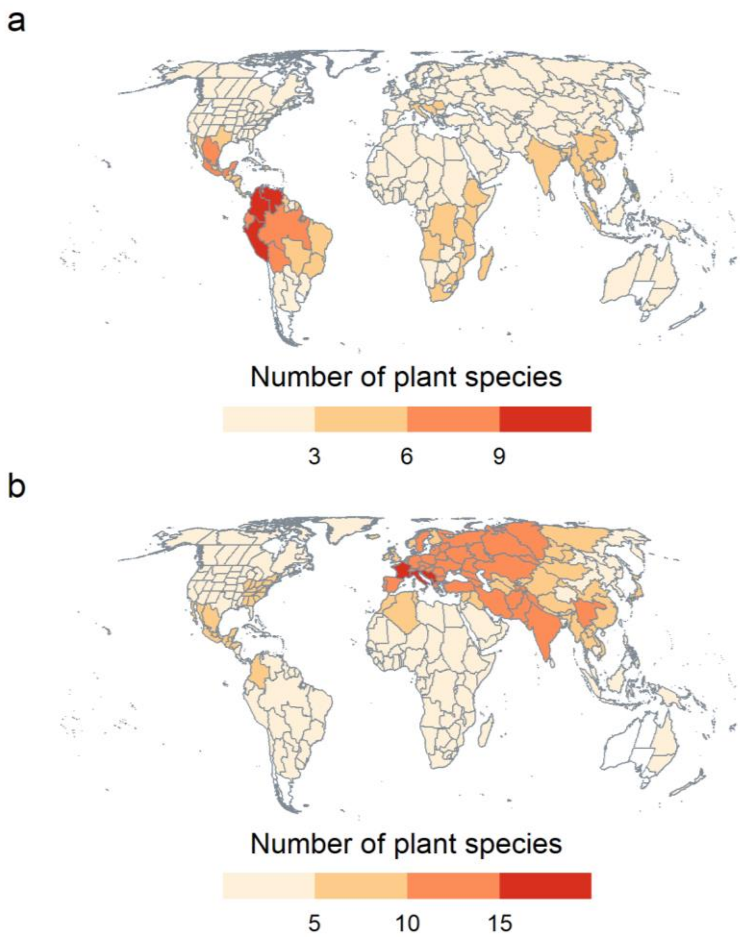

Figure 3.

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.

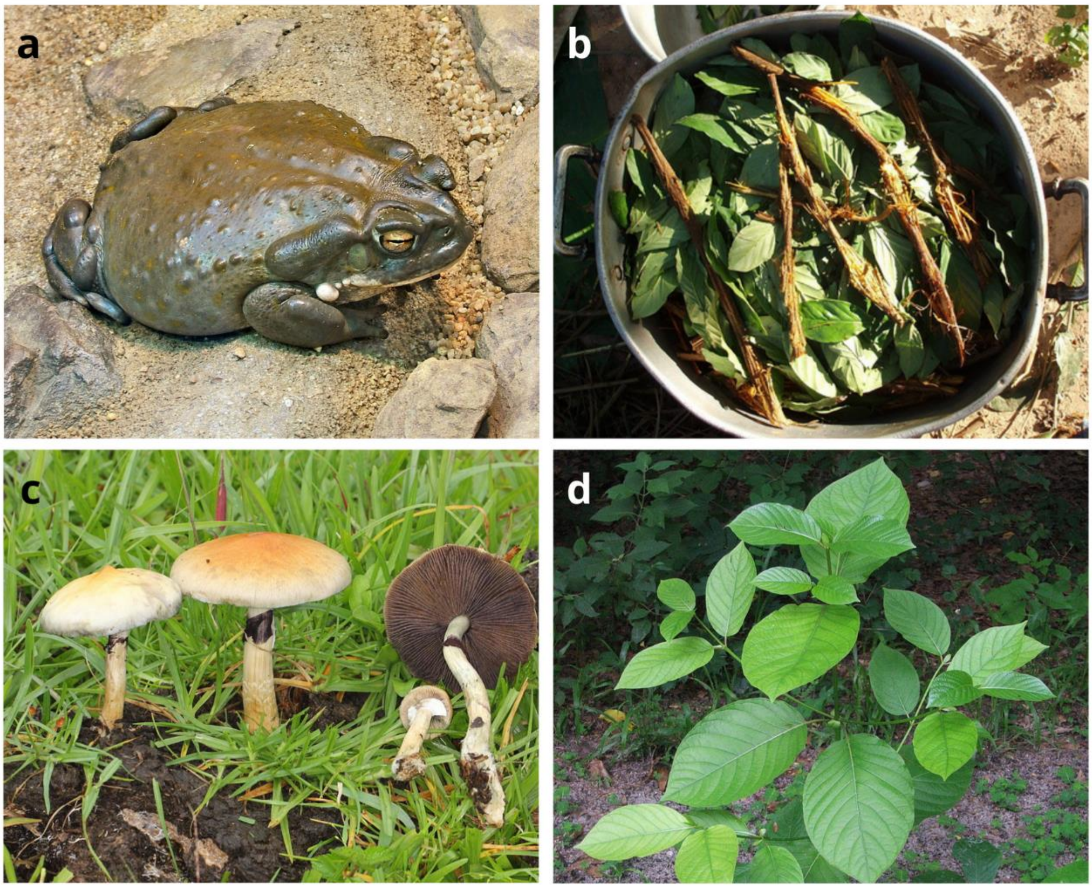

Figure 4.

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.

Appendix

Table of Contents

Appendix S1: Full list of search terms

Refer to csv file named “Appendix_S01_dark_web_search_terms.csv” for the full list of search terms supplied to search through DATACRYPTO.

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

Overview

We processed the collected advertisements from DATACRYPTO to identify if wildlife were traded.

First, we removed exact duplicates, which we defined as advertisements with the exact same text description. Next, we removed fuzzy duplicates within sellers, which we defined as advertisements that were greater than 80% similar based on Levenshtein distance (using the "ratio" function from the python package "python-Levenshtein", version 0.12.0). For fuzzy duplicates, we only compared advertisements by the same seller. Exact and fuzzy duplicates may have occurred due to cross-marketplace postings of the same seller or sellers with different usernames posting the same advertisements. After removing both exact and fuzzy duplicates, 354,635 advertisements remained.

We then searched the remaining advertisements for exact matches to the keywords supplied originally to the database (see Methods in main text). We manually examined these advertisements to determine if wildlife was traded.

Since the remaining unexplored advertisements were numerous (>300k), we used topic modelling, a natural language processing method (Griffiths and Steyvers 2004), to categorize advertisements based on their topics (see below for detailed methods of topic modelling). This process resulted in 47 topics and we removed advertisements that belonged to topics we deemed as not related to the wildlife trade (e.g., bank account information or prescription drugs). This topic modelling process removed 134,596 advertisements.

Next, we removed listings based on a separate list of keywords generated as the most common unigrams and bigrams. This removed a further 130,020 advertisements. Finally, for the remaining 82,114 advertisements, we manually scanned to detect if wildlife was traded, resulting in 3,332 advertisements.

Details of Topic Modelling and Topic Labelling

The purpose of the topic modelling was to identify topics that did not involve the trade of wildlife and exclude advertisements categorized to these topics from further investigation.

First, we performed standard text cleaning methods to prepare the text for topic modelling. We converted all text to lower case, removed punctuation, removed extra spaces, and removed numbers. Then, we removed English stop words (from python package "nltk", version 3.4.5). Next, we stemmed words using the Porter stemmer (from "nltk" package).

We tokenized by unigrams and excluded unigrams found in greater than 95% of advertisements and also excluded unigrams found in less than 5% of advertisements. This was achieved using the "CountVectorizer" function from the python package "scikit-learn" (version 1.0.1).

Next, we performed topic modelling using a Latent Dirichlet Allocation (LDA) model. We tuned the model, testing multiple values for the number of topics, ranging from 1 to 85 topics. We chose the model with the lowest log-likelihood score (Griffiths and Steyvers 2004), which was, in our case, 58 topics. To implement the LDA modelling, we used the "LatentDirichletAllocation" function from the "scikit-learn" package.

We assigned each advertisement a topic determined by the LDA prediction with the highest proportion (of a topic) for a given advertisement. To determine a label for a topic (e.g., prescription drugs or banks accounts), we first randomly sampled advertisements from each topic. We chose to restrict sampling to advertisements with over 0.5 proportion of a topic. We manually determined the topic by scanning through a sample of advertisements for a given topic. Examples of topics we determined were: credit card numbers, computer software, e-books, cannabis/THC vapes, Viagra and other prescription drugs, and LSD. We removed from consideration topics that we suspected could include wildlife or that included advertisements with wildlife in the sample. For example, one topic included peyote, which is a small cactus. Other topics we did not consider contained a mixture of different drugs that we could not rule out if wildlife was traded or not. Overall, we did not consider 11 topics, leaving 47 topics for further investigation for removal.

We performed sampling for each remaining topic, stratified by the predicted proportion an advertisement was (from LDA) from that topic (e.g., 10 samples from 0.5 to 0.6 predicted probability, 10 samples from 0.6 to 0.7, etc.). We then labelled each advertisement sampled as being relevant to the given topic. Next, for each topic, we identified the predicted probability that it contained all relevant advertisements. For example, if advertisements from the topic "e-books" were only relevant if the predicted proportion of the topic was 0.7 or greater, we only selected advertisements with over 0.7. Overall, this topic modelling process resulted in excluding 134,596 advertisements from further analysis for wildlife trade from 47 topics.

References

Griffiths TL, Steyvers M. 2004. Finding scientific topics. PNAS. 101: 5228–5235. doi:10.1073/pnas.0307752101

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

Refer to csv file named “Appendix_S03_excluded_taxa.csv” for the full list of taxa we found traded on the dark web but we excluded from our analyses because they are commercially produced for either agricultural, forestry, aquaculture, or apiculture reasons. Refer to Table S3 for a description of the columns. Note, we excluded all species of the genera *Cannabis*, who trade was widespread on the dark web (>100k advertisement’s) and is also produced commercially. Finally, we excluded two advertisements trading human (*Homo sapiens*) skulls, because humans are not traditionally considered being part of wildlife trade.

Table S3. Column descriptions for the data file “Appendix_S03_excluded_taxa.csv”

Column	Description
gbif_name	The name of the taxon according to GBIF
gbif_rank	The taxonomic rank of the taxon (i.e., species, genus) according to GBIF
gbif_id	GBIF’s unique identifier for the taxon
reason_excluded	The reason why the taxon was excluded from our analysis.
kingdom	The taxonomic kingdom of the taxon according to GBIF
phylum	The taxonomic phylum of the taxon according to GBIF
class	The taxonomic class of the taxon according to GBIF
order	The taxonomic order of the taxon according to GBIF
family	The taxonomic family of the taxon according to GBIF
genus	The taxonomic genera of the taxon according to GBIF
species	The taxonomic species of the taxon according to GBIF

Appendix S4: Wildlife advertisement category definitions

Table S4. Categories of traded wildlife. Each taxon-advertisement combination was assigned one of four categories: raw/dead, processed/derived, by-product, or live.

Category	**Definition**	**Example**
raw/dead	Wildlife is in its natural physical form, representing either the whole organism or parts/section of the organism that has not been altered extensively.	Dried leaves, whole mushroom, feathers
processed/derived	Wildlife was altered and not immediately recognisable as the wildlife product	Toad poisons, powdered substances
by-product	A product that wildlife externally produces, i.e. secondary product	Honey
live	Wildlife specimen is alive	Whole plants, plant cuttings, live animals (e.g., parrots)

Appendix S5: Wildlife advertisement end use definitions

Table S5. End use categories of traded wildlife. We assigned each taxon-advertisement an end use depending on what was being advertised and how the seller specified the traded taxon. For some advertisements, we assumed the end use based on the context of the advertisement. For example, we assumed live parrots were for the end use of being a household pet. Another common example includes when a seller advertises a plant for its drug properties but doesn't explicitly mention it's for recreational drug use. In these cases, we assumed the advertisement's end use was 'drug'.

End use	**Definition**	**Example**
Drug	Chemical or natural substances taken for enjoyment or leisure purposes rather than medical reasons. We included drug precursors in this category.	Magic mushrooms, DMT from *Mimosa tenuiflora* rootbark
Medicine	A substance that is claimed/purported to be beneficial for the treatment of disease, illness or injury, including food supplements.	Natural Viagra, lung tonic
Food (raw)	Food product consisting of just the one wildlife specimen, unadulterated and in its natural form.	Honey, animal meat
Food (processed)	Food product containing of at least one wildlife specimen, altered so it is no longer in its natural form	Meat jerky
Cosmetic	Wildlife products and/or their derivatives being used with the intention of altering someone's appearance	Botox, breast growth 'supplements'
Accessory	Fashion accessories or any fashion apparel items that aren't clothing	Belt, handbag, shoes, briefcase
Clothing	Wildlife products that are used as an item of clothing	Snakeskin jacket, fur coat
Pet	A live animal is being sold for the purpose of pet trade	Macaw parrot
Decorative	Wildlife product advertised for decorative purposes	Elephant ivory, African dan masks, animal skins
Ritual	Wildlife that does not have any health benefit and is not taken for enjoyment or leisure. Has historical records of being used for ritual/religious practices.	Kambo (secretions of the Giant monkey frog)
Poison	Substance used with the intent to cause death, injury or harm. Includes incapacitating agents (i.e., date rape drugs: Devil's breath). Includes venom.	Ricin, Devil's breath
Weapon	A bioweapon, physical weapons used with the intention of causing physical harm	Diphtheriae, E. coli
Drug paraphernalia	Any equipment, product or accessory intended for making, using or concealing drugs.	Wooden marijuana grinder box

Appendix S6: Methods for drug verification and classification

We identified the drug classes (Table S6a) and active substances (Table S6b) of the taxa sold as drugs on the dark web. We distinguished taxa with known pharmacological effects from those with unsubstantiated effects. We classified the drug class (e.g., depressant, stimulant, psychedelic) and identified the main active substance(s) of a taxon from the scientific peer-reviewed literature (See Table S6c for full list of references). We found that some taxa did not have known pharmacological effects or had different effects. For example, sellers advertising *Tagetes lucida* claimed it to be a hallucinogenic, however the literature did not support this and instead indicated sedative properties (Pérez-Ortega, González-Trujano et al. 2016). Several plants did not have known active drug chemicals but instead contained a chemical, considered to be a 'facilitator', meaning it causes another chemical to become activated. For example, we classified the chemical harmine as a facilitator due to its use in ayahuasca to enable the psychedelic compound DMT to be orally active (Brito-da-Costa, Dias-da-Silva et al. 2020). We recorded the facilitated chemical as their own separate drug class. Other taxa contained precursor chemicals used to manufacture a drug (e.g., safrole harvested from *Sassafras albidum* to manufacture MDMA (Kemprai, Protim Mahanta et al. 2020)). For these taxa with precursors, we classified the drug class based on the what the precursor becomes (i.e., MDMA for *Sassafras albidum*) and recorded the precursory chemical found in the taxa separately.

References

Brito-da-Costa, AM, Dias-da-Silva, D, Gomes, NGM, Dinis-Oliveira, RJ, Madureira-Carvalho, Á (2020) Toxicokinetics and Toxicodynamics of Ayahuasca Alkaloids N,N-Dimethyltryptamine (DMT), Harmine, Harmaline and Tetrahydroharmine: Clinical and Forensic Impact. Pharmaceuticals 13, 334.

Kemprai, P, Protim Mahanta, B, Sut, D, Barman, R, Banik, D, Lal, M, Proteem Saikia, S, Haldar, S (2020) Review on safrole: identity shift of the 'candy shop' aroma to a carcinogen and deforester. Flavour and Fragrance Journal 35, 5-23.

Pérez-Ortega, G, González-Trujano, ME, Ángeles-López, GE, Brindis, F, Vibrans, H, Reyes-Chilpa, R (2016) Tagetes lucida Cav.: Ethnobotany, phytochemistry and pharmacology of its tranquilizing properties. Journal of Ethnopharmacology 181, 221-228.

Table S6a. The classes of drugs that were known to be in plants, fungi, and animals traded on the dark web.

Drug class	Definition	Example
Depressant	Slow down the functions of the central nervous system. Lower doses generally induce relaxation and sedation. High doses may cause unconsciousness. Depressants can also produce euphoria.	Alcohol, cannabis, valium, opiods
Stimulant	Speed up the message between the body and your brain. Increases heart rate, blood pressure and body temperature. Makes you feel more alert and energetic.	Cocaine, ecstasy, nicotine
Psychedelic	A class of hallucinogenic drugs that can cause visual and auditory hallucinations, and often a substantially altered state of consciousness.	Mescaline, LSD, psilocybin, and DMT

Deliriant	Causes delirium and hallucinations.	Datura, Brugmansia, Benadryl
Toxin	A harmful organic substance.	Grayanotoxin
Dissociative	Distorts sensory perceptions and produces a feeling of detachment from the self and the environment.	Ketamine, Salvia divinorum
Facilitator	Facilitates the uptake of another chemical with desired effects.	Harmine allows DMT to be orally active.

Table S6b. The active substance/s, precursor chemical, or facilitating chemical found in taxa traded on the dark web as drugs.

Chemical	**Notes**
Apigenin	Antianxiety effects.
Arecoline	Parasympathomimetic stimulant.
Atropine	An anticholinergic that can cause deliriant hallucinations.
Caffeine	A central nervous system stimulant.
Cathinone	Stimulant effects, found in Khat.
Cocaine	Natural alkaloid in Coca plants, extracted to make cocaine (crack)
Coumarins	Aromatic organic compounds found in many plants.
Cytisine	A toxic alkaliod found in certain plants of Fabaceae.
Ephedrine	A stimulant which occurs in the plant genus Ephedra.
Ergine	Ergoline alkaloid, psychedelic effects.
Grayanotoxin	A group of neurotoxins produced in some plant species of the Ericaceae fmaily.
Harmine	Hallucinogenic alkaloid found in Caapi & syrian rue (harmaline is its hydrogenated form)
Ibogaine	A psychedelic described as having oneirogenic and dissociative effects.
Kavalactones	A group of lactone compounds found in kava roots
Lactucin	Analgesic and sedative properties
Leonurine	A pseudoalkaloid that has been isolated from Leonotis leonurus.
MDMA	MDMA, found in some sassafrass plants
Mescaline	A psychedelic compound found in certain cacti species.
Methyltryptamines	Organic compounds that are serotonin analogues and produce psychedelic effects. Examples include NMT, DMT, 5-MeO-DMT, and Bufotenin.
Mitragynine	Induces mild stimulating effect at low doses and opioid-like effects at higher doses.
Multiple	Multiple chemicals present without clear indication of a sole active substance.
Muscimol	Found in Amanita muscaria.

Nicotine	An alkaloid found in the Solanaceae family that has stimulant and anxiolytic effects.
Nuciferine	A sedative found within *Nymphaea* and *Nelumbo nucifera.*
Opiates	Alkaloid compounds found in the opium poppy including morphine and codeine.
Psilocin	A serotonergic psychedelic substance similar to LSD and DMT found in certain mushroom species.
Psilocybin	A psychedelic prodrug compound of psilocin found in certain mushroom species.
Safrole	A precursor to MDMA.
Salvinorin A	A dissociative hallucinogen found in *Salvia divinorum*.

Table S6c. References used to verify and categorize drug classes and main active substance(s) of taxa advertised as drugs. The citation for each individual taxon can be found in Appendix S10, in the 'reference' column.

Citation	**Full reference**
(Alffonso, Votena et al. 2016)	Affonso, R. C. L., A. P. L. Voytena, S. Fanan, H. Pitz, D. S. Coelho, A. L. Horstmann, A. Pereira, V. G. Uarrota, M. C. Hillmann, L. A. C. Varela, R. M. Ribeiro-do-Valle and M. Maraschin (2016). "Phytochemical Composition, Antioxidant Activity, and the Effect of the Aqueous Extract of Coffee (Coffea arabica L.) Bean Residual Press Cake on the Skin Wound Healing." Oxidative Medicine and Cellular Longevity **2016**: 1923754.
(Agurell, Holmstedt et al. 1969)	Agurell, S., B. Holmstedt, J.-E. Lindgren and R. E. Schultes (1969). "Alkaloids in certain species of Virola and other South American plants of ethnopharmacologic interest." Acta chemica scandinavica **23**(3): 903-916.
(Al-Hebshi and Skaug 2005)	Al-Hebshi, N. and N. Skaug (2005). "Khat (Catha edulis)—an updated review." Addiction biology **10**(4): 299-307.
(Allen, Gartz et al. 2009)	Allen, J. W., J. Gartz and D. Molter (2009). "The Occurrence, Cultivation, and Chemistry of Psilocybe ovoideocystidiata, a new Bluing Species (Agaricales) from Ohio, Pennsylvania and West Virginia." Ethnomycological Journals: Sacred Mushroom Studies **8**: 70-81.
(Amor-Prats and Harborne 1993)	Amor-Prats, D. and J. B. Harborne (1993). "New sources of ergoline alkaloids within the genus Ipomoea." Biochemical Systematics and Ecology **21**(4): 455-461.
(Anastos, Lewis et al. 2006)	Anastos, N., S. W. Lewis, N. W. Barnett and D. N. Sims (2006). "The Determination of Psilocin and Psilocybin in Hallucinogenic Mushrooms by HPLC Utilizing a Dual Reagent Acidic Potassium Permanganate and Tris (2, 2′-bipyridyl) ruthenium (II) Chemiluminescence Detection System." Journal of forensic sciences **51**(1): 45-51.
(Ansari, Mahmood et al. 2021)	Ansari, A., T. Mahmood, P. Bagga, F. Ahsan, A. Shamim, S. Ahmad, M. Shariq and S. Parveen (2021). "Areca catechu: A phytopharmacological legwork." Food Frontiers **2**(2): 163-183.
(Arthur, Loo et al. 1967)	Arthur, H., S. Loo and J. Lamberton (1967). "Nb-Methylated tryptamines and other constituents of Acacia confusa Merr. of Hong Kong." Australian Journal of Chemistry **20**(4): 811-813.
(Asgarpanah and Ramezanloo 2012)	Asgarpanah, J. and F. Ramezanloo (2012). "Chemistry, pharmacology and medicinal properties of Peganum harmala L." African Journal of pharmacy and pharmacology **6**(22): 1573-1580.
(Ballabeni, Tognolini et al. 2010)	Ballabeni, V., M. Tognolini, C. Giorgio, S. Bertoni, R. Bruni and E. Barocelli (2010). "Ocotea quixos Lam. essential oil: In vitro and in vivo investigation on its anti-inflammatory properties." Fitoterapia **81**(4): 289-295.
(Bennett 1992)	Bennett, B. C. (1992). "Hallucinogenic plants of the Shuar and related indigenous groups in Amazonian Ecuador and Peru." Brittonia **44**(4): 483-493.
(Bhattacharya, Bose et al. 1978)	Bhattacharya, S., R. Bose, P. Ghosh, V. Tripathi, A. Kay and B. Dasgupta (1978). "Psychopharmacological studies on (-)-nuciferine and its Hofmann degradation product atherosperminine." Psychopharmacology **59**(1): 29-33.
(Boriollo, Silva et al. 2017)	Boriollo, M., T. Silva, M. Rodrigues-Netto, J. Silva, M. Marques, C. Dias, J. Höfling, M. Resck and N. Oliveira (2017). "Reduction of doxorubicin-induced genotoxicity by Handroanthus impetiginosus in mouse bone marrow revealed by micronucleus assay." Brazilian Journal of Biology **78**: 1-12.

(Borovička, Rockefeller et al. 2012)	Borovička, J., A. Rockefeller and P. G. Werner (2012). "Psilocybe allenii–a new bluing species from the Pacific Coast, USA." Czech Mycology **64**(2): 181-195.
(Brahmachari, Gorai et al. 2013)	Brahmachari, G., D. Gorai and R. Roy (2013). "Argemone mexicana: chemical and pharmacological aspects." Revista Brasileira de Farmacognosia **23**(3): 559-567.
(Chao and Der Marderosian 1973)	Chao, J.-M. and A. H. Der Marderosian (1973). "Ergoline Alkaloidal Constituents of Hawaiian Baby Wood Rose, Argyreia nervosa (Burm. f.) Bojer." Journal of Pharmaceutical Sciences **62**(4): 588-591.
(Dey, Mukherjee et al. 2017)	Dey, A., A. Mukherjee and M. Chaudhury (2017). Chapter 10 - Alkaloids From Apocynaceae: Origin, Pharmacotherapeutic Properties, and Structure-Activity Studies. Studies in Natural Products Chemistry. R. Atta ur, Elsevier. **52:** 373-488.
(Edwards, da Costa Rocha et al. 2015)	Edwards, S. E., I. da Costa Rocha, E. M. Williamson and M. Heinrich (2015). "Lapacho Handroanthus impetiginosus (Mart. ex DC.) Mattos." Phytopharmacy: An Evidence-Based Guide to Herbal Medicinal Products **234**.
(Freye and Levy 2010)	Freye, E. and J. V. Levy (2010). "Pharmacology and abuse of cocaine, amphetamines, ecstasy and related designer drugs." Pharmacology of cocaine, Springer: 49-60.
(Gartz 1992)	Gartz, J. (1992). "New aspects of the occurrence, chemistry and cultivation of European hallucinogenic mushrooms." Supplemento agli Annali dei Musei Civici di Rovereto Sezione Archeologica, Storia e Scienze Naturali **8**: 107-124.
(Gartz 1996)	Gartz, J. (1996). "Observations on the Psilocybe cyanescens complex of Europe and North America." Ann. Mus. Civ. Rovereto **12**: 209-218.
(Gartz, Allen et al. 1994)	Gartz, J., J. W. Allen and M. D. Merlin (1994). "Ethnomycology, biochemistry, and cultivation of Psilocybe samuiensis Guzmán, Bandala and Allen, a new psychoactive fungus from Koh Samui, Thailand." Journal of Ethnopharmacology **43**(2): 73-80.
(Gartz and Moller 1989)	Gartz, J. and G. Moller (1989). "Analysis and cultivation of fruit bodies and mycelia of Psilocybe bohemica." Biochemie und Physiologie der Pflanzen **184**(3-4): 337-341.
(Gaujac, Aquino et al. 2012)	Gaujac, A., A. Aquino, S. Navickiene and J. B. de Andrade (2012). "Determination of N,N-dimethyltryptamine in Mimosa tenuiflora inner barks by matrix solid-phase dispersion procedure and GC–MS." Journal of Chromatography B **881-882**: 107-110.
(Gibbons and Arunotayanun 2013)	Gibbons, S. and W. Arunotayanun (2013). Natural product (fungal and herbal) novel psychoactive substances. Novel psychoactive substances, Elsevier**:** 345-362.
(Gotti and Clementi 2021)	Gotti, C. and F. Clementi (2021). "Cytisine and cytisine derivatives. More than smoking cessation aids." Pharmacological Research **170**: 105700.
(Gromek, Kisiel et al. 1992)	Gromek, D., W. Kisiel, A. Klodzińska and E. Chojnacka-Wójcik (1992). "Biologically active preparations from Lactuca virosa L." Phytotherapy Research **6**(5): 285-287.
(Gümüşçü, Arslan et al. 2008)	Gümüşçü, A., N. Arslan and E. O. Sarıhan (2008). "Evaluation of selected poppy (Papaver somniferum L.) lines by their morphine and other alkaloids contents." European Food Research and Technology **226**(5): 1213-1220.
(Hattesohl, Feistel et al. 2008)	Hattesohl, M., B. Feistel, H. Sievers, R. Lehnfeld, M. Hegger and H. Winterhoff (2008). "Extracts of Valeriana officinalis L. s.l. show anxiolytic and antidepressant effects but neither sedative nor myorelaxant properties." Phytomedicine **15**(1): 2-15.
(Huhn, Pütz et al. 2005)	Huhn, C., M. Pütz, R. Dahlenburg and U. Pyell (2005). Sassafras oils as precursors for the production of synthetic drugs: Profiling via MEKC-UVD. Beiträge zum XIV, GTFCh-Symposium.
(Jansen, Kleerekooper et al. 2012)	Jansen, S. A., I. Kleerekooper, Z. L. M. Hofman, I. F. P. M. Kappen, A. Stary-Weinzinger and M. A. G. van der Heyden (2012). "Grayanotoxin poisoning: 'mad honey disease' and beyond." Cardiovascular toxicology **12**(3): 208-215.
(Keller, Schneider et al. 1999)	Keller, T., A. Schneider, P. Regenscheit, R. Dirnhofer, T. Rücker, J. Jaspers and W. Kisser (1999). "Analysis of psilocybin and psilocin in Psilocybe subcubensis GUZMAN by ion mobility spectrometry and gas chromatography–mass spectrometry." Forensic science international **99**(2): 93-105.
(Kemprai, Protim Mahanta et al. 2020)	Kemprai, P., B. Protim Mahanta, D. Sut, R. Barman, D. Banik, M. Lal, S. Proteem Saikia and S. Haldar (2020). "Review on safrole: identity shift of the 'candy shop' aroma to a carcinogen and deforester." Flavour and Fragrance Journal **35**(1): 5-23.
(Kerchner and Farkas 2020)	Kerchner, A. and Á. Farkas (2020). "Worldwide poisoning potential of Brugmansia and Datura." Forensic Toxicology **38**(1): 30-41.
(Klein, Kalam et al. 2015)	Klein, M. T., M. Kalam, K. Trout, N. Fowler and M. Terry (2015). "Mescaline concentrations in three principal tissues of Lophophora williamsii (Cactaceae): implications for sustainable harvesting practices." Haseltonia **2015**(20): 34-42.
(Koenig and Hilber 2015)	Koenig, X. and K. Hilber (2015). "The Anti-Addiction Drug Ibogaine and the Heart: A Delicate Relation." Molecules **20**(2): 2208-2228.
(Koroch, Juliani et al. 2009)	Koroch, A. R., H. R. Juliani, D. Kulakowski, H. Arthur, J. Asante-Dartey and J. E. Simon (2009). Voacanga africana: chemistry, quality and pharmacological activity. African Natural Plant Products: New Discoveries and Challenges in Chemistry and Quality, Citeseer. **1021:** 363-380.

(Koturevic 2020)	Koturevic, B. M. (2020). "Extraction and Identification of Atropine from "Legal High" Plant Species." Archibald Reiss Days **10**.
(Krizevski, Bar et al. 2010)	Krizevski, R., E. Bar, O. Shalit, Y. Sitrit, S. Ben-Shabat and E. Lewinsohn (2010). "Composition and stereochemistry of ephedrine alkaloids accumulation in Ephedra sinica Stapf." Phytochemistry **71**(8): 895-903.
(Kumar, Madaan et al. 2008)	Kumar, S., R. Madaan and A. Sharma (2008). "Pharmacological evaluation of Bioactive Principle of Turnera aphrodisiaca." Indian journal of pharmaceutical sciences **70**(6): 740-744.
(Lai, Tin-Wa et al. 1973)	Lai, A., M. Tin-Wa, E. Mika, G. Persinos and N. Farnsworth (1973). "Phytochemical investigation of Virola peruviana, a new hallucinogenic plant." Journal of Pharmaceutical Sciences **62**(9): 1561-1563.
(Laussmann and Meier-Giebing 2010)	Laussmann, T. and S. Meier-Giebing (2010). "Forensic analysis of hallucinogenic mushrooms and khat (Catha edulisForsk) using cation-exchange liquid chromatography." Forensic science international **195**(1-3): 160-164.
(Leung, Smith et al. 1965)	Leung, A. Y., A. H. Smith and A. G. Paul (1965). "Production of psilocybin in Psilocybe baeocystis saprophytic culture." Journal of Pharmaceutical Sciences **54**(11): 1576-1579.
(Lim 2014)	Lim, T. K. (2014). Eschscholzia californica. Edible Medicinal and Non Medicinal Plants: Volume 8, Flowers. T. K. Lim. Dordrecht, Springer Netherlands**:** 622-632.
(MacLean, Johnson et al. 2013)	MacLean, K. A., M. W. Johnson, C. J. Reissig, T. E. Prisinzano and R. R. Griffiths (2013). "Dose-related effects of salvinorin A in humans: dissociative, hallucinogenic, and memory effects." Psychopharmacology **226**(2): 381-392.
(Maphanga, Skalicka-Wozniak et al. 2022)	Maphanga, V. B., K. Skalicka-Wozniak, B. Budzynska, A. Skiba, W. Chen, C. Agoni, G. M. Enslin and A. M. Viljoen (2022). "Mesembryanthemum tortuosum L. alkaloids modify anxiety-like behaviour in a zebrafish model." Journal of Ethnopharmacology **290**: 115068.
(Maroyi 2022)	Maroyi, A (2022) "Medicinal uses, phytochemistry and pharmacological properties of Dioscorea dregeana (Kunth) T. Durand & Schinz". Medicinal Plants v. 14, pp. 57-63-2022 v.14 no.1.
(Mata, Contreras-Rosales et al. 2021)	Mata, R., A. J. Contreras-Rosales, J. A. Gutiérrez-González, J. L. Villaseñor and A. Pérez-Vásquez (2021). "Calea ternifolia Kunth, the Mexican "dream herb", a concise review." Botany **100**(2): 261-274.
(Miroddi, Calapai et al. 2013)	Miroddi, M., G. Calapai, M. Navarra, P. L. Minciullo and S. Gangemi (2013). "Passiflora incarnata L.: Ethnopharmacology, clinical application, safety and evaluation of clinical trials." Journal of Ethnopharmacology **150**(3): 791-804.
(Musshoff, Madea et al. 2000)	Musshoff, F., B. Madea and J. Beike (2000). "Hallucinogenic mushrooms on the German market — simple instructions for examination and identification." Forensic Science International **113**(1): 389-395.
(Nagamine-Pinheiro, Fagg et al. 2021)	Nagamine-Pinheiro, N., C. W. Fagg, S. M. Gomes, R. C. Oliveira and J. Sonsin-Oliveira (2021). "Vegetative anatomy, morphology and histochemistry of three species of Malpighiaceae used in analogues of the Amazonian psychoactive beverage Ayahuasca." Flora **275**: 151760.
(Novak, Salemink et al. 1984)	Novak, M., C. Salemink and I. Khan (1984). "Biological activity of the alkaloids of Erythroxylum coca and Erythroxylum novogranatense." Journal of ethnopharmacology **10**(3): 261-274.
(Nsuala, Enslin et al. 2015)	Nsuala, B. N., G. Enslin and A. Viljoen (2015). ""Wild cannabis": a review of the traditional use and phytochemistry of Leonotis leonurus." Journal of ethnopharmacology **174**: 520-539.
(Ogunbodede, McCombs et al. 2010)	Ogunbodede, O., D. McCombs, K. Trout, P. Daley and M. Terry (2010). "New mescaline concentrations from 14 taxa/cultivars of Echinopsis spp. (Cactaceae) ("San Pedro") and their relevance to shamanic practice." J Ethnopharmacol **131**(2): 356-362.
(Patel, Soni et al. 2011)	Patel, S. S., H. Soni, K. Mishra and A. K. Singhai (2011). "Recent updates on the genus Passiflora: a review." International Journal of Research in Phytochemistry and Pharmacology **1**(1): 1-16.
(Pellegrini, Rotolo et al. 2013)	Pellegrini, M., M. C. Rotolo, E. Marchei, R. Pacifici, F. Saggio and S. Pichini (2013). "Magic truffles or Philosopher's stones: a legal way to sell psilocybin?" Drug testing and analysis **5**(3): 182-185.
(Pérez-Ortega, González-Trujano et al. 2016)	Pérez-Ortega, G., M. E. González-Trujano, G. E. Ángeles-López, F. Brindis, H. Vibrans and R. Reyes-Chilpa (2016). "Tagetes lucida Cav.: Ethnobotany, phytochemistry and pharmacology of its tranquilizing properties." Journal of Ethnopharmacology **181**: 221-228.
(Petricevich, Salinas-Sánchez et al. 2020)	Petricevich, V. L., D. O. Salinas-Sánchez, D. Avilés-Montes, C. Sotelo-Leyva and R. Abarca-Vargas (2020). "Chemical Compounds, Pharmacological and Toxicological Activity of Brugmansia suaveolens: A Review." Plants **9**(9): 1161.
(Petruczynik, Wróblewski et al. 2020)	Petruczynik, A., K. Wróblewski, J. Misiurek, T. Plech, K. Szalast, K. Wojtanowski, T. Mroczek, G. Szymczak, M. Waksmundzka-Hajnos and P. Tutka (2020). "Determination of Cytisine and N-Methylcytisine from Selected Plant Extracts by High-Performance Liquid Chromatography and Comparison of Their Cytotoxic Activity." Toxins **12**(9): 557.
(Pinheiro, Alcântara et al. 2014)	Pinheiro, M. L. P., C. E. P. Alcântara, M. de Moraes and E. D. de Andrade (2014). "Valeriana officinalis L. for conscious sedation of patients submitted to impacted lower third molar surgery: A randomized, double-blind, placebo-controlled split-mouth study." Journal of pharmacy & bioallied sciences **6**(2): 109-114.

(Rumalla, Jadhav et al. 2008)	Rumalla, C. S., A. N. Jadhav, T. Smillie, F. R. Fronczek and I. A. Khan (2008). "Alkaloids from Heimia salicifolia." Phytochemistry **69**(8): 1756-1762.
(Saitoh, Noma et al. 1985)	Saitoh, F., M. Noma and N. Kawashima (1985). "The alkaloid contents of sixty Nicotiana species." Phytochemistry **24**(3): 477-480.
(Satora, Pach et al. 2005)	Satora, L., D. Pach, B. Butryn, P. Hydzik and B. Balicka-Ślusarczyk (2005). "Fly agaric (Amanita muscaria) poisoning, case report and review." Toxicon **45**(7): 941-943.
(Sauvain, Rerat et al. 1997)	Sauvain, M., C. Rerat, C. Moretti, E. Saravia, S. Arrazola, E. Gutierrez, A.-M. Lema and V. Muñoz (1997). "A study of the chemical composition of Erythroxylum coca var. coca leaves collected in two ecological regions of Bolivia." Journal of ethnopharmacology **56**(3): 179-191.
(Schimpl, da Silva et al. 2013)	Schimpl, F. C., J. F. da Silva, J. F. d. C. Gonçalves and P. Mazzafera (2013). "Guarana: Revisiting a highly caffeinated plant from the Amazon." Journal of Ethnopharmacology **150**(1): 14-31.
(Schwelm, Zimmermann et al. 2021)	Schwelm, H. M., N. Zimmermann, T. Scholl, J. Penner, A. Autret, V. Auwärter and M. A. Neukamm (2021). "Qualitative and Quantitative Analysis of Tryptamines in the Poison of Incilius alvarius (Amphibia: Bufonidae)." Journal of Analytical Toxicology. **46**(5): 540–548.
(Senn-Irlet, Nyffenegger et al. 1999)	Senn-Irlet, B., A. Nyffenegger and R. Brenneisen (1999). "Panaeolus bisporus — an adventitious fungus in central Europe, rich in psilocin." Mycologist 13(4): 176-179.
(Simons and Marten 1971)	Simons, A. and G. Marten (1971). "Relationship of Indole Alkaloids to Palatability of Phalaris arundinacea L. 1." Agronomy Journal **63**(6): 915-919.
(Singh, Narayanan et al. 2017)	Singh, D., S. Narayanan, B. Vicknasingam, O. Corazza, R. Santacroce and A. Roman-Urrestarazu (2017). "Changing trends in the use of kratom (Mitragyna speciosa) in Southeast Asia." Human Psychopharmacology: Clinical and Experimental **32**(3): e2582.
(Smith, Dharmaratne et al. 2001)	Smith, K. K., H. R. W. Dharmaratne, M. W. Feltenstein, S. L. Broom, J. T. Roach, N. P. D. Nanayakkara, I. A. Khan and K. J. Sufka (2001). "Anxiolytic effects of kava extract and kavalactones in the chick social separation-stress paradigm." Psychopharmacology **155**(1): 86-90.
(Soares, Duarte et al. 2017)	Soares, D., L. P. Duarte, A. D. Cavalcanti, F. C. Silva, A. D. Braga, M. T. Lopes, J. A. Takahashi and S. A. Vieira-Filho (2017). "Psychotria viridis: Chemical constituents from leaves and biological properties." Anais da Academia Brasileira de Ciências **89**: 927-938.
(Sobiecki 2002)	Sobiecki, J. F. (2002). "A preliminary inventory of plants used for psychoactive purposes in southern African healing traditions." Transactions of the Royal Society of South Africa **57**(1-2): 1-24.
(Sobiecki 2008)	Sobiecki, J. (2008). "A review of plants used in divination in southern Africa and their psychoactive effects." Southern African Humanities **20**(2): 333-351.
(Stríbrný, Borovicka et al. 2003)	Stríbrný, J., J. Borovicka and M. Sokol (2003). "Levels of psilocybin and psilocin in various types of mushrooms." Soudni Lekarstvi **48**(3): 45-49.
(Sukrong, Zhu et al. 2007)	Sukrong, S., S. Zhu, N. Ruangrungsi, T. Phadungcharoen, C. Palanuvej and K. Komatsu (2007). "Molecular analysis of the genus Mitragyna existing in Thailand based on rDNA ITS sequences and its application to identify a narcotic species: Mitragyna speciosa." Biological and Pharmaceutical Bulletin **30**(7): 1284-1288.
(Szopa, Pajor et al. 2020)	Szopa, A., J. Pajor, P. Klin, A. Rzepiela, H. O. Elansary, F. A. Al-Mana, M. A. Mattar and H. Ekiert (2020). "Artemisia absinthium L.—Importance in the History of Medicine, the Latest Advances in Phytochemistry and Therapeutical, Cosmetological and Culinary Uses." Plants **9**(9): 1063.
(Tsujikawa, Kanamori et al. 2003)	Tsujikawa, K., T. Kanamori, Y. Iwata, Y. Ohmae, R. Sugita, H. Inoue and T. Kishi (2003). "Morphological and chemical analysis of magic mushrooms in Japan." Forensic Science International **138**(1): 85-90.
(Van Court, Wiseman et al. 2022)	Van Court, R. C., M. S. Wiseman, K. W. Meyer, D. J. Ballhorn, K. R. Amses, J. C. Slot, B. T. M. Dentinger, R. Garibay-Orijel and J. K. Uehling (2022). "Diversity, biology, and history of psilocybin-containing fungi: Suggestions for research and technological development." Fungal Biology **126**(4): 308-319.
(Warren, Dham-Nayyar et al. 2013)	Warren, JM, Dham-Nayyar, P, Alexander, J (2013). “Recreational use of naturally occurring dimethyltryptamine--contributing to psychosis?” Aust N Z J Psychiatry **47**, 398-9.
(White 1957)	White, E. (1957). "Evaluation of further legumes, mainly Lupinus and Acacia species for alkaloids." New Zealand Journal of Science and Technology **38**.

659

Appendix S7: Methods to obtain native plant distributions

To obtain the native distributions of traded plants, we used the Kew Plants of the World Online database (POWO 2022). POWO, utilises the World Geographical Scheme for Recording Plant Distributions (WGSRPD) (Brummitt 2001). The WGSRPD, has four geographic units for recording plant distributions. POWO, uses the 'level 3' geographic unit which records distribution at the country scale or by political subdivisions for large countries. Large countries that are subdivided are: Argentina, Australia, Brazil, Canada, Chile, China, India, Mexico, South Africa, USA, and Russia. The shapefiles and geographic unit codes were obtained from the WGSRPD Github repository (Desmet and Page 2007).

For each traded plant species we used scientific names to retrieve Life Sciences Identifiers (LSID) from POWO. This was done by using the 'get_pow' function from the 'taxize' package (Chamberlain & Szöcs 2013). We manually verified species with more than one result, by using the POWO database to determine the accepted species name. We then retrieved native distributions from POWO with the 'pow_lookup' function from 'taxize' (Chamberlain & Szöcs 2013). We cross referenced this data with the 'level 3' shapefile data from the WGSRPD Github repository (Desmet and Page 2007).

References

Brummit RK. 2001. World Geographical Scheme for Recording Plant Distributions., 2nd edition. Hunt Institute for Botanical Documentation, Carnegie Mellon University, Pittsburgh. Available from https://github.com/tdwg/wgsrpd.

Chamberlain SA, Szöcs E. 2013. taxize: taxonomic search and retrieval in R. F1000Research **2**:191.

Desmet, P, Page, R (2007) 'World Geographical Scheme for Recording Plant Distributions (WGSRPD).' Available at https://github.com/tdwg/wgsrpd [Accessed 1/4/2022].

POWO (2022). Plants of the World Online. Facilitated by the Royal Botanic Gardens, Kew. Published on the Internet; http://www.plantsoftheworldonline.org/ [Accessed 1/4/2022].

Appendix S8: Dataset of taxon-advertisement combinations

Refer to csv file named "Appendix_S08_taxon_advertisement_dataset.csv" for the full dataset of each taxon-advertisement combination. Refer to Table S8 for a description of the columns.

Table S8. Column descriptions for the data file "Appendix_S08_taxon_advertisement_dataset.csv"

Column	Description
gbif_name	The name of the taxon according to GBIF
ad_id	A unique identifier for the advertisements. Taxon-advertisements from the same advertisements with have the same 'ad_id'.
market_id	A unique identifier for the marketplace the advertisement was advertised in
seller_id	A unique identifier for the seller who listed the advertisement
date	The date the advertisement was recorded by DATACRYPTO
category	The category of the taxon-advertisement. See Appendix S4 for category definitions.
end_use	The end use of the taxon-advertisement. See Appendix S5 for end use definitions.
how_processed	How the wildlife was processed.
what/physical	What physical component of the wildlife was being advertised.
wild_harvested	If the wildlife was being advertised as wild harvested.

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

Table S9. The number of taxa and advertisements for each taxonomic rank. There were occasionally multiple taxa per advertisement, thus, what is displayed is the number of taxon-advertisement combinations, which is greater than the total number of advertisements.

Taxonomic rank	Number of taxa	Cumulative proportion of all taxa	Number of taxon-ad combos	Cumulative proportion of all taxon-ad combos
subspecies	2	0.011	14	0.003
species	152	0.819	3,902	0.897
genus	17	0.910	102	0.920
family	10	0.963	58	0.933
order	4	0.984	236	0.987
class	1	0.989	4	0.988
kingdom	2	1.000	52	1.000

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

Refer to csv file named "Appendix_S10_taxa_key.csv" for the traded taxa and their characteristics, including: taxonomy, drug information, IUCN status, and GISD status. Refer to Table S10 for a description of the columns.

Table S10. Column descriptions for the data file "Appendix_S10_taxa_key.csv"

Column	Description
gbif_id	GBIF's unique identifier for the taxon
gbif_name	The name of the taxon according to GBIF
gbif_rank	The taxonomic rank of the taxon (i.e., species, genus) according to GBIF
kingdom	The taxonomic kingdom of the taxon according to GBIF
phylum	The taxonomic phylum of the taxon according to GBIF
class	The taxonomic class of the taxon according to GBIF
order	The taxonomic order of the taxon according to GBIF
family	The taxonomic family of the taxon according to GBIF
genus	The taxonomic genera of the taxon according to GBIF
species	The taxonomic species of the taxon according to GBIF
subspecies	The taxonomic subspecies of the taxon according to GBIF
iucn	The IUCN Red List status for each species. NA indicates the taxon is not a species while NE indicates the species has not been evaluated by the IUCN to date.
iucn_threat	The level 5 (Biological resource use) IUCN threat code for a species. For more information, see https://www.iucnredlist.org/resources/threat-classification-scheme
gisd_listed	If the species is listed as invasive in the GISD.
drug_class	The drug class of the species, if it is a verified drug. See Appendix S6 for methods.
drug_chemical	The active chemical of species, if it is a verified drug. See Appendix S6 for methods.
drug_precursor	If the species contains a precursor, the precursor chemical is listed in this column. See Appendix S6 for methods.
drug_chemical_facilitated	If the species contains a chemical that is a facilitator, the facilitator chemical is listed in this column. See Appendix S6 for methods.
drug_reference	The citation to a peer-reviewed research article verifying the species contains a chemical that is a drug. See Table S6c for the full reference.

Appendix S11: Detailed results of taxonomic diversity

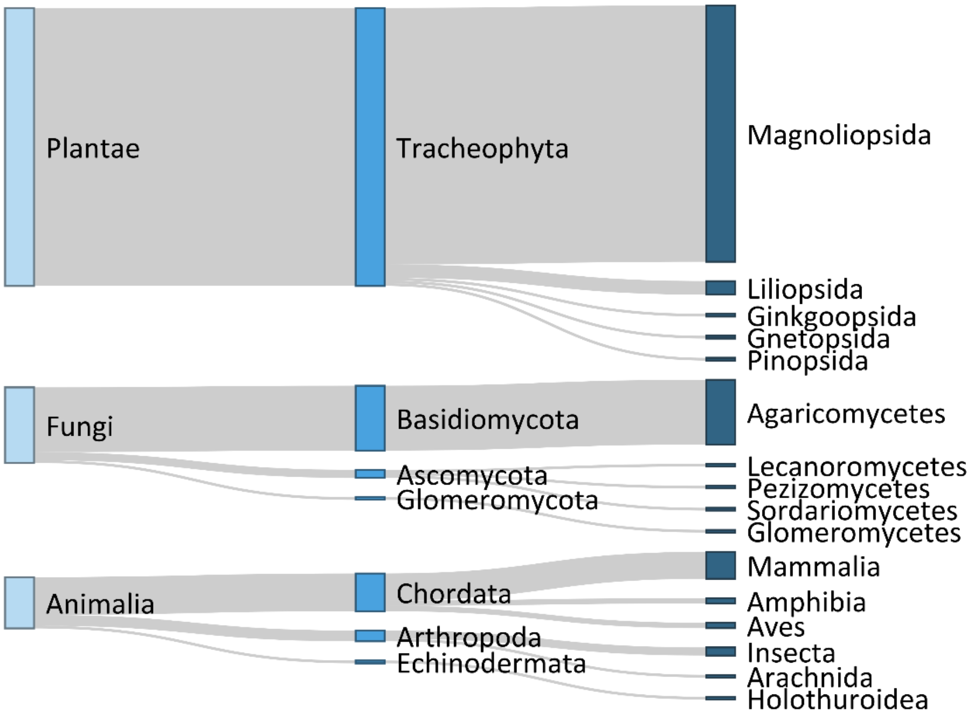

Figure S11.
Taxonomic diversity of species traded on the dark web. Bar widths correspond to the number of species found traded (n = 154). The first column represents taxonomic kingdom, middle column represents the phylum, and rightmost column represents the order. Taxa identified to a rank above species are not displayed. The six species of bacteria traded are not displayed.

Appendix S12 Detailed results of species with known drug properties

Table S12a. The number of advertisements and species with verified drug properties by drug class, stratified by taxonomic kingdom. See Appendix S6 for methods to derive drug classes and Table S6a for definitions of drug classes.

Kingdom	Drug Class	Number of ads	Number of species
Fungi	psychedelic	1,440	19
Plantae	psychedelic*	963	22
Plantae	facilitator	393	3
Plantae	depressant	378	9
Plantae	stimulant	321	11
Plantae	dissociative	100	1
Plantae	anxiolytic	77	6
Fungi	deliriant	25	1
Fungi	depressant	25	1
Animalia	psychedelic	15	1
Plantae	deliriant	9	2
Animalia	toxin	2	2

* Three species of plants contained a precursor (i.e., safrole) to a psychedelic (MDMA): *Cinnamomum camphora* (3 ads), *Cinnamomum parthenoxylon* (14 ads), and *Sassafras albidum* (16 ads). See Appendix S6 for more information on drug classification.

Table S12b. The number of advertisements and species with verified drug properties by active chemical, stratified by taxonomic kingdom. See Appendix S6 for methods to derive drug classes and Table S6a for definitions of drug classes. Note, harmine is the only chemical on this list that is a facilitator.

Kingdom	Active chemical	Number of ads	Number of species
Fungi	Psilocybin	1,440	19
Plantae	Methyltryptamines	752	10
Plantae	Harmine	393	3
Plantae	Mitragynine	238	2
Plantae	Mescaline	141	4
Plantae	Nuciferine	121	2
Plantae	Salvinorin A	100	1
Plantae	Apigenin	54	1
Plantae	Cocaine	38	2
Plantae	MDMA	33	3
Fungi	Psilocin	30	5
Plantae	Ibogaine	26	2
Fungi	Muscimol	25	1
Animalia	Methyltryptamines	15	1
Plantae	Ergine	11	3
Plantae	Atropine	9	2
Plantae	Several candidates	9	3
Plantae	Coumarins	7	1
Plantae	Lactucin	6	1
Plantae	Leonurine	6	1
Plantae	Kavalactones	4	1
Plantae	Nicotine	4	1
Animalia	Grayanotoxin	2	2
Plantae	Cathinone	1	1
Plantae	Ephedrine	1	1

Appendix S13: Detailed results of advertisement category by taxonomic kingdom

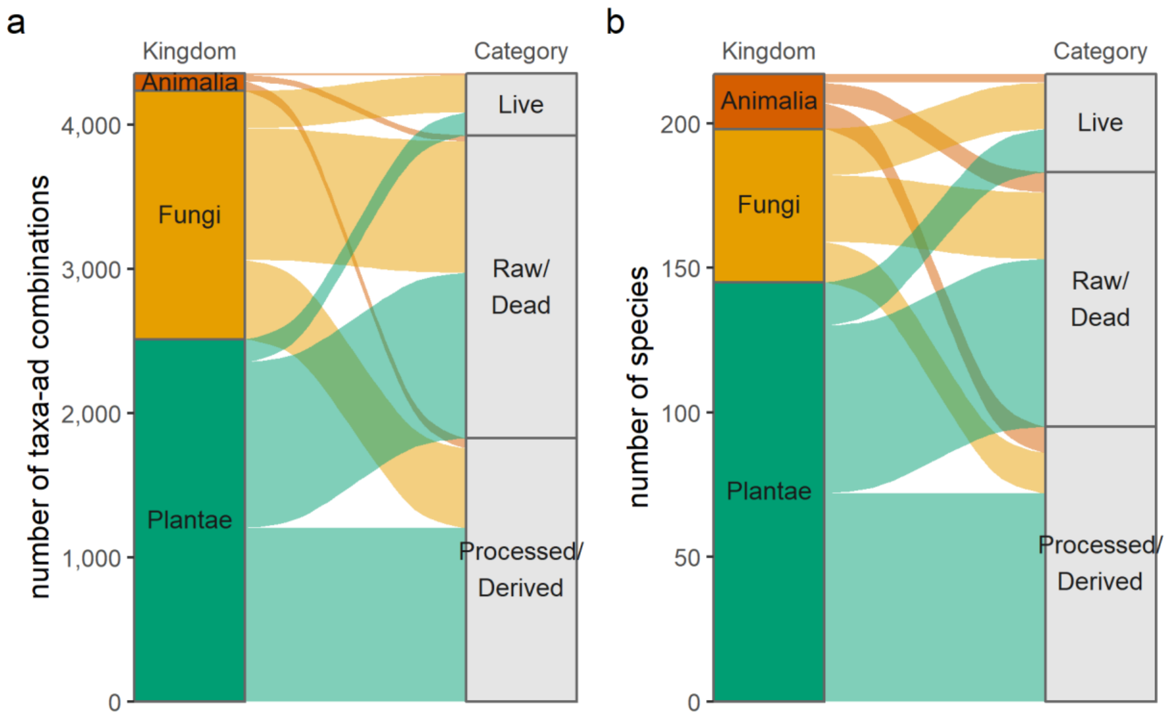

Figure S13. Characteristics of the 'category' of wildlife traded on the dark web. (a) The number of taxon-advertisement combinations stratified by category and (b) number of species stratified by end category. Note that some taxon-advertisement and species had more than one category. Category definitions can be found in Appendix S4. Advertisements and species of Bacteria are not shown (4 advertisements; 6 species). Also, advertisements with the category of by-product are not shown, which consisted of 4 advertisments, 2 species (*Apis laboriosa* and *Apis dorsata*), one Family (Bufonidae), and one Order (Scorpiones).

Appendix S14: Dataset of plant species richness by geographic areas

Refer to csv file named “Appendix_S14_plant_spp_richness” for the data file containing the plant species native richness by geographic area. See Appendix S7 for methods. Refer to Table S14 for a description of the columns.

Table S14. Column descriptions for the data file “Appendix_S14_plant_spp_richness”

Column	Description
LEVEL3_COD	The code of the country/subdivision according to WGSRPD. See Appendix S7 for details.
LEVEL3_NAM	The name of the country/subdivision according to WGSRPD. See Appendix S7 for details.
n_spp	The number of plant species native to the given location. See Appendix S7 for details.
category	The category of what the ‘n_spp’ value refers to: • “All species” indicates this row represents the species richness of *all* plant species in the given location. • “Drug species” indicates this row represents the species richness of all species *with* verified drug properties in the given location. • “Non-drug species” indicates this row represents the species richness of all species *without* verified drug properties in the given location.

Appendix S15: Detailed results on species advertised as wild harvested

Table S15. Species traded on the dark web that are described by sellers as wild harvested along with their IUCN red list status. The number of advertisements in this table indicates the number of advertisements that a seller describes this species as wild harvested.

Species	Kingdom	Number of ads	IUCN
Psilocybe cubensis	Fungi	8	NE
Psilocybe subaeruginosa	Fungi	8	NE
Amanita muscaria	Fungi	6	NE
Psilocybe semilanceata	Fungi	6	NE
Mitragyna speciosa	Plantae	5	LC
Lophophora williamsii	Plantae	3	VU
Tabernanthe iboga	Plantae	3	LC
Mimosa tenuiflora	Plantae	2	LC
Panaeolus cyanescens	Fungi	2	NE
Psilocybe cyanescens	Fungi	2	NE
Apis dorsata	Animalia	1	NE
Apis laboriosa	Animalia	1	NE
Apostichopus japonicus	Animalia	1	EN
Craterellus cornucopioides	Fungi	1	NE
Ophiocordyceps sinensis	Fungi	1	VU
Psilocybe mexicana	Fungi	1	NE
Psilocybe subcubensis	Fungi	1	NE

Appendix S16: Detailed results on market and seller characteristics

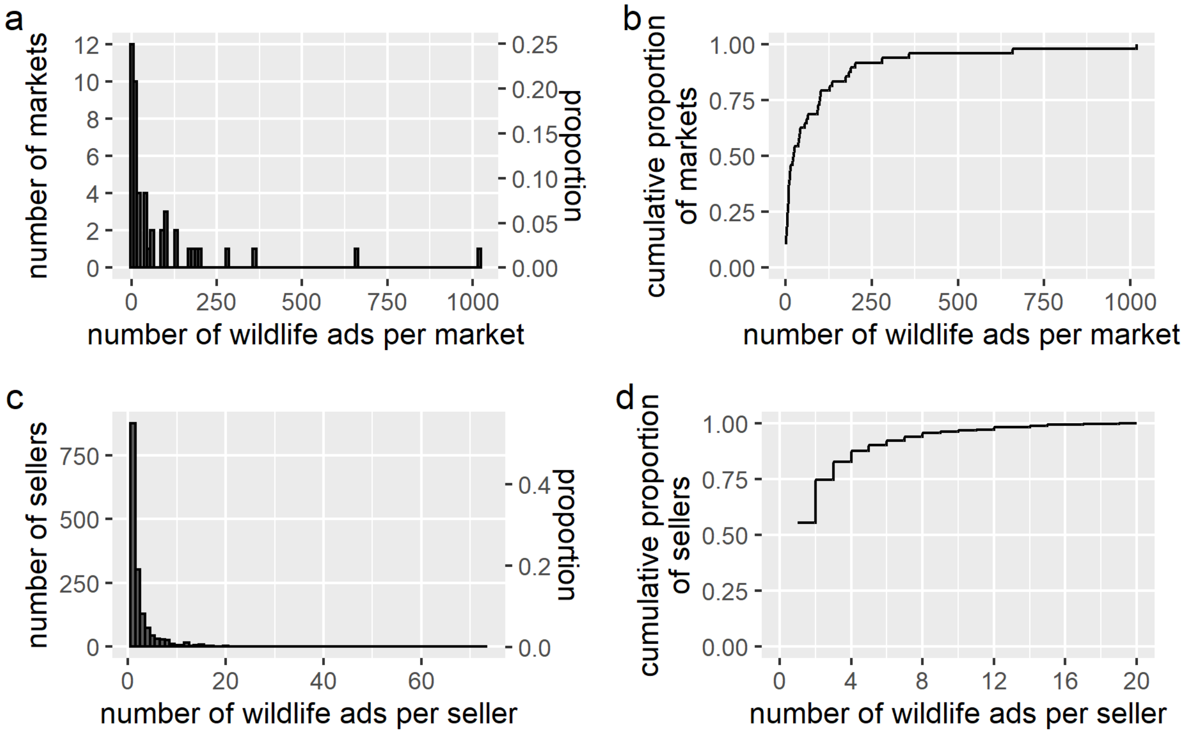

Figure S16. (a) Distribution of the number of wildlife advertisements per marketplace, where the bin width is 10 advertisements. (b) The cumulative distribution of the proportion of marketplaces by the number of wildlife advertisements in each marketplace. (c) Distribution of the number of wildlife advertisements per seller, where the bin width is 1 species. (d) The cumulative distribution of the proportion of sellers by the number of wildlife advertisements per seller.

Appendix S17: Detailed results on marketplace and species relationships

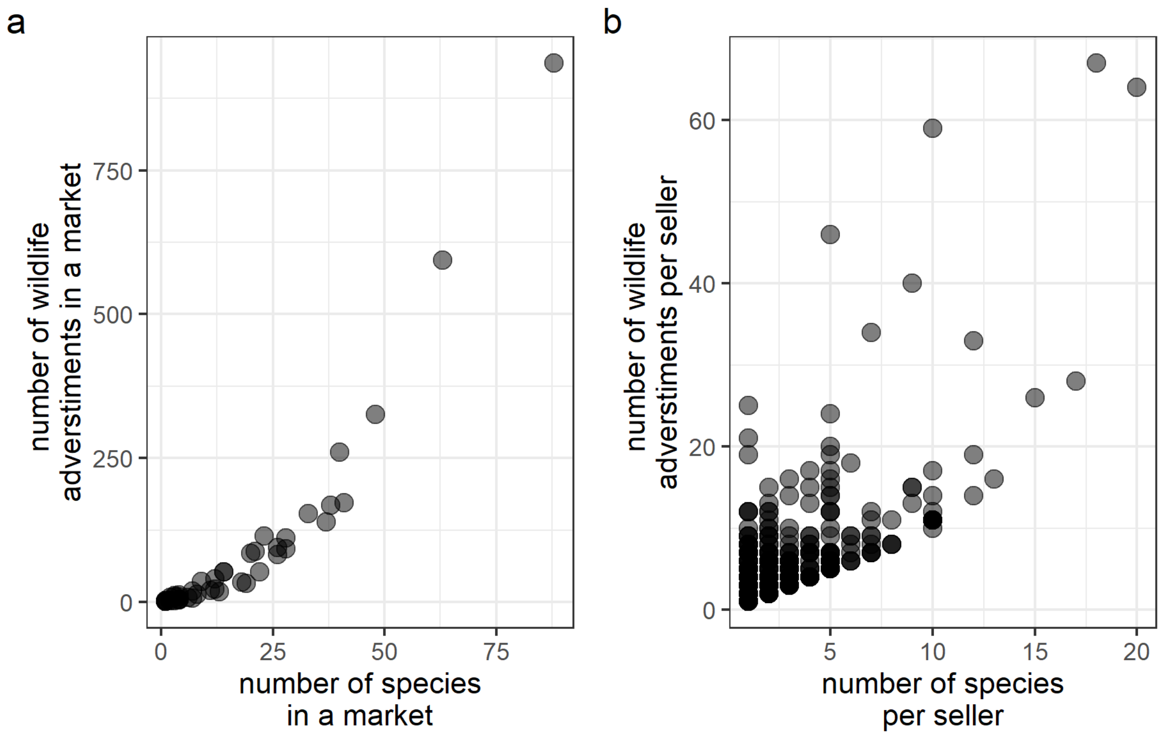

Figure S17. The relationship between (a) the number of species in a marketplace compared to the number of wildlife advertisements in a marketplace, and (b) the number of species per seller compared to the number of wildlife advertisements per seller. In general, the number of species found in a given marketplace was positively correlated with the number of wildlife advertisements found in a marketplace. Also, the number of species traded by a given seller was positively correlated with the number of wildlife advertisements for a seller. Yet, most sellers only had 1 advertisement, and thus one species (Appendix S16).

Appendix S18: Detailed results of taxonomic trends over time

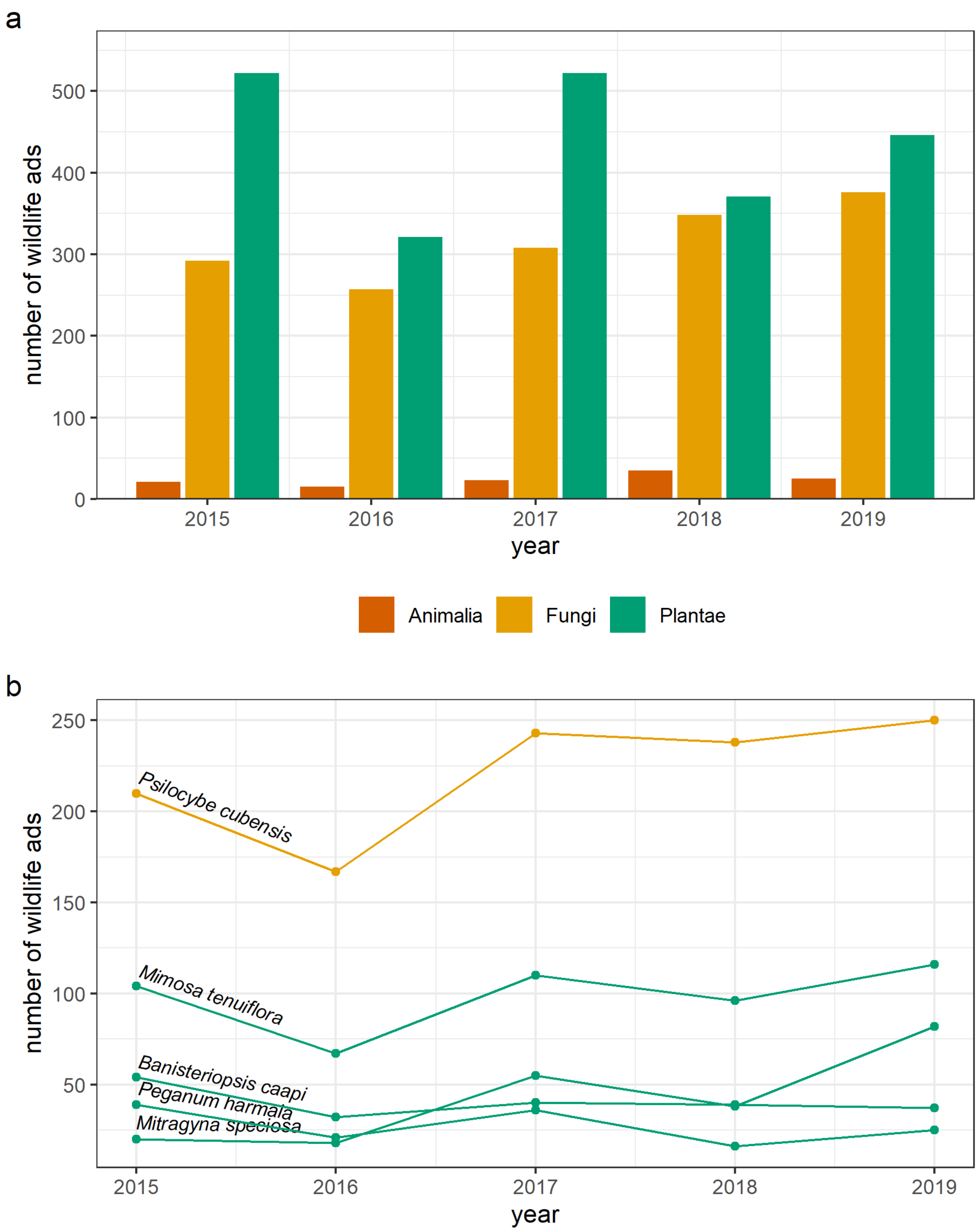

Figure S18. Time series aggregated by number of advertisements per year, (a) by kingdom and (b) for the top 5 traded species. Years 2014 and 2020 were excluded due to incomplete data for the years. Bacteria were not visualized here because they were advertised in 4 advertisements.