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Insects and spiders on the web: Monitoring and mitigating online exploitation of species and services

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ABSTRACT

Exploitation of insects and spiders through commercialization represents a serious threat to rare species and to common species that provide valuable ecological services. The speed, scope, and anonymity, of online commerce places full monitoring and managing of exploitation beyond the resources available to regulatory agencies. To assess the level of online commerce of insect and spider species and services and to test the feasibility of focused searches by student-specialists to generate "leads" for regulatory agencies to pursue, a group of entomology students lead by entomologists and wildlife biologists performed a directed search for sales of insect and spider species listed on CITES Appendices, the IUCN Red List, and the U.S. Endangered Species List, and species that provide services. Focused searches by student-specialists proved effective, locating sales of 79 listed species across all lists. The proportion of listed species discovered for sale varied from 2% to 55% across protected lists and the sale prices of species varied from 2 to 3850 USD. The number of listed species for sale also varied across platforms with less than 6 found on either Amazon or Alibaba and more than 30 found on Etsy and Ebay. In contrast to the listed species, numbers of insects and spiders sold to provide services can range in the billions of individuals and total sales can range in the millions USD. While all species for this purpose do provide a service, they each present unique risks to other species in their genera, guild, and to the larger ecological community, in some cases threatening ecological functions. To effectively monitor the impact of invertebrate service species, we propose incorporating these "livestock" into the existing regulatory framework used for vertebrates.

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1. Introduction

There is recent evidence and concern that the internet is facilitating commerce that is detrimental to rare and endangered wildlife (Yu and Jia, 2015) and some useful frameworks of how illegal wildlife trade on the internet could be monitored have been developed (Stringham et al., 2021). In this study we extend the methods in these frameworks (e.g. web-crawlers, monitoring by experts) by demonstrating that undergraduate students can effectively survey the web for potentially detrimental sales of species within a taxa in which they are developing expertize (e.g. arthropods) and we discuss the results and the unique advantages of this mode of survey.

While the internet is only decades old, and undergraduate monitors are novel, commerce in wild organisms and all its consequences is ancient. Plants and animals have been collected in the wild and exchanged for other items or services throughout all of human history (van Uhm, 2016). While wild populations can benefit from commercialization under specific conditions such as wildlife "farming" (Tensen, 2016), most populations suffer negative consequences either directly through over-exploitation (Hall et al., 2008) and the long-term evolutionary and ecological impacts of domestication (Mathews et al., 2005). Escaped domesticated individuals can also cause indirect negative impacts through pathogen transmission and causing shifts in shared habitats (e.g. facilitating the spread of invasive plants) (Mallinger et al., 2017; Graystock et al., 2015; Meeus et al., 2011). There are many examples of plants and animals that have been driven to the brink of extinction by the collection of specimens from wild populations (Hall et al., 2008), and several examples of species that were "saved" by domestication but now exist only as domesticated relatives to their wild progenitors (Petruzzello, 2020). While some "domesticated" species develop traits that make successful reintroduction into the wild unlikely (Kelley et al., 2006), frameworks are being continually tailored to maximize the potential for success (Seddon et al., 2007).

Not all species are equally at risk to be negatively impacted by commercialization. One factor that is known to be positively correlated with the probability of exploitation through commercialization is monetary value and several factors have been shown to increase the relative value of species. Relative value is positively correlated with rarity (Vall-llosera and Cassey, 2017; Verma, 2016), and esthetics (Vall-llosera and Cassey, 2017). Rare, beautiful organisms (e.g. large colorful birds; Frynta et al., 2010) or those that utilized as products for use as a medical treatment (e.g. bear bile, Feng et al., 2009) or decoration (e.g. ivory; Tensen, 2016) fetch the highest prices. Alternatively, for some groups being accessible and abundant can be a greater risk factor than monetary value (Pires and Clarke, 2012). Beyond factors that influence a species' potential to be commercialized, there are several factors that influence the probable magnitude of any negative impacts on species or populations. The primary factors influencing the magnitude of exploitation impact are reproductive capacity (Hutchings et al., 2012) and abundance, which synergistically are negatively correlated with "value" (Verma, 2016; Courchamp et al., 2006). Direct human exploitation pressure has been assessed to be a less severe risk factor for most plant and animal species especially compared to broader scale factors like habitat loss/degradation and competition with invasive species (Duenas et al., 2018). However, when the number of individuals of a species or individual populations of a species is low, commercialization can become a major risk factor (Courchamp et al., 2006) and this risk is compounded for species that face other threats such as habitat loss through deforestation (Symes et al., 2018). Furthermore, species with limited potential to recover due to reproductive capacity or aggregated population structure (Militz et al., 2018). While the relative value and associated risk of exploitation and the magnitude of impact are governed by separate factors, these forces are not independent of each other. As species become rarer their economic value increases and exploitation pressure and impact (on shrinking populations) continually increases in a phenomenon that has been termed the "anthropogenic Allee effect" (Courchamp et al., 2006).

One group of organisms at particularly high risk from exploitation through commercialization are invertebrates, specifically insects and arachnids (New, 2005). The USFWS list of *threatened* and *endangered* species provides a clear example of this risk. Of the 191 insects and arachnids listed as endangered, threatened or "under review", collection pressure is denoted as a significant risk factor for 60 of those species (31%) (https://ecos.fws.gov/ecp/). Determining the role of collecting in invertebrate extinctions is complicated by the lack of any data on most extinctions that take place before the species has even been described, and the fact that most extinctions are due to multiple factors (Régnier et al., 2015). The large copper butterfly (*Lycaena dispar*) provides an example of the negative impacts of collection. The extirpation of this species from Great Britain is known to have been preceded by intense collection pressure (Duffey, 1968, 1977). Several factors increase the risk of exploitation in this group including their relatively small size, which makes them easy to conceal and ship (Actman, 2019). Further problems include the likely lack of recognition of rare invertebrates among enforcement agents (based on general decline in knowledge of insects; Gangwani and Landin, 2018), recent rapid declines in overall abundance and extremely rapid decline for specific subgroups (Sánchez-Bayo and Wyckhuys, 2019), small population sizes with a meta-population structure for rare species (Almeida et al., 2017), and the value of "services" that certain invertebrate species provide — pollinators, predators of pests, decomposers (Losey and Vaughan, 2006).

Even if the risk to invertebrate species is clear, there is often a sociocultural perception that invertebrates are of less importance than vertebrate species and should therefore be prioritized lower for allocation of protection and conservation resources (Régnier et al., 2015). There are several reasons why invertebrates should not be relegated to lower priority for protection, conservation, or enforcement of collection and commerce restrictions. One reason is that invertebrates are the largest group of animals (Régnier et al., 2015). Insects and arachnids comprise 7 million species which constitutes 80% of all animal species (Stork, 2018; Zhang, 2013). Not only are invertebrates the largest group of animals, they also play a disproportionate role in the functioning of almost all natural and managed ecosystems (Losey and Vaughan, 2006). Specifically, insects and arachnids form the base of most food chains, they suppress pests such as weeds and other insects, they pollinate wild and cultivated plants, and they play a key role in decomposition of dung and dead plants and animals (Losey and Vaughan, 2006). While the role of insects in pollination, pest suppression, are generally known and appreciated, novel applications of insect services such as forensics (Tomberlin et al., 2011) and using bees to keep large mammals (e.g. elephants) out of crops (Scheijen et al., 2019) are constantly being developed. Despite the large proportion of biodiversity accounted

for by insects and arachnids and the vital services they provide, the vast majority of species and their ecological roles remain undescribed (Stork, 2018; Noriega et al., 2018). This lack of knowledge for such an important group of organisms serves to highlight the importance of understanding and managing threats they face since losses of multiple species could result in unforeseen impacts on biodiversity and the functioning of ecosystems (Cardinale et al., 2012).

Given the importance of insects and arachnids and their unique susceptibility, the goal of this study was to evaluate collection and commerce as one potential threat to these species and the services they provide. Specifically, one objective was to survey the prevalence of online sales since that mode of commerce has been shown to represent a growing threat to biodiversity (Yu and Jia, 2015) by lowering barriers to wildlife trade–both legal and illegal (Lavorgna, 2014). Factors inherent to the internet that lower barriers include speed, anonymity, and a worldwide customer base (Cleva and Kish, 2009). A second objective was to determine if undergraduate students under the supervision of professional entomologists within a university setting could effectively conduct these surveys. We hypothesized that they would be effective because they acquire specimens for education and outreach purposes, they understand the organization of invertebrate taxa, they are highly motivated to conserve insect species and services, and they have ready access to "expert" faculty and staff.

As a first step in assessing these threats, we quantified sales of species listed as being endangered, threatened or at particular risk from commercialization and we examined the sustainability of species that are sold to provide a "service", such as pest suppression or pollination. We incorporated two methods that have been tested for their potential to improve the efficiency of internet monitoring in other taxa, employing experts, and, utilizing automation (Vaglica et al., 2017). In contrast to earlier studies, our monitors were undergraduate students of entomology and this mid-level of expertize between amateur and professional provides some unique opportunities including substantially increasing the level of monitoring at a relatively low cost and providing an active learning opportunity for the students in these issues and monitoring methods. In addition to evaluating online sales of species and services, we compared the level of sales and the safeguards to prevent prohibited sales across platforms. Through these efforts we provide a snapshot of the scope of online sales across platforms, and we develop provisional plans to (1) aid in the detection of potentially illegal sales of protected species, and, (2) to incorporate regulation of sales of invertebrates that provide services into existing regulatory frameworks for vertebrate livestock.

2. Methods

Our survey of online sales of insects and arachnids was divided into two major groups, *imperiled species* and *service species,* and was conducted explicitly across four platforms we considered major (eBay, Amazon, Etsy, and Alibaba) by searching the scientific and common names of each species with no additional text, the names plus the word "sale" and the species names plus the name of the platform on Google (Google Inc.). Additional smaller platforms that were not one of the four major platforms were grouped as "other" and were recorded as they were encountered in searches using only the name of a species. All species were searched once and searches were conducted between October and November 2019 with links to sales identified in the initial search rechecked to determine if it they were still "live" as indicated in presented tables. We did not record when an advertisement was posted but only links for target arthropods that were ostensibly available for purchase were recorded as live. To stay within our ethical framework, we did not initiate any purchases that presumably would have been subsequently canceled. Searches were conducted in the United States (specifically Ithaca, New York) and thus results represent information as it would be accessed by a potential customer in this region (e.g. *Amazon.com* not *Amazon.UK*).

2.1. Research Ethics

As this project involved searching for and analyzing data from web sites without prior permission, we sought guidance from the Cornell Institutional Review Board (IRB) regarding adherence to ethical guidelines for this mode of research. The IRB concurred with our assessment that the research we report on in this paper falls outside the strict rules governing "human subject" research because it meets the following three criteria; (1) all data we accessed was publicly available on open access sites, (2) there was no interaction between researchers and parties posting items for sale, and, (3) no personal data is reported in the main paper or supplemental files. Based on this guidance, and in agreement with two of the most recent surveys of online wildlife commerce (Xu et al., 2020, 2019), we conclude that prior permission was not required to acquire, analyze, and report this data.

2.2. Platform profiles

To provide general context on the relative amount of illegal trade compared to overall volume and other factors that might influence the optimal allocation and mode of efforts to limit illegal sales we compiled the following on each major platform (eBay, Amazon, Etsy, and Alibaba), (1) annual revenue, (2) the number of years a corporation has been conducting online commerce, and, (3) location in which an online platform is incorporated. We also profiled their stated policies regarding prohibition of sales of insects or arachnids from any of our "search lists", as well as the existence of a "reporting forum" that allows notification of the platform if any prohibited organisms are found for sale. Total and proportional sales of insect and arachnid species, prices, and sustainable sourcing are compared across platforms including the smaller "other" platforms.

2.3. Imperiled species

While we realize many species at risk do not appear on any official list, for this study we defined a set of species as "imperiled" that appear in a subset of categories on one of three major conservation listings. We chose the term "imperiled" following definition of the United States Geological Survey (USGS, 2022) which applies the term to species that face specific perils but vary in their current biological and legal status. The subset of categories included *endangered* (in current high risk of extinction), *threatened* (at risk of becoming endangered), or at risk of consequences from commerce so severe that they warrant restricted or regulated commerce over at least a subset of the species range. Specifically, our focal set of imperiled species included insects and spiders on the following lists: the Convention on International Trade in Endangered Species (CITES) Appendices I, II, and III [at risk from commerce], the "critically endangered" section of International Union for the Conservation of Nature (IUCN) Red List [endangered], and the United States Fish and Wildlife Service lists of endangered and threatened species [includes endangered and threatened species and explicitly limits commerce in listed species]. We acknowledge that some of the species we include in this category are not currently rare (e.g. several on the CITES Appendices II and III), but all the species addressed in this section have been deemed to be in current or potential danger of unacceptable negative consequences if collection and commerce are not regulated. The CITES and IUCN lists are international in scope and CITES restrictions are enforced in the US. We limited our survey of the IUCN Red List to critically endangered due to time constraints. The USFWS list is for species in the US and commerce is prohibited for these species. The legality of sales of individuals in the CITES depends partly on their origin or provenance. We intended to establish this for each sale instance, but we discovered that there was insufficient information to allow this for most instances, so we do not report this data. Thus, we cannot characterize the legality of many of the instances from the CITES Appendices. It should be noted that any purchase of an individual specimen from the CITES Appendices that does not have full provenance represents a risk for the prospective purchaser. For every species on each of these lists we searched using full scientific names and, when available, the common name along with the word "sale" on Google, additionally, we searched each species within the major platforms (eBay, Amazon, Etsy, and Alibaba). Resource constraints prevented inclusion of synonyms. For all listed species found for sale on any site, we recorded the links, platforms, and prices. We marked each platform as either positive (the species was found for sale) or negative (no sale of that species was found) and thus the total number of "instances" of sales for a single species ranged from 0 (no positive for sales) to 5 (species available on all four major platforms and at least one other platform). To complement our data on the proportion of species for sale online with the number of "instances" that individual species are offered for sale, we collaborated with the e-commerce monitoring and protection company TrackStreet (https://www.trackstreet.com/). They donated their expertise in using their advanced web-crawlers and other techniques to search for instances of sales of three butterfly species; *Papilio chikae*, *Teinopalpus imperialis*, and *Trogonoptera brookiana*.

2.4. Service species

We define service species broadly as any species that performs a function with a tangible value to humans. We focused on three services: pest suppression, pollination, and education/entertainment. Specifically, we focused on species that are either reared or collected in the wild and are purchased and released in an open setting to perform a specific task. Three groups not included in our study were; (1) any species that are sold only for use in enclosed structures like greenhouses (e.g. predatory mites such as *Phytoseiulus persimilis*), (2) species such as the European honey bee, *Apis mellifera,* whose pollination services are more often "rented" rather than outright purchased, and, (3) species that are purchased as "specimens" live or dead in units of less than 50. Furthermore, as a domesticated species that is widely naturalized in feral populations throughout the world, threats associated with *Apis mellifera* in particular are unique from that of native, undomesticated species being used for pollination services, and whole bodies of literature have been devoted to this subject at the neglect of native species (Genersch, 2010; vanEngelsdorp and Meixner, 2010). To evaluate annual sales of species providing the three focal services in the United States, we reviewed published sources to estimate the (1) number of species in each service category, (2) the number of individual insects sold, and, (3) the annual monetary value of sales. Published values for most categories could not be found in peer-reviewed publications so estimates were made by combining values from several sources. Since the dearth of data is a key finding we report detail on these foundational values in the results section.

Table 1
Profiles of major platforms and polices on imperiled insects and arachnids.

Platform	Founded	Location	Revenue[1]	Stated Policy on Restricted Sales					Reporting Forum[2]
				CITES Appendices			IUCN Red List	US ESA	
				I	II	III			
Amazon	1994	Bellevue, WA	$232.89	**Y**	**Y**	**Y**	*N*	**Y**	**Y**
Ebay	1995	San Jose, CA	$10.74	*N*	*N*	*N*	*N*	*N*	**Y**[3]
Etsy	2005	Brooklyn, NY	$0.60	**Y**	*N*	*N*	*N*	**Y**	**Y**
Alibaba	1999	Hangzhou, Zhejiang	$56.15	**Y**	**Y**	**Y**	*N*	*N*	**Y**

1 Billion USD from 2018. 2 Accessible link or contact for reporting potential infractions. 3 A forum exists to report prohibited sales but there is no prohibition against selling endangered wildlife

3. Results

3.1. Platform profiles

The four platforms we focused on for directed assessment of prohibited sales varied widely in terms of volume of sales, policies regarding prohibition of restricted sales, and a clear, functional mechanism for reporting prohibited sales. Amazon is by far the largest with over 230 billion USD sales reported in 2018 and more than 4x the size of its nearest competitor Alibaba at 56 billion (Table 1). The volume of sales from eBay is on the same order of magnitude as Alibaba and Etsy is the newest (established 2005) and smallest at less than 1 billion USD of annual sales. In terms of specific, stated policies on prohibition of sales that we were able to find on platform policy sites, all platforms except eBay restrict sales of species on the CITES Appendix I list (Table 1). Only Amazon and Alibaba have policies that pertain to restrictions on sales of species on the CITES lists in Appendices II and III. None of the major platforms have policies that restrict sales of species on the IUCN Red List. Amazon and Etsy have policies regarding sales of species listed as Endangered or Threatened by the USFWS under the ESA but eBay and Alibaba do not. All platforms have some mechanism for reporting instances of prohibited sales or other infractions but these mechanisms are not necessarily clear or straightforward to access.

3.2. Imperiled species

Ninety-eight species of insects and arachnids are listed on CITES and fifty-four (55%) of those can be found for sale on Amazon, eBay, Etsy, Alibaba, and other sites (Table 2). Out of the three species included in Appendix I, one was found for sale (33%), fifty-one can be found for sale out of the seventy-four in Appendix II (69%), and two can be found for sale out of the twenty-one in Appendix III (10%) (Table 2). eBay has the most species available for sale (44% of all CITES insects were sold on this site), followed by Etsy (29%), "other sites" (17%), and Amazon (3%). None are found on Alibaba, and only Amazon sells any insect from Appendix I. The price for the only Appendix I listed species found for sale (*Papilio chikae*) was $109.99. The average price for species listed on Appendix II was $245.62 (range: $3-$3850), and $393.39 (range: $267-$520) for a species on Appendix III. The average price for a CITES-listed insect is $249.67 across all sites.

Out of the 364 insect and arachnid species listed as "critically endangered" on the IUCN Red List, seven (2%) are being sold online (Table 2). The highest sale price was $2000, and the lowest price was $0.01, with a mean price of $340. The highest price found was for *Aleochara freyi,* a rove beetle (family Staphylinidae) apparently caught in the wild and sold on a site outside the four major platforms (i.e. one grouped as an "other platform" in this study). The platform that had the most endangered insects being sold on it was eBay, with six (2%) while none were found on Amazon or Etsy.

Of the 191 insect and spider species listed on the ESA, nineteen (10%) were found being sold online (Table 2; see Appendix 1 for complete list). Eleven of these species are tarantulas (family Theraphosidae) and the remaining eight are butterflies (order Lepidoptera). Five of the tarantula species are listed as endangered while the other six are in the petition stage. Three of the butterfly species are listed as endangered and the other five are in the petition stage. Put together, this means that at least eight endangered insect and spider species are being sold commercially online for an average price of $50 (range: $2-$100), one threatened species for $6 and ten species "under review" for an average of $52 (range: $6-$278) (Table 2).

Utilizing their webcrawler, TrackStreet found three sale instances for *P. chikae* which is the same as we found for this species. This species carries the highest level of prohibition against sales and shipping both internationally [*P. chikae* is listed on Appendix 1 on CITES] and in the U.S. [listed as "endangered" (Nowak, 1993) making it "illegal to possess, sell, deliver, transport, or ship" in or into the country]. Both "direct search" and "web-crawler" methods yielded the same small number of results. In contrast, the TrackSteet webcrawler found 13 instances of *T. imperialis* and 59 instances of *T. brookiana* while we recorded 3 and 4 respectively.

Table 2
Summary of online commerce in imperiled insects and arachnids across major platforms.

Platform	CITES Appendices			IUCN Red List	US ESA		
	I	II	III	Critically Endangered	Endangered	Threatened	Other
Total Species	3	74	21	364	95	11	85
Amazon[1]	1 [0.33]	2 [0.03]	0 [0.00]	0 [0.00]	1 [0.01]	0 [0.00]	2 [0.02]
Ebay[1]	0 [0.00]	41 [0.55]	2 [0.10]	6 [0.02]	3 [0.03]	0 [0.00]	7 [0.08]
Etsy[1]	0 [0.00]	27 [0.36]	1 [0.05]	0 [0.00]	0 [0.00]	0 [0.00]	3 [0.04]
Alibaba[1]	0 [0.00]	0 [0.00]	0 [0.00]	1 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]
Other[1]	0 [0.00]	17 [0.23]	0 [0.00]	2 [0.01]	8 [0.08]	0 [0.00]	11 [0.13]
Any[2]	1 [0.33]	51 [0.69]	2 [0.10]	7 [0.02]	8 [0.08]	0 [0.00]	10 [0.12]
Mean Price {Min-Max}	$110 {$110-$110}	$246 {$3-$3850}	$393 {$267-$520}	$340 {$0-$2000}	$50 {$2-$100}	$0 {$0-$0}	$52 {$6-$278}
Consequences:	Fines	Fines	None	None	Fines	Fines	Variable
Enforcement:	Variable[3]	Variable[3]	None	None	USFWS	USFWS	USFWS

1 Number of species, [proportion]; individual species may be for sale on multiple platforms. 2 The number of species [proportion] in category for sale on any platform. 3 Enforcement agency varies by country; USFWS in US

3.3. Service species

Across all categories of services we surveyed, both the numbers of individuals and the total value of sales for insects released annually in the United States were vast. Numbers of individuals released ranged from tens of millions to billions and sales ranged from hundreds of thousands of dollars to tens of millions (Table 4). While the total numbers of individuals released was large and the multiple species were available for purchase for each service, a single species accounted for at least 90% of the number of individuals released for each of our three service categories (Table 4). Estimation of values for each service required the integration of multiple sources including several not from peer-reviewed publications.

3.3.1. Pest Suppression

Within this category we found a broad set of 32 species, including 15 predators and parasitoids of pest insects (Warner and Getz, 2008). These species are primarily biological control agents for herbivorous insect pests but also include some parasitoids of insect pests associated with livestock production (Warner and Getz, 2008). In addition to these species, 17 species of herbivorous insects intended for release to control weed species were found but they do not appear to be available currently, so they were not included in estimates of numbers released or total sales. The value of annual sales of insects for pest suppression in non-enclosed settings was estimated to be over 17 million dollars based on the median value (27.5 million) of Warner and Getz (2008) estimate of 25–30 million dollars and assuming 65% of this total (OTA 1995) directed towards crops that are not in enclosed spaces (e.g. not greenhouses). Among these species, *Hippodamia convergens*, the convergent lady beetle, accounted for 3 million dollars (Flint and Dreistadt, 2005) or 17%. This volume of *H. convergens* accounts for 91% of the individuals with 3 billion estimated to be released annually (Flint and Dreistadt, 2005). Based on the remaining sales value for species other than *H. convergens* (almost 15 million dollars) and the average cost per individual (from Warner and Getz, 2008), the number of individuals of other species released is just under 300 million (Table 4).

3.3.2. Pollination

Velthuis and Van Doorn (2006) estimate that over 22 million bumble bees (bees in the genus *Bombus)* are sold annually in the United States. The majority of these pollinators (95%) are deployed to pollinate tomatoes grown in greenhouses (Velthuis and Van Doorn, 2006) leading to an estimate that just over 1 million (the remaining 5%; Table 4) are released in non-enclosed areas at an average cost of $181.45 per colony (Owen, 2016) and a total cost of just over 500 thousand dollars (Table 4). While there are at least 6 species of pollinators sold, including several bees in the family Megachilidae, the primary species, *Bombus impatiens*, accounts for 98% of both the individuals released and the total cost (Table 4). Potential for over-estimation of individuals and cost exists in defining the 5% of bumble bee species not released for pollination of greenhouse tomatoes as released in non-enclosed areas since some of these could be released to pollinate other greenhouse crops. Conversely, the inability to quantify releases of megachilids would lead to under-estimation of the total since this group is released primarily in non-enclosed areas.

3.3.3. Entertainment

The largest total annual sales for any of the services surveyed was for “entertainment” at 22 million dollars (Table 4). We labeled this service entertainment because these insects are released to serve no function other than to fly and be observed. Based on literature and internet surveys, butterflies (insects in the order Lepidoptera) are the predominant taxa released primarily for observation. The estimate stems from an opinion article by Lockwood (2006) that postulates (based on extrapolations from producers) that there are 11 million butterflies released each year. Assuming a cost of USD$2 per butterfly that yields an estimate of $22 million dollars spent on butterflies for release (Table 4). Note that the cost per butterfly decreases as the order becomes larger (https://weddings.costhelper.com/butterflies-release-cost.html). To be conservative, the estimate presented in Table 4 is based on the lowest cost per butterfly corresponding to orders of 100–200 butterflies. Smaller orders of 30–60 or 12–24 butterflies would be 2–3 times more expensive (https://weddings.costhelper.com/butterflies-release-cost.html). Although 10 butterfly species can be legally sold in the US (Wheling, 2019), it has been estimated that 99% of butterflies sold for release are comprised of two species, monarchs (*Danaus plexippus*) and painted ladies (*Vanessa cardui*) (New, 2008). Between these two species, the calculations that form the basis of Lockwood (2006) indicate that *V. cardui* accounts for 89% of the market (JAL personal communication) and given recent publications warning against mass releases of monarchs (e.g. Davis et al., 2020) estimates of at least a 90% market share for *V. cardui* appear justified. Based on those assumptions, almost 20 million dollars are spent each year to release nearly 10 million painted lady butterflies.

4. Discussion

We found a substantial number of insect and spider species for which commerce is potentially restricted (e.g. species listed on the CITES Appendices) or prohibited by national (e.g. species that are designated as endangered or threatened in the U.S.) or international laws openly for sale online. There was a high level of variation across the lists of species we surveyed in the number and proportion of species available for sale but a fairly consistent lack of information necessary to characterize those sales for which legitimacy depends on full knowledge of their provenance. One positive finding was that only a single species listed on CITES Appendix 1, the Luzon peacock swallowtail, *Papilio chikae*, (Supplemental 1) was found for sale. Unfortunately, only three insect and spider species are listed on this appendix, which lists species for which commerce is highly regulated under international treaty, while over three hundred are listed as “critically endangered” on the IUCN Red List, which carries no protection. Only 7 of the 364 species of insects and spiders on the IUCN Red List were found to be for sale, which can be taken as some indication that the current risk to this group from commerce is

small. However, examples such as the large, charismatic Wallace's giant bee, *Megachile pluto*, and the Cyprus beetle, *Propomacrus cypriacus*, both of have been offered for sale at over thousand US$, imply that some, and perhaps all, of Red List insect and spider species should be reconsidered for protection under CITES (Vereecken, 2018). Sales of species on Appendix I are the simplest to interpret because there is a ban on trade for commercial purposes and permits are required for import and export for any reason (USFWS, 2020). These arthropod species are threatened by extinction, and export is allowed only in exceptional circumstances such as research or law enforcement with the country of origin's confirmation that taking those specimens will not negatively impact the species' chance of survival (USFWS, 2020). One potential exception could be if the species is reared specifically to produce specimens for sale since this would not put an undomesticated individual at risk. Also covered by the CITES treaty, 74 species of insects and spiders are listed on Appendix II. This appendix includes species not necessarily threatened by imminent extinction, but that require trade regulation to avoid threatening their survival. To be listed on either Appendices I or II, a species must have been found to be currently or potentially threatened and then approved for listing by the Conference of the Parties (CoP) (USFWS, 2014). Species on Appendix II can be sold and exported but commerce is strictly regulated and sellers must obtain a permit specifying that individual organisms were obtained in a way that does not pose a threat to the species (USFWS, 2014). We found almost 70% of the insect and spider species listed on Appendix II were available for sale and it was difficult to determine if they were sustainably sourced (e.g. through a directed "farming" program) or if the seller had the proper permits. The value of some species on Appendix II is clearly high with one selling for $3850 (Table 2) and high values are associated with high risk levels (Verma, 2016). In our survey, we found clear proper provenance was not provided for most of the spiders and insects offered for sale which makes it difficult for any potential buyer or regulator to determine which sales are legitimate. One group that provides a clear example of this difficulty are the spiders in the family Theraphosidae, known as tarantulas. Tarantulas are commonly sold as pets and while many are reared in captivity, overharvesting in the wild is reported to be the main cause of losses of individuals in wild populations (Fukushima et al., 2019).

Appendices I and II prohibit exportation of listed species without proper clearance regardless of where the individual organism originated. In contrast, commerce in species on Appendix III requires a permit only when sourced from countries that requested protection for that species (USFWS, 2016). Sale of individual organisms on Appendix III do not require a permit if they are sourced from countries that did not request regulation, but these transactions do require a certificate of origin to certify they did not originate from a prohibited area. While this tiered system provides necessary flexibility, it adds an additional layer of complication to determining if individual organisms for sale were legally and sustainably sourced.

Monitoring and regulating commerce of species protected by CITES falls to different governmental units across the world. Under the CITES treaty enforcement of sales and exportation, prohibition is undertaken by each member country. In the United States, the Endangered Species Act (ESA) designates that CITES is to be carried out and enforced by the U.S. Fish and Wildlife Service (USFWS, 2020). While the United States has been found to have one of the most sophisticated CITES enforcement programs compared to many other countries that have signed the agreement, it faces very substantial challenges (Alagappan, 1990). According to the 2013–2015 U.S. CITES implementation report, the U.S. Fish and Wildlife Service inspected traders, producers, and markets, had border controls, conducted random or intelligence-based inspections to check cargo, mail shipments, passengers, and vehicles at the border, and undertook "special enforcement operations focused on internet-based wildlife trafficking" (USFWS, 2015). However, full monitoring and enforcement of illegal wildlife trafficking online is not possible with less than 250 special agents in the U.S.F.W.S. Office of Law Enforcement (Goyenechea and Indenbaum, 2015) to handle the entire range of duties.

While enforcement of restrictions of international trade of species listed on the CITES Appendices alone exceeds allocated resources within the U.S. Fish and Wildlife Service, the agency is also tasked with enforcing regulations at the national level pertaining to species listed under the Endangered Species Act (USFWS, 2018). Endangered species legislation in the U.S. has multiple components including development of a conservation plan that includes establishing a "critical habitat". The criminal penalties for killing an endangered species can be as serious as a year in prison and $50,000 in fines, and civil penalties can range up to $25,000 per violation and penalties for transportation and commerce are only slightly less severe (NOAA, 2008). While these consequences may seem severe enough to effectively prevent commerce of listed species, they are balanced against a potentially high profit margin for items that can be sold for hundreds of dollars and, given the challenges involving enforcement, a relatively low risk of being caught (Harrison et al., 2016).

Our results demonstrate numerous prohibited insect and spider species are being offered for sale occurring despite the current efforts to limit illegal at national and international levels. A test of incorporating alternate monitoring methods indicates that our results underestimate both the scope and the fluidity of this illegal commerce. While our methods discovered a substantial number of sales, we were primarily concerned with determining the proportion of focal species for sale and the profile of major and minor platforms where they are offered for sale. Collaboration with TrackStreet allowed us to more deeply investigate three species found for sale to determine how many total "instances" of sales were available online. The higher totals from TrackStreet stem primarily from identifying a large number of "other" platforms and, to a lesser degree, from price fluctuations as we counted each novel price as a novel instance of sale of a species. *T. imperialis* and *T. brookiana* are ranked *Near Threatened* (Gimenez Dixon, 1996) and *Least Concern* (Böhm, 2018) respectively on the IUCN Red List and like almost all species with those ranks, there is no restriction on sales. However, the large number of instances found illustrates the utility of web crawler systems to monitor species that could become imperiled if conditions change (e.g. major habitat loss) or if a spike in sales portends increased collection pressure. Synergistic integration of additional technologies such as "machine learning" could make the monitoring process even more effective (Xu et al., 2019).

One potential source of assistance for the overburdened government agencies tasked with regulation of illegal wildlife sales online could come from the online commerce platforms where the species are sold. These platforms can be held liable for illegal transactions with a value of over $350 (Williams, 2015) so they could choose to make efforts to limit illegal sales of protected species to limit their legal liability, to maintain or improve user perception that they are environmentally responsible, and to act on their own environmental philosophy (Williams, 2015). These factors have led to varying levels of commitment and activity. Three of the largest online

commerce platforms, Alibaba, eBay, and Etsy are members of the Coalition to End Wildlife Trafficking Online (https://www.worldwildlife.org/pages/coalition-to-end-wildlife-trafficking-online) and Amazon recently signed a joint statement which included a "commitment to protect the environment by embracing sustainable practices" (https://opportunity.businessroundtable.org/ourcommitment/). The tangible actions an online platform could take include a clear policy excluding listing any species that is prohibited from commerce at the national or international level. Amazon, Alibaba, and Etsy have clearly stated, yet vague policies, unlike eBay (Table 1). None of the major platforms have a clear list of restricted species. Beyond a static list, sellers and buyers could much more easily avoid unwitting prohibited wildlife transactions if a searchable list was provided on the platform. Sellers seeking to thwart the prohibitions could be impeded by automatic "tagging" of items with scientific names matching restricted names or common names or images. These tags could be overcome by slight intentional misspellings, but the tagging could introduce some important standards.

Regardless of the steps taken to minimize listings of illegal wildlife items for sale, some sellers will manage to circumvent them. This inevitability raises the necessity of periodic monitoring of platforms and removal of illegal items. Monitoring can be aided by tools like the ones employed by TackStreet but this automated monitoring will still require a substantial amount of human labor. The Coalition to End Wildlife Trafficking Online organizes "citizen scientists" to make additional observations and all four of the major platforms provide "reporting forums" allowing anyone using the site to bring illegal items to their attention (Table 1). The reporting forums are potentially very useful since the volume of traffic on the sites is very high creating substantial potential for illegal activity to be found and reported. Williams (2015) reports that when eBay's senior manager of global corporate affairs was alerted of a butterfly being illegally offered for sale it was removed the next day. Unfortunately, the reporting forums do not seem to go to a high-ranking executive. As part of this project we reported a specimen of *Papilio chikae* for sale to Amazon on October 30, 2019 and one of the students reported again on December 14, 2019. After both reports, we were assured that the item would be removed and after the second report the student was promised a $5 gift certificate in appreciation. As of February 16, 2022 the item is still listed for sale and the student has not received the gift certificate. To be effective and to encourage continued reporting, items identified need to be removed quickly and perpetrators need to be banned from future listing privileges.

While management of illegal sales can be challenging on major platforms because of their large volume, regulation of smaller platforms presents its own set of unique challenges (Lavorgna, 2014). Some of these smaller sites are consistently responsible and respond rapidly to queries but others are difficult to contact and some may not be under pressure to respond to regulators or concerned conservation specialists from other countries. Species listed by the U.S. Fish & Wildlife Service under ESA guidelines provide an illustrative example of the importance of these "other" platforms. Considering that list, of the 85 species in the petition process, 11 (13%) are for sale on "other" platforms compared to 12 (14%) across all the major platforms (see Tables 2 and 3). Even more striking, 8 (8%) of the 95 endangered species were for sale on other platforms compared to 4 (4%) on the major platforms. Our survey uncovered 12 smaller platforms and there are almost certainly some we did not find. To monitor and enforce restrictions on the larger group of smaller platforms entails a different set of challenges compared to working with the four primary web marketplaces. A change in monitoring or enforcement policy from one of the major platforms impacts a high volume of sales with the impact potentially lasting over a long period. Changes in policy on smaller platforms impact a smaller volume of overall sales and probably illegal sales and only lasts as long as the platform exists.

If monitoring smaller platforms is already problematic, monitoring sales through social media platforms is nearly impossible. Considering that social media platforms are built to facilitate virtual interactions, sales are decentralized and even more unregulated. User accountability and credibility is difficult to control, since social media platforms provide tools that promote anonymity. For example, platforms like Facebook, Instagram, and Twitter allow users to freely create and delete groups, posts, and threads leaving little trace of illegal activity. For this reason, it is likely that many online illegal insect sellers are choosing to migrate to social media platforms as it facilitates their illegal activities. Even though social media platforms grant flexibility and autonomy to their users, there

Table 3
Summary of online commerce in imperiled insects and arachnids from minor platforms.

Platform		CITES Appendices			IUCN Red List	US ESA		
	All Lists	I	II	III	Critically Endangered	Endangered	Threatened	Other
Total Species	653	3	74	21	364	95	11	85
Arachnophiliacs[1]	8 [0.01]	0 [0.00]	8 [0.11]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]
Auction-net.co.uk[1]	1 [0.00]	0 [0.00]	1 [0.01]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]
Backwaterreptiles[1]	5 [0.01]	0 [0.00]	4 [0.05]	0 [0.00]	1 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]
Fearnottarantulas[1]	3 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	1 [0.01]	0 [0.00]	2 [0.02]
Insect-classifieds[1]	1 [0.00]	0 [0.00]	1 [0.01]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]
Jamiestarantulas[1]	1 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	1 [0.01]
Lepidopexchange[1]	1 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	1 [0.01]	0 [0.00]	0 [0.00]
Minibeast.uk[1]	1 [0.00]	0 [0.00]	1 [0.01]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]
Myhomenature[1]	1 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	1 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]
Pinchersandpokies[1]	10 [0.02]	0 [0.00]	1 [0.01]	0 [0.00]	0 [0.00]	4 [0.04]	0 [0.00]	5 [0.06]
Swiftinverts[1]	2 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	0 [0.00]	1 [0.01]	0 [0.00]	1 [0.01]
Undergroundreptiles[1]	4 [0.01]	0 [0.00]	1 [0.01]	0 [0.00]	0 [0.00]	1 [0.01]	0 [0.00]	2 [0.02]
Total:[2]	38	0	17	0	2	8	0	11

1 Number of species, [proportion]; individual species may be for sale on multiple platforms. 2 Total instances of sales across all minor platforms; includes multiple sales of individual species.

is a group of sites commonly referred to as the "dark web" that are intentionally hidden completely unregulated. A primary purpose of these sites is to evade law enforcement agencies to facilitate illegal activities. Despite the unregulated status, a recent study found almost no illegal wildlife trade advertised within the "dark web" platform, suggesting that the lack of successful monitoring in the "surface web" has been normalized (Harrison et al., 2016). There have been suggestions for incorporating machine learning algorithms into social media platforms for tracking illegal wildlife trade, but social media platforms have been reluctant to incorporate them since it involves data sharing and cross-platform collaboration (Di Minin et al., 2018). This prompts a reevaluation of current strategies for monitoring illegal online sales in social media platforms.

Many of the general considerations discussed above regarding insects and spiders are applicable to other larger animals such as mammals, birds, and reptiles, but one important difference between our focal insects and spiders and these other groups is that while invertebrates are small of stature, they play outsized roles in their ecosystems (Losey and Vaughan, 2006). This aspect of insects and spiders presents both some unique challenges and some opportunities in terms of commerce for several key species (Table 4).

The utilization and even commercialization of species that provide services could benefit imperiled species through service provision (e.g. pest suppression) by reducing the use of pesticides (Van Lenteren, 2012). This benefit could be enhanced if the species being utilized to provide the service is in need of conservation although there are inherent risks to rearing and redistribution (Michaud, 2018). There are multiple species commercially available to provide each service but we will focus on and profile the dominant species for each one. The widest array of species is available for pest management with over 200 species available worldwide for releases in both closed (e.g. greenhouses) and open areas (Van Lenteren, 2012) and 32 of those species available in North America (Warner and Getz, 2008). Although the pool of species that could suppress pests is large, provision of this service is dominated by the convergent lady beetle, *Hippodamia convergens* (Flint and Dreistadt, 2005). Because this species builds up massive populations in California's Central Valley and aestivates in the Sierra Nevada mountains as the valley begins to heat and dry in early June, they can be collected and shipped very cheaply (as little as $1 per 1000 adults; Flint and Dreistadt, 2005). This species collected and shipped in this way are usually ineffective in open field releases as they tend to disperse quickly following release (Michaud, 2018). While there have been some promising results for controlling aphid outbreaks in tunnel production systems. (Hall, 2014) this is a very small market segment compared to the large number of ladybugs collected, shipped, and released.

Similar to the convergent lady beetle, commercialization of the common eastern bumble bee, *Bombus impatiens*, can provide an essential service, in this case pollination, within specific agricultural production systems (Owen, 2016). The connection between the utilization of *Bombus* spp. and conservation is not as clear as for the use of *H. convergens* which can ostensibly reduce the amount of pesticides applied. One potential benefit of the use of alternate pollinators would be if they increased efficiency of production resulting in less area under cultivation leaving more area for the majority of species not suited to cultivated areas, a concept that has been termed "land sparing" (Balmford et al., 2005; Green et al., 2005). Compared with the European honeybee, *Apis mellifera*, non-Apis pollinators can be more effective depending on the agricultural system. In watermelon (*Citrullus lanata*), *Bombus impatiens* outperformed *Apis melllifera* in seed set (Stanghellini et al., 1998). In another case, *Bombus impatiens* performed just as well as *Apis mellifera* in blueberry systems along many different metrics (Stubbs and Drummond, 2001). Even in crops where *Apis mellifera* may outperform native or non-*Apis* managed pollinators, these alternative pollinators may serve as effective and reliable supplements to the fair-weather honey bee (Brittain et al., 2013). Native bees visit crops in weather conditions that are considered unfavorable for *Apis mellifera*, particularly with respect to rosaceous crops (Vicens and Bosch, 2000). There is also a large body of evidence suggesting that pollinator diversity is important in agricultural output in crops and systems which require insect pollination (Garantonakis et al., 2016; Brittain et al., 2013).

Unlike the convergent lady beetle and the eastern bumble bee, the painted lady butterfly, *Vanessa cardui*, is not valued for an agricultural function it performs, but rather an esthetic one. This butterfly provides memorable experiences (New, 2008) and psychological or physiological benefits to observers (Bratman et al., 2019). While this mode of benefit may be more difficult to conceptualize and quantify, clear benefits resulting from positive interactions with nature (Rakow and Eells, 2019) and specifically insects (Ko et al., 2016) have been demonstrated and are clear enough to the general public that they profess a quantifiable "willingness to pay" to maintain charismatic species such as butterflies (Diffendorfer et al., 2014; Degenhardt and Gronemann, 1998).

Balanced against the benefits associated with the commercialization of the three services and the insect species that provide them, there are potentially substantial risks. The risks within our study scope of species released into open space to provide a specific service can be divided into two categories. These categories include negative impacts from collection or habitat disruption, and negative impacts following release including impacts on the "consumer" or more general public (Michaud, 2018).

Among the three species we profiled that are the primary purveyors of their respective services, only the convergent lady beetle

Table 4
Annual field releases of insects to provide services in the U.S.

Service	Number of Species Sold	Number of Individuals Sold	Annual Sales ($)
Pest Management	32	3,297,552,072[1,2]	17,875,000[1]
Hippodamia convergens[3]	–	3,000,000,000[2]	3,000,000[2]
Pollination	6	1,115,000[4]	508,060[4,5]
Bombus impatiens[3]	–	1,110,000[4]	498,988[4,5]
Entertainment	10[6]	11,000,000[7]	22,000,000[8]
Vanessa cardui[3]	–	9,900,000[9]	19,602,000[9]

1 Warner and Getz (2008). 2 Flint and Dreistadt (2005). 3 Primary species in category representing over 90% of individuals released. 4. Velthuis and van Doorn (2006). 5 Owen (2016). 6 Wheling (2019). 7 Pyle et al. (2010); from Lockwood (2006). 8 https://weddings.costhelper.com/butterflies-release-cost.html. 9 New (2008) – from Taylor (2004); Lockwood - communication

faces substantial risk at its collection sites. In the past bumble bee queens were collected in such great numbers to initiate colonies that the practice became a cause for concern, however Velthuis and Van Doorn (2006) report that following the adoption of queen rearing in commercial systems, the level of collecting for this purpose has been very low since 1995. Similarly, rearing of the painted lady butterfly involves very little collecting and any specimens collected will likely have negligible impact on this species that is known to be abundant, adaptable, and have an extremely broad distribution including all continents except Australia and Antarctica (Shields, 1992).

For the convergent lady beetle, the estimated 3 billion adults beetles collected each year (Flint and Dreistadt, 2005) as they take refuge from the hot dry conditions in the Central Valley in the cooler Sierra Nevada mountains (Hagen, 1962) raises concerns that there could be an impact on that population (Ferguson, 2014). While the number of adult beetles shipped annually is large and almost certainly underestimates the number collected or harmed in the collection process, estimating sustainability will depend on relationship of the number collected to the total number in the Sierra Nevada population. Given a rough estimate that every acre of alfalfa in the Central Valley can produce around 50,000 adult lady beetles (Dickson et al., 1955) and just over 500,000 acres of alfalfa grown in the Central Valley (https://hayandforage.com/article-2560-california-alfalfa-acres-set-a-new-low.html) there could be 25 billion adult lady beetles arising from this primary producer of ladybeetles. Of those 25 billion, it is reasonable to estimate that only half will survive the winter (Mercer et al., 2020) leaving a population of less than 13 billion. Given that these estimates do not account for mortality during migration, wildfires, pesticide use, and any impact of climate change, current collection levels may not be sustainable in the long term and the high level of agricultural productivity in California depends on pest suppression from these local lady beetle populations.

For all three species profiled, risks that occur after release probably outweigh risks from collection and habitat disruption. Impacts on the released species can generally be divided into introduction of pathogens, parasites or parasitoids, introduction of maladapted gene combinations, and competition with local populations for resources. Evidence exists for pathogens being spread by release of butterflies (Aguirre et al., 2012; Boppré and Vane-Wright, 2012) and released lady beetles have been shown to carry high loads of both pathogens and parasitoids (Bjørnson, 2008). For pollinators, while we are not specifically addressing the impact of *Apis mellifera* in this study, there is a longer and larger data set on the potential impact of transport and utilization of this species on native bees that can complement the smaller but growing data set on the impact of managed bumble bees on native bees. Both honeybees and bumblebees have been shown to expose native bees to parasites (Graystock et al., 2014) and pathogens (Alger et al., 2019; Colla et al., 2006). In a review of the literature on effects of pathogens vectored by managed bees, Mallinger et al. (2017) found that significant negative impacts on native populations were reported in 70% of the studies. Through these mechanisms, honeybees can have negative impacts on individual plant-pollinator relationships and more broadly on plant-pollinator networks (Valido et al., 2019).

Beyond the pathogens and parasitoids released insects may harbor, the greatest threat to populations near the release area may be posed by the genetic profiles of the released individuals. These insects are often shipped long distances and they are all capable of dispersing great distances further once released. Genes that may have been well adapted from the original location of these insects may be maladaptive in the release areas for populations of lady beetles (Sethuraman et al., 2015). This is particular concern for convergent lady beetles, *H. convergens*, because they are collected from a western population and often released into an eastern population with which they are known to hybridize (Sethuraman et al., 2015; Obrycki et al., 2001). Similar concerns have been expressed for butterflies (Aardema et al., 2011) and, although less of a threat due to their mating system (single female per hive), bumble bees (Velthuis and Van Doorn, 2006).

While there is a substantial body of literature on maladaptive genes, parasites and pathogens from released organisms impacting locally extant native species, there can also be impacts mediated through competition for resources. No reports of evidence of competition impacts of augmentatively released predators were found in the literature but size differential among immature coccinellids can lead to asymmetric competitive effects and negative interactions exacerbated by size differential has been reported between native coccinellids and species released for classical biological control (Turnipseed et al., 2014). Furthermore, negative impacts of released insects are not always restricted to the species being released. Boppre and Vanewright (2012) review several instances of released or escaped butterflies impacting native species, and *Harmonia axyridis* is a classic example of a released lady beetle that went on to displace many native species on its way to becoming the most common coccinellid in the world (Michaud, 2018). Among bees, significant negative impacts of competition by managed bees on native bees were recorded in 53% of studies reviewed (Mallinger et al., 2017).

The final risk from releasing insects to perform services is the most difficult to quantify but may ultimately be the most important. This risk pertains to the public perception of insects and spiders, two taxa that suffer from a perception problem (Polák et al., 2020; Nash, 2004; Morris, 1987). This risk is most acute for release of butterflies since the whole reason for releasing them is to interact with them through observation. Bumble bees and lady beetles are sometimes observed for a short time after release, but that is not why they are released. As outlined above there can be a positive aspect to the observation and interaction with butterflies both in terms of improving the perception of insects and nature in general (Boppré and Vane-Wright, 2012; New, 2008), but there can also be a negative influence in this area especially if the mortality rate is high before or directly after butterflies are released (Pyle, 2010). Mortality and suffering is a negative outcome that observers of all ages can understand but a more subtle influence can be the realization that these living creatures have been made products for our pleasure and that even if they survive the release they have very little chance of survival for more than a few hours and even less of a chance of reproducing (Pyle, 2010).

4.1. Monitoring and managing commerce to promote sustainability

Commerce involving insects and spiders has potential to either enhance or reduce the viability of individual species and the

sustainability of the systems that depend on them. Commerce in species that are prohibited for sale is always a threat to sustainability and steps should be taken to identify and reduce the volume of these sales. In contrast, there is a level and mode of commerce in insect species that provide services that could enhance sustainability. A framework for monitoring and managing commerce of both imperiled and service species to promote sustainability is suggested below.

4.1.1. Imperiled species

All the imperiled focal species in this study are listed because they are in danger of imminent extinction or they face unacceptably severe threat from commerce. Thus, commerce involving these species is unsustainable for them and since biodiversity is a key component of sustainability more generally it has broader implications. There are rules in place on each of the major platforms and laws at national and international levels to deal with illegal sales. What appears to be lacking is the resources to fund sufficient monitoring and reporting of infractions. By the late 1990's the USFWS and other wildlife law enforcement agencies recognized that the volume of trade on the internet is too large, the pace of transactions too rapid, and the laws around the world too complex to fully monitor and enforce (Cleva and Kish, 2009). One strategy employed by these agencies to deal with the massive task of managing web-based wildlife trafficking is to act on "leads" provided by the public and non-profit organizations (Cleva and Kish, 2009). The USFWS accepts information regarding potentially illegal wildlife sales via a dedicated email address (fws_tips@fws.gov) and by phone with the FWS TIPs (1-844-FWS-TIPS) line and they offer financial rewards for information leading to enforcement actions (https://www.fws.gov/midwest/news/ReportWildlifeCrime.html). Several independent efforts exist to monitor and report illegal wildlife commerce including the World Wildlife Fund, TRAFFIC, and the International Fund for Animal Welfare including a citizen science program called the Wildlife Cyber Spotter Program. This program has been very effective as they report 10,000 illegal sales across 22 platforms (https://www.endwildlifetraffickingonline.org/cyber-spotters) but these efforts are almost exclusively focused on products derived from vertebrates. Several factors including smaller geographic ranges, sensitivity to local conditions, and rapidly fluctuating population sizes combine to indicate that while there are key insights to be gleaned from programs designed for vertebrates, they might not be an optimal fit for invertebrates. While it might seem intuitive that sales platforms would resist the additional monitoring potential that non-enforcement entities could provide, it is important to note that such activity could facilitate removal of illegal or unsustainable sales which is a stated policy for most platforms.

4.1.2. Service species

One approach to developing modes of sustainable utilization for service species is to compare the value of utilization with a broadly defined cost of utilization that incorporates externalities (DiTommaso et al., 2016). The economic value of releasing these insects can be estimated by determining the cost of alternatives or the losses associated with reduced service provision if the release is not made (Losey and Vaughan, 2006). One complication in calculating the value of releases is that while the released insects can provide some level of the intended service, the service is often not provided effectively or efficiently. Lady beetle releases provide a classic example of this result. Releases of convergent lady beetles are notorious for not providing adequate pest suppression. In fact, released beetles most often disperse from the target field before they eat any pests (Michaud, 2018). In contrast, commercially produced bumble bees are considered "superior pollinators" in some crops under specific conditions such as cooler, windier weather (Martin et al., 2019). Considering both lady beetles and bumble bees we advocate only deploying them in situations where the probability of successfully providing the service outweighs the risk. While this set of conditions may not be clear yet for bumble bees, it is clear for lady beetles that releases into fully open habitats do not meet these criteria. Releases in "tunnel" production systems can be very effective (Hall, 2014) but these represent a growing, but relatively minor middle point between closed (e.g. greenhouse) and open (e.g. corn field) habitats. Limiting the use of these two groups to situations where efficacy is high will facilitate reduced use of pesticides and profitable production without a high risk of negative consequences. Designing agricultural production systems to attract and facilitate predators and pollinators should always be a top priority and it should be the only way services are utilized in any situation where the costs outweigh the benefits (Michaud, 2018).

Considering releases of painted lady butterflies, the cost in terms of risk within the species and even to other insects is probably relatively low. However, the potential to bias biogeographical studies of *V. cardui* and the potential for creating profoundly negative experiences with these butterflies must also be considered (Pyle, 2010). Balancing the substantial potential for harm with the equivocal potential benefits leads to an inescapable conclusion that there is no level of butterfly releases that will promote overall sustainability.

4.1.3. Conclusion

This study demonstrates that committed, enthusiastic, students led by trained specialists can uncover illegal sales across a range of platforms. A program specifically focused on invertebrates could take advantage of techniques and technologies developed for monitoring vertebrates and plants and adapt them to the specific challenges inherent with illegal invertebrate commerce. An ongoing program funded jointly by the major platforms and the U.S. Fish and Wildlife Service within a university setting could fill much of the gap in monitoring online sales and report in an unbiased manner to all funding parties. Independent monitoring would synergistically complement enforcement efforts and decrease liability for commerce platforms by facilitating the rapid removal of illegal items and potentially advising on the legality or sustainability of invertebrate related items before they are listed for sale. Involving students would have the added benefit of education and training for a group that is self-selected for their interest in these issues.

While the goal in managing commerce in restricted species is to eliminate it completely, there is a non-zero level of commerce in service species that, at least theoretically, promotes sustainability. At the national level in the US, sales and interstate transportation of the three primary service species (Table 4) do not require permits (APHIS, 2019; Wheling, 2019; Linder, 2018) and while this regulatory strategy may facilitate commerce in these species, it is unclear that it promotes sustainability. The challenge in developing a

strategy to move towards the optimal level of commerce in service species is that for both predators and pollinators, generally accepted projections of the optimal level and accurate estimates of the current level of commerce are not available. Determining the optimal level of service augmentation through the release of insect species that provide services could be approached through review and synthesis of existing data. Unfortunately, there is very little data available or being gathered on which to base estimates of current levels of commerce in service species. Fortunately, a national reporting structure already exists in the US that could be adapted to track commerce in these insect species and the essential services they provide. Since 1999 the United States Department of Agriculture has gathered, collated, and disseminated data on livestock production and quality in the US as part of the Livestock Mandatory Reporting Act (USDA, 2020). This program currently covers vertebrate livestock and derived products including beef, pork and poultry and we propose that invertebrates, specifically the three primary service species, *H. convergens*, *B. impatiens*, and *V. cardui* be added to the list of species being monitored. Combining a synthetic assessment of the positive and negative impacts of releasing insect species with accurate data on the volume of individuals being released will allow development of a comprehensive national regulatory framework that facilitates maintenance of the essential services insects provide in perpetuity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2022.e02098.

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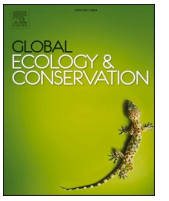

Corrigendum

Corrigendum to "Insects and spiders on the web: Monitoring and mitigating online exploitation of species and services" [Glob. Ecol. Conserv. 36 (2022) e02098]

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