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Review

Quantitative Investigation of Wildlife Trafficking Supply Chains: A Review☆

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ABSTRACT

The illicit wildlife trade is a pervasive and global problem that has far-reaching impacts on both society and the environment. Aside from threatening numerous species around the world and acting as a potential disease transmission vector for several zoonotic diseases, including the COVID-19 pandemic, this complex system is often linked with other illicit networks such as drugs, weapons, and human trafficking. The annual monetary value of wildlife trafficking is estimated to be over twenty billion USD, and, unfortunately, wildlife trafficking has several unique characteristics that make it difficult to disrupt in an effective and efficient manner. There has been much research and media awareness around wildlife conservation and moral issues surrounding the illicit wildlife trade, but little is known about the supply chain structures and operations of these illicit networks, especially from a quantitative, analytical perspective. This research reviews wildlife trafficking through an operations and supply chain lens. By understanding the unique challenges faced in impeding wildlife trafficking, we present opportunities to resolve them using analytical techniques. We provide the groundwork for future developments in detection, interdiction, reduction, and possibly, elimination of illicit wildlife trade.

1. Introduction

Wildlife crime, harvesting and trade contrary to national law [1]," has a strong negative impact on animal populations and the environment. The illegal wildlife trade facilitates the introduction of invasive species, climate change, land degradation, and biodiversity loss [2]. Illicit Wildlife Trade (IWT) can also harm communities by introducing and spreading zoonotic diseases, which have become a topic of heavy debate since the beginning of the COVID-19 pandemic. The United Nations Environment Programme estimates that 75 percent of all emerging diseases are being transferred to humans through animals; and, that this transfer is accelerated by habitat destruction and wildlife crime [3]. Collectively, IWT activities threaten environmental conservation, socio-economic development, and national security. Crimes against the environment are estimated to be worth \$91 to \$259 billion (USD) annually, while those against wild animals alone are believed to be valued anywhere between \$5 to \$35 billion (USD) per year [1]. These high revenues are a result of the strong global demand for wildlife and wildlife products. Some of the demand drivers are cultural, including using live, trafficked animals as pets or status symbols; some are fashion-driven (e.g., using fur for clothing); some are medicinal (e.g., using animal parts in traditional medicine). Regardless of the driver, demand continues to increase despite the heightened focus on preservation, conservation, and sustainability in the last decade.

When looking at its annual value, IWT ranks only behind drug, human, and weapons trafficking, and IWT often converges with these other forms of organized crime [1]. Unfortunately, this makes IWT highly profitable [3], and criminal organizations utilize profits from IWT to finance other criminal activities [4,5]. The vari-

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ous uses and high demand for wildlife products attract criminal organizations and incentivize their participation in the illicit trade. Wildlife crime networks often share organizational similarities and resources with other forms of organized crime. Unfortunately, the estimated monetary value of wildlife crimes is said to be growing at nearly three times the rate of the world economy [3]. Due to the high profitability of IWT activities, criminals are able to grow their resource bases to facilitate their participation in weapons, drug, and human trafficking [6]. Hence, IWT often acts as an enabler of other illicit crimes.

Even with increased international recognition, four important challenges limit prevention and interdiction efforts for IWT. First, it is difficult to estimate the true scale of IWT from available data. The limited data are often skewed towards specific regions and species [1, pg. 24] and are fragmented between various governments and wildlife protection organizations, thus providing an imprecise picture. Second, IWT is an incredibly broad issue with a huge array of countries and species involved, as well as types of products and uses. Trafficked animals are used for human consumption, traditional medicine, status symbols, artifact creation, financial investments, and exotic pets [1]. This is one of the unique challenges compared to other types of illicit activities where there is typically limited variation in the uses and types of commodities that are traded. IWT is a global issue with known traffickers from more than 150 different countries. This highlights the challenge of creating legislation that is consistent across countries to prevent geographic displacement of trafficking activities. Cooperation is key to effective enforcement; however, other geopolitical interests among countries may override enforcement efforts. Third, IWT groups operate complex supply chains capable of transferring various animal products between countries without detection [1, pg. 19]. In many cases, the corresponding financial transactions are multiple small transactions, each amounting to less than ten thousand dollars, to avoid detection by the banking system. In addition, these organizations are capable of quickly adapting to threats from interdiction activities by switching the origin and transit countries or substituting less heavily regulated species [1, pg. 13]. Finally, the volume of resources dedicated to combating wildlife trafficking is relatively small, in comparison to other forms of organized crime [7]. Furthermore, in some countries, it is culturally acceptable to use or consume illicit wildlife products, and corrupt officials may even condone it. IWT is often considered a less serious crime compared to other trafficking activities involving humans, weapons, and drugs. However, disregarding IWT-related activities not only undermines conservation efforts but also encourages other organized illicit activities. All of these factors increase the difficulty of detecting, interdicting, and disrupting IWT supply chains.

In this paper, we aim to provide an introduction to IWT for operations researchers. While the operations research literature provides tools to combat some of the stated issues, more data-driven research is needed to uncover and understand the supply chain structure, operations, and drivers of these illicit networks. Data is more available than it has been in the past, though there is still substantial room for improvement, and researchers have become increasingly aware of the need for a coordinated and global approach to combating wildlife trafficking networks. Operations research and analytics are uniquely well-positioned to rapidly advance understanding of IWT operations and provide effective strategies for reducing, and possibly eradicating, wildlife crime. Analytics provides many tools for dealing with limited and unbalanced data sets and accurately predicting future trends. Work on network interdiction, allocating scarce resources, and predicting the behavior of adversaries is prevalent in the operations research literature. Recent work has focused on problems where parties actively learn new information as they make operational decisions. All of these techniques can be applied to the problems presented by IWT, but they require adaptations and tailoring to illicit wildlife networks. This research can help policymakers:

1. understand demand and supply drivers and describe IWT supply chains;
2. characterize the illicit supply chain operations via sophisticated detection methods;
3. develop interdiction strategies and determine the most effective use of limited resources;
4. characterize the reactions of traffickers to various interdiction strategies; and
5. identify cross-border and coordinated collaboration strategies for effective enforcement efforts.

The rest of the paper is organized as follows. In Section 2, we provide additional background information on wildlife trafficking. Section 3 highlights the challenges and major issues in combating and researching wildlife trafficking. In Section 4, we present opportunities and possible solutions from the operations research and analytics literature to overcome these challenges. In Section 5, we provide three example cases that highlight the use of analytical methods for combating IWT. Finally, Section 6 summarizes our review and offers additional research directions.

2. Background of Wildlife Trafficking

2.1. Wildlife Trafficking as an Illicit Supply Chain

The wildlife trade is not a modern phenomenon; it has been around for thousands of years. Ancient European cultures used ivory for jewelry and tools. The Romans wiped out elephant populations in northern Africa and Asia Minor, due to their desire for ivory. In the early 1900s, the British parliament recorded a first regulation attempt by accepting a convention "designed to ensure the conservation of various species of wild animals in Africa" [8]. It took another seventy-five years for the countries affected by wildlife trade to form a conference to adopt a convention on the export, import, and transit of certain species of wild animals and plants, which is known as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).

Today wildlife crime involves illegal trade across international borders, spanning over 150 countries and more than 37,000 species of animals and plants [9]. With such a scale, it is challenging, if not impossible, to develop a single model that captures all of the illicit supply chains used in wildlife trafficking. However, it is important to understand the demand/supply drivers, possible routes, and actions that can be taken by the traffickers and criminal convergence with other illicit trafficking operations. Increased awareness and better quantification of the damage IWT wreaks on our society and values would encourage the formation of partnerships and collaborations with governments, non-profits, industry, and academia.

2.1.1. Drivers of Demand and Supply

The **demand** for wildlife products is fueled by four primary drivers [10]: i) need for sustenance; ii) cultural importance and status symbols; iii) financial investments; and iv) traditional medicine.

- *Wildlife as sustenance:* For thousands of years, hunting wild animals for food has been a common and necessary practice. Many people in central African countries rely on bushmeat as a protein source and for income [11]. Due to current and projected population growth, lack of domesticated protein, and modern hunting methods, the demand for wildlife in central African countries is increasing [11]. Of the African pangolins that are captured, 50 percent of them are directly consumed compared to 41 percent that is sold. Western countries typically rely on domesticated animals as a protein source, but growing crops, such as soybeans, to feed these animals often increases deforestation and habitat destruction [12]. Balanced solutions that ensure the continued viability of wild animal populations while also meeting the protein requirements of local societies are necessary. In addition to sustenance, some wildlife products can be consumed as gourmet delicacies. For instance, pangolin meat is considered a delicacy in China and Vietnam.

- *Wildlife products as cultural relics or status symbols:* In many countries, wildlife products are often regarded as valuable luxury items. For instance, owning rhino horn- or ivory-based art, carvings, or jewelry is considered to be a status symbol. In addition to their personal value, some wildlife products are also used for gift-giving or bribery (in other criminal organizations). The exotic pet trade is another common use for trafficked wildlife, most often birds and reptiles. Demand for radiated tortoises from Madagascar first increased in the 1980s and 1990s as a result of demand from collectors in the United States, Japan, and Europe [13]. In recent years, the primary growth in demand has occurred in Southeast Asia as incomes in those countries rise and discretionary spending increases [6, pg.5-6]. The last twenty years of increased trafficking for the exotic pet trade have destroyed decades of progress in the conservation of these rare animals [13].
- *Wildlife products as an asset and financial investment:* Demand for wildlife products can be influenced by their potential to function as financial investments. For example, investments in ivory are comparable to investments in silver and gold [6, pg. 108]. After China joined CITES, ivory-carving workshops reduced their production by the early 2000s, helping elephant populations in Africa to recover. In 2008, CITES had a controversial ruling to allow ivory stockpiles to be sold, assuming that “flooding the market” would reduce the price of ivory and ultimately reduce the attractiveness of ivory as an investment. Instead, these sales backfired, removing the ban on ivory, normalizing ivory ownership, and generating new demand [14]. By 2018, to stop the growing demand, China closed all of the domestic ivory markets. However, this real-life experiment demonstrated the difficulty of controlling and reducing demand. Furthermore, investors often do not care about the sustainability of the relevant animal populations because extinction would only make their investments more valuable. With limited supply, wildlife products continue to preserve their value as an asset.
- *Wildlife products in traditional medicine:* The World Health Organization (WHO) reports that traditional and complementary medicine is an important healthcare resource and 88% of member states acknowledge the use of traditional medicine [15]. China, India, and several African countries have a stronger emphasis on traditional medicine. The economic value of traditional medicine in China was estimated to be over $40 billion USD in 2020. By 2025, the market for traditional medicine in China is estimated to exceed $100 billion USD [16] due to traditional Chinese medicine receiving a wider reception outside of China as well. Unfortunately, some specific animal products used in traditional medicine are subject to over-harvesting and poaching, depleting populations past sustainable levels. Some animal parts that have received a controversial reception include tiger bones or teeth (or jaguar bones/teeth due to diminishing populations), rhino horns, and pangolin scales. While there is scant scientific evidence, ground-up pangolin scales are said to help with arthritis, lactation, and many other ailments. In some cases, patients may see results because of the placebo effect [16].

All of these facets increase the complexity of reducing the demand for trafficked wildlife. Additionally, a lack of public awareness regarding the threats of extinction harms efforts to curb demand. All of these different drivers and end uses for trafficked wildlife require coordinated and tailored approaches to increasing public awareness and reducing demand.

The **supply** for the aforementioned demand drivers of wildlife crime comes from poaching. Due to declines in tourism and its associated revenues, poaching functions as a source of income for many people in rural communities where trafficked species are prevalent [6, pg. 136, 188]. Currently, poaching is a very profitable business. For instance, the supplies to capture a pangolin in Cameroon are estimated to cost between $3 and $5, but hunters can receive up to $30 for a larger live pangolin [1]. Trafficking organizations have been documented producing YouTube videos to teach people how to capture certain animals to increase their supply pool [1]. These organizations are able to exploit local communities to increase their supply when there is a lack of adequate support and legitimate income opportunities [1].

Some Asian businessmen considered starting government-sanctioned farms for bears, tigers, snakes, or turtles, to increase supply and stop poaching from the wild. However, this turned out to be another solution that backfired. While wildlife product bans reduced the societal approval of wildlife consumption, wildlife farming reversed these notions and increased demand [17]. Furthermore, many animals on these farms are treated inhumanely and killed to supply the black market for animal body parts [18].

It is vital that conservation groups and authorities collaborate with local communities as they are often key partners in prevention initiatives. Sustainable strategies for generating livelihoods for local people are critical to reducing the supply of trafficked wildlife [1]. Successful past initiatives have directly engaged local communities and equitably shared benefits and management rights with them. Regulation is needed to ensure that private companies, which seek to financially benefit from natural resources, fairly share the financial benefit with local communities and are required to respect the opinions and rights of local people [1].

2.1.2. Illicit Supply Chain Structure

IWT impacts many countries in many different ways. Some countries may only be a source where wildlife is exported from, and others may function as transit countries that get caught in between the supply and the demand, and still, others function as destination countries with large demand centers for certain products. In reality, a single country may play different roles in supply chains for different wildlife products. There exists a simple understanding of IWT supply chain structures based on marking involved locations or paths as a *source, transit*, and *destination* [19,20]. While even marking certain locations as a *source, transit, destination, or a combination* of these designations is an important classification [1, ch8], it is not sufficient compared to the supply chain network and structure analysis we are used to observing in licit supply chains. In addition, illicit organizations have to be more agile and dynamic with capabilities of quickly adapting to threats from interdiction activities by switching the origin and transit countries or substituting less heavily regulated species (see, for instance, [1, p. 13]. Hence, some classifications may change or evolve over time. For instance, in the late 90s and early 2000s, Asia was marked as both *source* and *destination* for pangolins. Recent evidence and seizure data show a significant increase in the capturing of African pangolin species to supply the demand in Asia. This is due to the vast population decline of Asian pangolins, regulations to protect the remaining population, and the increased demand among international markets [21]. In fact, China and the United States were identified as the most common destinations for international pangolin trafficking during the six-year period from 2010 to 2015 [22].

Note that similar to a licit supply chain, IWT supply chains have *retailers, distribution centers/middlemen, manufacturing/processing facilities*, and *sources* [10]. While the products flow from sources to retailers via various transportation modes and quantities, the financial flows are in reverse order. Depending on the type of IWT product (e.g., live animal, fresh/frozen meat, animal byproduct, or animal artifact), the locations labeled as *retailers, distribution centers/middlemen*, and *manufacturing/processing facilities*, as well as transit options, vary. Some retailers include physical outlets (that prefer to source on-demand, as opposed to keeping inventory) and online platforms (e.g., the most common way to access illicit products). For instance, some products are readily sold on eBay, Facebook Marketplace, and Instagram, whereas the upstream portions of the supply chain are relatively hidden. A recent report shows an increase in the number of Facebook pages for wildlife product sales, even when such content is an obvious violation of the companys policies [23]. Additionally, there are a significant amount of bribes and corruption at nodes to ensure the flow of the materials. We discuss in detail additional challenges related to determining IWT supply chain structures in Section 3.

Strategies to effectively combat the demand and supply of illicit wildlife products face several challenges. The varied reasons illicit wildlife products are demanded, the cultural and societal barriers that prevent people from moving away from the consumption of endangered species, and the need for legitimate sources of income all make this a very challenging and multifaceted problem. In order to successfully reduce the prevalence of IWT, strategies must attack the interrelated issues of demand, supply, and alternatives to generating an income [1]. Strategies that do not address all three issues can lead to replacement effects. We discuss additional challenges of IWT supply chain modeling in more detail in Section 3.

2.2. Similarities/Differences with other Illicit Supply chains

Wildlife trade has a number of differences from other illicit domains that shape its supply chains. Yet, there is limited research that discusses these similarities and differences. [5] present a comparative analysis of drug and wildlife trafficking in terms of market size, smuggling operations, and actors involved. They also discuss the possible linkages between drug and wildlife trafficking. More recently, [24] expanded on this paper to reveal the overlaps and synergies of wildlife and drug trafficking, providing concrete examples of where these markets co-exist [25], on the other hand, compare cocaine, wildlife, and sand illicit networks and operations. They define illicit networks as "*the interactive network of actors engaged in and materially, financially, and socially linked by the sourcing, transit, storage, and delivery of illicitly traded goods to consumers.*" They offer a number of attributes related to network structure (number of actors, shipment volume, shipment value, captured value per actor) and operational environment (environmental harms, societal harms, saliency of harms, and disruption intensity). Based on their analysis of expert opinions, illegally traded wildlife has the most distinct and diverse attributes compared to the other illicit networks.

Summarizing and expanding the analysis of [25], we offer the comparison in Table 1 for illicit networks associated with wildlife trade [1,6,20], human trafficking [26–28], drug trafficking [5,24], weapons trafficking [29], adulterated products, counterfeit products [30], illegal products [31], and smuggling of historical and cultural artefacts [30,32]. Note that the adulterated products are obtained by the addition of a foreign or inferior substance or element, compared to the regular production process, as in drugs, processed foods, and other chemical products, whereas counterfeit products are forged products formulated in imitation of brand authentic products with the intent to deceive, such as fake luxury items. We have chosen this list of illicit activities to highlight because they are most often linked in the literature and by policymakers or donors such as the UNODC [1,2,33]. Note that there are existing operations research models and interdiction tools for human, drug, and weapon trafficking (see Section 5). With Table 1, our goal is to offer preliminary insights into the usability of these existing models for other lesser-studied illicit categories.

The characteristics we consider for the comparison are linked with dimensions that enable the mapping of supply chains and interdiction of illicit networks. Specifically, we consider whether or not i) these networks are covert; ii) products are openly marketed in regular channels (without the use of the dark web); iii) products are perishable/non-perishable; iv) products are reusable; and v) the products or related activities are easy for authorities to identify. Additionally, we include the possible transportation modes involved in the distribution of illicit materials and the possibility of mingling with licit supply chains. Finally, we compare the legality of these networks and their potential disease impact. Supporting the statement of [25], IWT has the most diverse set of illicit supply chain attributes, and the majority of those attributes are product-dependent. Table 1's legend includes various letters to indicate the presence of the attributes. 'Y,' indicating 'yes,' refers to the possibility of a particular illicit activity having that specific characteristic. For instance, drug trafficking has 'Y' marked for travel modes of air, car/truck, ocean, and parcel since there is a possibility that each one of these modes could be used in drug trafficking. 'PD' represents illicit operations that have different product types (e.g., live, perishable (fresh/frozen), or artifacts). 'H/M/L' either refers to 'always/sometimes/rarely' for *covertness* or 'high/medium/low impact' under *disease impact*. Finally, 'LS' refers to a particular characteristic being 'location-specific,' or dependent on the location of the illicit activity.

Table 1 illustrates the differences between IWT compared to other illicit domains. Firstly, in terms of product heterogeneity, as we will discuss later in Section 3.1, the illicit wildlife trade has the largest variety of products, while other illicit networks have rather homogeneous offerings. Secondly, the wildlife trade spans a larger geographical region and has expanded, global supply chains. Some of the countries in the supply chain may not consider the trade of certain wildlife to be illegal or may not have sufficient training to identify the products properly. Therefore, many of the characteristics of wildlife trafficking have the mark "product-dependent", "location-specific," or "both." Finally, wildlife products often exist in a grey area of uncertain legality. They can be openly marketed and are often expected to be *regulated* (as opposed to banned). They have the largest potential to be mingled with licit supply chains, closely followed by adulterated or counterfeit products and then human/labor trafficking. In some cases, illicit wildlife products may enter licit supply chains and be intertwined with labor trafficking simultaneously. One current example is the use of forced labor in illegal, unreported, and unregulated (IUU) fishing operations [34]. A more in-depth discussion of this topic is in Section 5.

While this initial comparison highlights the differences between IWT compared to other illicit networks, it also underscores that the supply chain models and network interdiction analysis built for drug trafficking or human trafficking in the literature are not sufficient for IWT. These characteristics offer additional challenges that do not exist in other illicit domains. We will expand more on this topic in Section 5 with explicit references and examples.

2.3. Negative Societal Impact of IWT

Wildlife trafficking can have negative implications for society and the environment. In this section, we highlight the negative impact of IWT on the spread of zoonotic diseases, including COVID-19, and the harms this causes to society. In addition, we discuss

Table 1
Illustrative variability in generalized comparison of illicit activities in different trafficking domains according to key characteristics typically explored by operations researchers and supply chain experts Legend: “Y”: Yes; “PD”: product-dependent; “H/M/L”: high (always)/medium (sometimes)/low (rarely); “LS”: location-specific

Characteristics	Wildlife	Humans	Drugs	Weapons	Adulteration	Counterfeit	Artefacts
Covert	PD, LS	H	H	H	PD	PD, LS	M
Openly marketed	PD, LS		PD, LS				
Perishable	PD				PD		
Non-Perishable	PD		Y	Y	Y	Y	Y
Reusable	PD	Y		Y	PD	PD	Y
Easy to Identify	PD		Y	Y			Y
Travel Modes: Air Travel	PD,LS	Y	Y	Y	Y	Y	Y
Travel Modes: Car/Truck Travel	PD,LS	Y	Y	Y	Y	Y	Y
Travel Modes: Ocean Travel	PD,LS		Y	Y	Y	Y	Y
Travel Modes: Parcel, LCL, FCL	PD, LS		Y	Y	Y	Y	Y
Questionable Legality: Gray area	PD, LS		PD, LS	PD, LS			LS
Disease Impact	H	M	L		L		
Mingling with Licit SC	PD	Y			Y	Y	

some of the specific impacts of IWT on the environment, including habitat degradation.

2.3.1. Zoonotic Diseases and COVID-19

Several epidemics and pandemics which are devastating to humans have been detected in recent times, including H1N1 swine flu, Ebola virus of 2014-16 in West Africa, Zika virus, SARS, and MERS. The significance of emergent infectious diseases to society is underscored once more by the COVID-19 pandemic. Unfortunately, zoonotic influence spans a very wide spectrum of diseases with diverse emergence pathways and underlying processes [35]. According to the IUCN, approximately forty percent of emerging infectious diseases in humans originate from wildlife [36]. The overall risks are higher for species subject to large volumes of unregulated trade, particularly because of higher levels of exposure and lax safety/sanitation measures. This report also notes that identifying high-risk practices, improving sanitary conditions, and improving animal welfare along supply chains, *whether the trade is legal or illegal*, is fundamental to reducing the likelihood of zoonotic disease transmission. Similarly, [37] advocate for novel analytical tools and decision support models via enhanced monitoring of illicit wildlife trade and supply chains.

The COVID-19 pandemic has given the wildlife trade a global spotlight due to claims regarding the possibility of the novel virus first being spread to humans by wildlife in Wuhan, China [38]. This is not the first time that a virus has roots in wildlife consumption, as Ebola, SARS-CoV, and HIV have all originated in wildlife [36,37]. The United Nations Environment Programme estimates that three-quarters of all emerging infectious diseases are started by a pathogen being passed from animals to humans [1, pg. 3]. This highlights the threat to humans, as the COVID-19 pandemic has killed over four million people and infected over 190 million people as of August 1, 2021 (https://coronavirus.jhu.edu/). COVID-19 and its variants continue to impact life across the globe. IWT is particularly risky when it comes to zoonotic diseases because it is unregulated. Hence, there are no safety protocols to prevent the transmission of disease. In response to the global coronavirus pandemic, there have been many policy changes in China regarding the wildlife trade. Major cities such as Beijing, Shenzhen, Zhuhai, and Wuhan, the virus starting point, have all issued bans on the consumption of wildlife [38]. The Standing Committee of the National People’s Congress, China’s top legislative body, issued a temporary ban on all wildlife trade in February 2020. This move was to alter the negative effects that the trade had on the health of the Chinese people. There is also a push to make the ban permanent, which will have major economic and controversial consequences if enacted [39].

At a recent United for Wildlife webinar, when asked about whether the COVID-19 pandemic has created a positive or negative impact on the illegal wildlife trade, Dennis Knauer, a border management expert, said it is a mixed result [40]. From an operational and resources perspective, he reported the pandemic had created more challenges. This is due to a drastic push to prevent the spread of the virus, which has forced many countries to enforce regulations imposed by CITES and cut enforcement staff. On the other hand, the pandemic has created a strategic opportunity for policymakers to make sustainable changes to the wildlife trade and substantially reduce the illegal trade. It is possible to promote a more sustainable and equitable wildlife trade by integrating diverse scientific disciplines and including data-driven risk analysis and solutions. Operations management and supply chain science have a prime opportunity to contribute, as discussed in more detail in Section 4.

2.3.2. Habitat Degradation

Wildlife trafficking can have unfortunate environmental and sustainability implications. Removing species in quantity can either affect the amount of prey (e.g., pangolins who are nearly gone from Asia), predators (e.g., cheetahs in the horn of Africa), or even canopy and living area (e.g., rosewood trees), thereby causing environmental degradation. This biodiversity and deforestation loss, in turn, affects people reliant on this wildlife or areas for their own economic means (licit). The combined impacts of deforestation and wildlife trade are severely underestimated [41]. The environmental degradation may take years and consume precious resources to try to restore if restoration occurs at all. [42] state that recovering endangered species resembles a resource allocation problem, e.g., a knapsack problem, in which a portfolio of recovery actions is chosen to achieve best a set of fundamental objectives, subject to a budget constraint. Unfortunately, the mathematical modeling approach requires decision-makers to articulate objectives and constraints and evaluate alternative allocation strategies to find which strategy best meets multiple objectives. Some of the objectives may include minimizing the number of extinctions, maximizing the number of species recovered, favoring some species over others, or minimizing the effect on other human activities. However, the quantification of these objectives is not necessarily easy. Some approaches include rationing the limited funds as species move toward extinction and prioritizing funds for recovering endangered species. However, a *proper* analytical model may help create ecosystem-based approaches to address the root cause of species endangerment.

2.4. What is currently being done to combat IWT?

The interest in stopping this crime and eradicating its detrimental effects came to global prominence in the mid-1970s. The Convention on International Trade in Endangered Species of Fauna and Flora (CITES) is a voluntary, international convention to regulate legal wildlife trade and protect threatened and endangered species of flora and fauna. CITES is not a law enforcement entity and has no authority over wildlife crime, i.e., CITES does not cover wildlife crime within national borders [9].

While the wildlife trade has existed since ancient times, its potential impact on environmental protection, sustainability, and preservation has come to prominence relatively recently. Hence, the addition and relevance of IWT to our understanding of the *global criminal economy* is a relatively new phenomenon. Despite the existence of CITES since 1975, only over the past decade have national and international strategies to combat wildlife trafficking and illegal trade of wild flora and fauna been elevated to high policy priorities [19,43]. Efforts to combat IWT focus on one of three pillars, such as those mentioned in the U.S. Strategy to Combat Wildlife Trafficking: increase law enforcement, improve international cooperation, and reduce demand. Developments in technology (e.g., drones), cooperation (e.g., mutual legal assistance), new donor funding (e.g., Paul G. Allen Family Foundation), education (e.g., capacity building for students and practitioners), and more all tend to fall within one of these three categories. The range of stakeholders working to combat wildlife trafficking and reduce the risks associated with the crime and its associated harms are similarly diverse: conservation organizations, law enforcement officials, criminal justice professionals, interdisciplinary scientists, diplomats, and the private sector (e.g., shipping companies) all bring expertise to the table.

In the Appendix, we provide a non-exhaustive list of non-profit organizations that are combating IWT or creating awareness of the issues. We also list possible data sources in the Appendix. Additionally, some corporations are taking steps to prevent wildlife trafficking among their operations. As an example, Maersk, the world's largest container ship and supply vessel operator, joined 40 other organizations in 2016 to combat the illegal wildlife trade in key shipping routes and ports [44]. Etihad Airways, which is the national airline of the UAE, began a collaboration with UAE's Ministry of Climate Change and Environment to combat wildlife trafficking. This partnership is aimed at countering trafficking in both their passenger and cargo operations and educating their customer and stakeholders on tactics used by wildlife criminals [45].

3. Key Wildlife Trafficking Challenges for Operations Researchers

3.1. Heterogeneous Products and Supply Chains: Ambiguity and International Cooperation

There are many species involved in IWT, and each species can be processed into a variety of goods prior to shipment. Almost 6,000 different species have been seized since 1999, and several of those species are sold in multiple markets as meat for consumption and other byproducts used in artifacts or sold for medicinal purposes [1, pg. 9-10]. Over the same time frame, no single species accounted for more than 5% of the seizure incidents, highlighting the diversity of trafficked species. A large number of potential species and uses makes the identification of trafficked species difficult for enforcement personnel who may not recognize the species of origin. This variety is one of the unique challenges in halting wildlife trafficking in comparison to other illicit trafficking activities [6]. Developing the ability to identify illegally obtained wildlife products in many locations across the globe for a variety of species is a challenge for those attempting to impede IWT. In United States airports, identification of all types of illegal goods is performed at a 5 percent success rate [3]. In most countries, there is little training for security workers that specifically focuses on the wildlife trade. In addition to searching for wildlife, officials also need to check for weapons, drugs, and other important contraband during inspections. There are limits to the number of items they can be trained to identify and have the time to search for on a regular basis. Traffickers are also skilled at hiding wildlife in inventive, if sometimes cruel, ways. For example, traffickers can shove the appendages of Malagasy tortoises into their shells and wrap them in duct tape to easily hide them in luggage or other objects to avoid scanners [13].

The heterogeneity of IWT supply chain structures also increases the difficulty of identifying trafficked species. IWT is a global issue with known traffickers from more than 150 different countries. No single country has been listed as the origin of more than 9% of the total amount of seized shipments [1, pg. 10]. There are a variety of origin and destination countries, with routes often shifting as a result of increased interdiction efforts. Profiling is a commonly used law enforcement practice in air travel; however, profiling wildlife traffickers and illegal products is made difficult when products are transported through multiple transit countries. The modes of transport are highly variable depending on the value and perishability of the product. Perishability is product-dependent, with items such as ivory being fully non-perishable, raw meat requiring refrigeration, and live animals (such as tortoises) potentially having a few days to be transported before needing to be settled and fed to survive. The lack of available data exacerbates this problem because there are relatively few data points for each species. This makes identifying the distinct supply chain structures difficult.

The inherent variability in illicit products and supply chain structures emphasizes the value of international cooperation. One of the major challenges of the enforcement community is trust between different organizations and agencies, or lack thereof [6, pg. 204]. IWT is a global problem with illegally harvested products traveling across multiple continents to reach their final destination. Wildlife products often cross international and continental borders, and these crossings are a potential choke-point for the supply chains. This necessitates communication and coordination between countries and across multiple agencies. Providing a global assessment of wild-life crime is challenging, because every country protects and acknowledges its animals, fish, timber, and other plant life in different ways [33]. Many countries are only concerned with enforcing laws relating to domestic species [46]. Regulations on which products are illegal often vary between countries. In addition, certain animal products may be legal when obtained from certain areas but illegal when obtained from others. This creates difficulties in determining the legality of wildlife trade across borders. It also hinders the collection and communication of data between different countries, governments, and organizations. Nearly three-quarters of the 131 countries in a CITES study punished wildlife trafficking violators with prison sentences of less than four years or with monetary fines [46]. Fines are often inconsistent, with maximum punishments being as low as 50 USD in Myanmar but reaching 800,000 USD in Indonesia [46]. International coordination is necessary to ensure traffickers cannot evade interdiction efforts and to minimize the resources needed to reduce illicit trade.

3.2. Data: Hidden, Limited, Fragmented, and Tacit

Data on wildlife trafficking networks are scarce, as a result of their hidden and illegal nature, which makes ascertaining the true scale of IWT difficult. The primary source of IWT data is seizure data from successful interdiction activities, but this can lead to biased information [1, p.24]. The absence of data on prices, criminal groups, and operations strategies used in IWT makes interpretation of existing seizure data difficult and hampers interdiction efforts [1, p.24]. IWT is a truly global problem, involving almost every country in the world and thousands of different species, but available data often focuses on charismatic species such as elephants and tigers. Data on the trafficking of birds, reptiles, spiders, and aquatic species are scarce in comparison [1, p.24]. CITES, which currently has 183 member countries, has collected Annual Illegal Trade Reports (AITRs) from its members since 2017. However, between 2017 and 2020, only 78 countries submitted AITRs for at least one of the three years [1, p.24]. In particular, there is almost no data on wildlife crime in Latin America which severely limits understanding of the state of wildlife crime in that region [1, p.24]. This further biases analysis of the scale and trends of IWT and, given what we know about the propensity for increased enforcement efforts to lead to geographic and species replacement effects, severely limits our understanding of how organized criminal groups will respond to increased interdiction efforts.

This lack of comprehensive data makes planning holistic interdiction activities difficult and prevents practitioners from accurately understanding the impacts of their actions. In addition, the data that is collected may be fragmented and incomplete. Seizure data are routinely missing key pieces of information, such as origin and transit countries for the illicit products [1, p.21]. The format and difficulty in accessing the data provide additional barriers to the successful quantitative analysis of IWT. [47] provide geospatial data standards to help advance efforts to combat wildlife trafficking. Geospatial data standards help enable a broader utilization of wildlife trafficking data across disciplines and sectors, accelerate aggregation and analysis of data across space and time, advance evidence-based decision-making, and reduce wildlife trafficking. Enforcement of IWT regulations is highly decentralized, and data may be fragmented across many countries and organizations, further hampering efforts to understand key characteristics of these networks [1, p.24].

In addition to data about IWT activities, there can also be a lack of supplementary data about the areas in which illegal harvesting is taking place. Much of the illegal harvesting takes place in extremely rural areas. For example, Malagasy tortoises are captured from the southern tip of Madagascar, and the geography makes it incredibly difficult to police as the area is very rural, and traffickers are never far from the coast, which effectively functions as an open border [13]. Reliable population, transit network, and GPS data about these areas can be unavailable or difficult to obtain. Reliable information about the population levels of trafficked species may also be difficult to obtain on a regular basis. All of this information plays an important role in assessing the state of IWT and determining strategies that simultaneously address both supply and demand while ensuring that individuals are able to support themselves without the need to engage in wildlife crime [1, p.19].

Recently, some portions of IWT supply chains have been moving online. Sales of exotic pets and some products from large cats have moved to social media websites and messaging apps [1]. This is a new and exciting source of potential data for researchers. However, as with other types of illicit trade, data collection and interdiction activities are often at odds with each other [26]. Authorities can shut down websites that host illegal activities, but the switching costs for sellers are low, and the trade quickly moves to new websites that reduce the visibility of trafficking activities without reducing the sales volume [1, p.25]. This dilemma is also present for sales that occur offline when authorities have to choose between allowing a shipment to reach its final destination to collect more data and confiscating the trafficked products to increase costs for traffickers [1, p.21].

Similar to other large supply chains, the flow of money in illicit wildlife trafficking is closely linked to the flow of goods. Trafficking operations often participate in money laundering to hide evidence of their activities [1, p.18]. Traffickers must spend money for supplies and transportation, and various members of the supply chain exchange money at each stage. This presents a unique opportunity to analyze both the movements and profitability of IWT operations. However, there has been little systemic assessment of the monetary flows associated with wildlife trafficking. Systematic collection of price and supply data is critical for providing insights into the structure of illicit supply chains that may enable their disruption.

There are many challenges in obtaining comprehensive and accurate data on illicit wildlife trafficking. However, recent trends toward online transactions and new agreements on data sharing present exciting opportunities to capture data that was not previously available. Operations research and analytics techniques can be applied to improve the quality of existing data and capture new information, as well as for prediction and interpretation.

3.3. Limited Resources and Corruption

While organized crime extends beyond national borders, so does corruption. Many illicit supply chains survive due to widespread corruption, by exploiting weaker governments, low-paid officials, and under-funded state institutions. Bribes and corruption are also common topics when combating IWT. It is estimated that bribes can make up 4-11% of the final value of trafficked goods [1]. Corruption amongst law enforcement officials presents a unique challenge when trying to identify and disrupt IWT supply chains [1]. Officials in remote areas who operate in isolation are most vulnerable to corruption, and interdiction strategies must take into account the likelihood of corruption when planning interdiction activities [13]. As an example, Indonesia contains thousands of small ports that do not have the resources necessary for proper enforcement and documentation. This opens up a significant opportunity for illicit trade to occur outside of Indonesia's 22 harbors open for official international trade [48]. Unfortunately, extensive corruption decimates the rule of law and produces devastating consequences for ordinary people.

Another example of corruption occurs in the official documentation and government permits. An obvious strategy to ensure the sustainability of animal populations is the use of a hunting permit system. For instance, in the Democratic Republic of the Congo, there is a hunting permit system for parrots. Nevertheless, most parrots are captured illegally due to the difficulties for individuals trying to obtain permits. The perceived risk of getting caught without a permit is outweighed by the difficulty of trying to obtain a legal permit [6]. This system can be further undermined by officials who issue permits contrary to the law and other forms of corruption. Effective allocation of resources may offer some level of alleviation to the corruption fueled by limited resources.

3.4. Agile Illicit Supply Chain Networks

Organized criminal groups participating in wildlife crime make use of sophisticated and complex transportation and finance networks [1, p.19]. Traffickers often specialize in certain products where they have close relationships with their customers [1, p.11]. The flow of goods in IWT supply chains occurs through established transportation channels such as passenger air travel, mail services, and containerized shipments. Modes of transport vary according to the product and its perishability. Transportation firms are often unwilling participants in wildlife trafficking due to the prevalence of forged documents and corruption [1].

Due to their illicit activities, criminal networks must avoid detection by constantly adapting and using complex hidden systems for transporting their products. When enforcement increases and harms profitability, traffickers pivot to less heavily regulated trade routes and species [1,49]. A coordinated and global effort to reduce wildlife trafficking is necessary because geographical displacement is very common when enforcement efforts increase. Gaps in regulation between countries leave openings for traffickers to avoid enforcement activities. For example, between 2016 and 2020, Nigeria emerged as an important transit country for the trade of ivory, pangolin scales, and rosewood. Similarly, Vietnam has arisen as a key destination for shipments of ivory and pangolin. These hotspots have likely emerged in response to increased enforcement efforts in neighboring countries, and they highlight the adaptability of IWT supply chains. Species displacement is also a major concern in wildlife trafficking. Species displacement is an issue where one species is illegal to harvest, but others that are nearly indistinguishable can be harvested and sold legally, as is the case for rosewood. The dominant species of rosewood sold in markets have changed many times over the years. Traffickers will often replace heavily protected species with another, often indistinguishable, species without alerting the buyer to the swap. Interdiction efforts must attack both supply and demand streams in a coordinated effort to avoid these displacement effects. While there has been more media attention for street markets and places where protected species are displayed openly, the volume of wildlife harvested illegally each year suggests that these locations are the minority and not the primary avenue for wildlife trafficking. Illegally obtained animal products are introduced into legitimate supply chains and sold in legal markets. This is often the case for European eels and rosewood products [1, p.11-13]. Once these products have been introduced into licit supply chains, it becomes extremely difficult to find and eliminate them. While it is difficult to detect and seize suspected illegal wildlife products, it can be even more difficult to verify that the product is illegal. It is challenging to determine the legality of an ivory bracelet or a product made of rosewood, for example. This highlights the importance of supply chain security and supplier evaluation to ensure that illicit products are detected before they contaminate legitimate supply chains. There is evidence that licit and illicit markets are closely tied to some wildlife products. When the legal market for ivory was sharply restricted, indicators show that the illicit market also went into steep decline [1].

The culmination of all of these factors presents many challenges when attempting to impede IWT operations. Strategies need to accurately predict and account for the adaptations of IWT supply chains to interdiction efforts, the effects of corruption of law enforcement officials on interdiction effectiveness, and the prevalence of illicit goods laundered into licit supply chains. Detailed and systematic analysis of displacement patterns and financial flows can assist in overcoming some of these challenges.

4. Opportunities for Operations Research Concerning Wildlife Trafficking

4.1. Handling Heterogeneity of Products and Supply Chains

Supply chain coordination is a popular area of research in the operations literature [50]. This area of research typically focuses on how to induce *cooperation between firms using some combination of contracts, information sharing, information technology, and joint decision making*. It is well documented that system-wide benefits increase when a coordination mechanism is used to ensure that the optimal decisions of each firm in isolation are also the decisions that are optimal for the supply chain as a whole [51]. These types of problems, especially **game-theoretic collaboration models**, are also applicable to IWT for coordination between different governments, nonprofits, and law enforcement agencies. However, humanitarian causes have received relatively little attention in the supply chain coordination literature [52]. Most of what is available focus on disaster relief operations and coordination for emergency transportation and supplies [53]. Most recently, [31] study the illegal product distribution in a network with multiple sources (origins) and sinks (destinations). Coordination is necessary for the success of interdiction efforts, but entities may have varying objectives that make coordination difficult. For example, different countries may only be interested in stopping the trafficking of their own native species and be less willing to devote resources to other species where their country functions as a transit location [46]. Political agreements can be useful for gaining commitments to work together, but operations approaches can help determine how the various parties' actions can be coordinated to obtain the greatest benefit. All of the models discussed previously can provide insight into where coordination is most beneficial and which countries and organizations need to act together to increase the success of interdiction approaches.

While the diversity of products in IWT and geographical spread deem it more challenging to map out and interdict, operations research models can offer some relief. For instance, **multi-item knapsack problems** could be expanded to allocate proper resources for choosing what to search for or how to train inspection officers. [54] consider applications in logistics sectors related, e.g., to transportation and maritime shipping. Given the limited resources for interdiction of illicit activities, determining the subsets of products to check at various airports and mailing/shipping inspections is challenging. Several characteristics of IWT require the development of new multi-item knapsack models and solutions. The possible perishability of wildlife products is one of the wrinkles. Wildlife products could be in various forms, including live (smuggled) species (e.g., exotic animals used as pets), fresh produce (e.g., meat products made of animals such as gorillas, pangolins, and alligators), animal by-parts (e.g., bear bile), and non-perishable products produced from animals (e.g., elephant tusk ivory, rhino horns, pangolin scales, etc.). The variety of the animals and types of products, as mentioned above, make it challenging to mathematically estimate the required resources that should be allocated to identify the products properly. The resources required to identify a meat-based product are not the same as those for capturing pangolin scales transported inside coffee cans. While the former may require additional lab work, the latter may be revealed by a detailed screening process or a trained agent. Another wrinkle is that multi-item knapsack problems may span multiple locations over multiple countries. For instance, pangolins are not a native species of many countries, and the agents working at checkpoints need to be trained properly to identify illicit products. Additionally, cooperation between countries is needed to distribute limited resources to high-impact areas effectively. Hence, supply chain coordination issues may need to be included inside a knapsack problem to ensure countries participate in ways that lead to optimal benefits for everyone.

4.2. Working to Uncover and Analyze Limited Data for IWT

4.2.1. Data Sources and Analytical Approaches for Data Detection and Prediction

Given the adversarial and decentralized nature of illicit wildlife trafficking, comprehensive high-quality data is scarce but has great potential for impact in the detection and analysis of wildlife trafficking. Additionally, the data that are present often require advanced tools to analyze the available datasets, quantify the limitations of the datasets, and augment standard data sources with widespread auxiliary data [47].

Recent international collaborative efforts have resulted in several centralized databases regarding wildlife trafficking and trade, such as the publicly available CITES Trade Database [9], the C4ADS (Center for Advanced Defense Studies) Wildlife Seizure Database [55], and the United States Law Enforcement Management Information System (LEMIS) Wildlife Trade Dataset [56]. [47] provided the datasets curated with their research publicly without any restrictions on access or use. In addition to broad centralized datasets, data scientists have analyzed different facets of wildlife supply chains through alternative data sources such as satellite imagery [57], acoustic monitoring [58], public media reports [59,60], and social media [61–63]. In another criminal context, to identify areas vulnerable to homicides in Brazil, [64] use the maps to facilitate the elicitation processes based on multiple-criteria analysis and spatial analysis. The wide data footprint combined with the adversarial nature of the illicit wildlife trade makes it a fruitful area to develop and validate data analysis techniques.

In addition to the cited data sources in the Appendix, the following analytical approaches can be used to obtain information on wildlife trade:

- **Satellite Data:** In addition to broad centralized datasets, researchers have leveraged alternative data sources to understand wildlife trafficking at different points in the various supply chains. Satellite-based data has proven useful in domains requiring large-scale detection due to its broad availability and increasingly high resolution. Researchers have used satellite tracking and imaging to detect illegal fishing vessels [57,65]. Satellite imagery has also been useful in detecting illegal logging [66], landcover mapping [67], and poverty mapping [68].
- **Acoustic Monitoring:** Automated acoustic analysis has been deployed in several settings for both monitoring biodiversity as well as human presence. Generally, these approaches rely on data collected from an array of sensors and are cost-effective when monitoring large areas of land that are otherwise difficult to survey visually or patrol. Acoustic techniques have been used to monitor diversity in both wildlife [58,69] and cities [70], as well as tracking elephants [71]. Notably, acoustic methods have also been successful at identifying illegal logging [72].
- **News Scraping:** Publicly available news reports have been shown to contain substantial additional information about the illegal wildlife trade. In [60], the authors demonstrate that scraping news data and court cases revealed more seizure events and a finer-grained analysis of the pangolin trade than was available through the CITES wildlife trade database. Automated analysis of news data similar to the analysis by [73] or hand-curated analysis by [60] can prove useful for augmenting centralized databases.
- **Online Markets:** Researchers have shown that IWT is often conducted by online markets such as on online auctions [61], forums [62], and social media groups [63]. In these settings, researchers can use social media data to analyze the network of individuals trading wildlife as well as estimate the extent to which online trade is conducted illegally. These online markets often provide a fine-grained picture of trade for specific species in a specific location as there is no central location for general wildlife trade, but rather specific sites for individual markets. Analysis of these online markets can be used to identify different agents conducting illegal wildlife trade, as well as call for regulations and monitoring of online trade.

4.2.2. Research Opportunities in Data Detection and Prediction

Each of the datasets and data collection techniques present their own strengths and weaknesses in monitoring wildlife trade for different species, resolutions, locations, and facets of illegal wildlife trade. As a result, a wide variety of methods have been developed to handle the challenges arising in this domain. These methods are developed to handle aspects like understanding *the trade network, removing data biases*, and *determining how to deploy strategies* that effectively uncover new data while also effectively preventing wildlife trade as discovered from known data:

- **Network Analysis:** Note that in terms of network analysis, a variety of the data sources concern data represented as networks, where agents are represented as nodes on the network, and edges represent trade or movement of wildlife between those agents. For instance, [74] identify the key countries in which wildlife trade occurs. They identify the smallest set of countries that account for all wildlife trade for different species in historical seizure data. Additionally, social networks such as those from social media have been used to identify online groups that may be responsible for illegal wildlife trade [63]. Link prediction, or estimating which unobserved connections are likely to exist but are unobserved in the data, has also proven useful for identifying hidden network structure and clustering agents involved in Rhino poaching [75] and identifying latent connections in crime networks [76]. Link prediction techniques can also model network dynamics, or how links may appear and disappear over time, as is the case with realistic trade networks. Furthermore, network analysis techniques may be used to understand the multiple trade networks concerning different species and help researchers understand whether these different trade networks interact with each other. Finally, advanced techniques may attempt to combine different network data sources, such as the network of physical wildlife trade, with the network of transactions to get an understanding of how flows of capital reflect the wildlife trade.
- **Dealing with Bias:** Given the adversarial nature of illegal wildlife trafficking, there is an inherent bias in the observed data. These biases may take the form of centralized datasets not covering the full scope of wildlife trade, as shown in [60] and mentioned in the data limitations in [77] or simply not having data due to undiscovered wildlife trade. In this regard, researchers have proposed a variety of models that attempt to yield actionable insights from biased data, such as Bayesian modeling [78,79] or modeling adversarial behavior in the data generation process [80]. Note that there are other unique research areas where missing data or data bias could be an issue. Some such areas that include vulnerable populations are forestry, medicine, human trafficking, and violent crime. For example, forestry has a lot of previous work on imputation, and these settings have low-data regimes and data bias (which is unaddressed by modeling approaches). K-nearest neighbor imputation, pretty common in forestry, is applicable when there is spatial smoothness that can be exploited and local effects that can be learned rather than higher-order connectivity as in other scenarios. [81] offer a review of suitable K-nearest neighbor imputation techniques. In medicine, [82] directly address the bias by using multivariate imputation by chained equations and variants. In the context of disaster response, [83] consider global constant-based imputation rules (e.g., optimistic, pessimistic, neutral, and popularistic), cluster (unsupervised learning)-based imputation rules (e.g., clustering with mean and mode and clustering with adjacent arc), decision tree-based imputation. Their findings state that the average success rate of the accuracy of the imputation method depends on the imputation method, post-disaster road status type (e.g., closed, partially blocked, or unrestricted), mapping focus, and the grid size of the map. In a recent review, [84] review the uncertainty experienced in responding to a disaster. It is noted that resolving the data issues related to the connectivity of the network, the transportation times (which likely impact the response time), and the costs are still valid concerns of post-disaster operations. In some other domains, researchers use im-

putation that involves training a model [85,86]. The lessons from these areas of research can be translated into resolving the data issues of IWT.
- **Data Exploration vs Exploitation:** Researchers have also looked into how to balance efforts towards both collecting new data and deploying additional resources based on existing data [79,87,88]. For instance, [88] develop and analyze a new bandit algorithm that plans park ranger patrol efforts so that wildlife is effectively protected and that locations are effectively explored. This new area of machine learning has potential uses in balancing data exploration and exploitation.

4.3. Disrupting Covert and Agile Supply Chain Networks

Traffickers operate complex and dynamic trafficking networks that require detailed strategies to disrupt. Disrupting these networks can be modeled as a **network interdiction problem** where enforcement authorities seek to increase interdiction efforts along specific transit routes to reduce the trafficker's profitability and force any resulting geographic displacement to be as costly as possible. There are many different types of network interdiction problems, and they have the advantage of capturing the follower's response to the leader's interdiction, which represents the geographical displacement common in IWT networks [89]. The stochastic network interdiction problem relaxes the assumption that the leader knows the costs along each arc and the effects of their interdiction activities [90]. This is very relevant to wildlife trafficking because most of the available data is seizure data from limited species and regions. Therefore, enforcement authorities are unlikely to have exact information about the costs traffickers face or the potential effectiveness of their interdiction. [91] also investigate a stochastic network interdiction problem and incorporate heterogeneous risk preferences into their analysis. It is unlikely that law enforcement and traffickers have identical risk preferences and these preferences may change as penalties for trafficking-related offenses increase. Several papers on network interdiction consider the context of smuggling drugs or nuclear weapons [31,92–99]. [27] describe the potential applications of the network interdiction problem in a human trafficking context. Binary knapsack interdiction problems can be used to model the species displacement effects present in wildlife trafficking [100,101]. In these problems, the leader chooses a subset of items to block the follower from utilizing subject to its own budget constraint [89]. In this scenario, interdiction activities may focus on legislation or ranger activities, such as identification training for inspection personnel or more frequent patrols to protect wildlife, which make certain species more difficult to traffic.

Network interdiction problems can also be used for network detection. [102] investigate a network interdiction problem where the leader chooses arcs to monitor and the follower attempts to avoid detection while traversing the network. These types of interdiction models can be used to determine monitoring locations for controlled shipments which allow illicit goods to be delivered to their final destination without seizure to provide additional information. [99] present a bilevel programming model for the corresponding Stackelberg game for effectively defending a set of population centers against attack by a limited number of intercontinental ballistic missiles. Several papers in the literature also study interdiction models where there are multiple rounds of decisions, and the leader learns more about the followers' optimization model in an online fashion [103,104]. [105] previously studied this type of sequential learning combined with game theory and tied it into the multi-armed bandit model. Multi-armed bandit models can also be used to learn more about network structure and prevalence in specific markets. This class of problems is often used to represent the classical explore vs. exploit trade-off [106]. [107] use a multi-armed bandit framework to model a problem where firms must balance exploring new oil fields with exploiting existing sources. They consider that once a site has been explored, additional information about neighboring sites is revealed. This can be highly applicable to IWT because seizure data often list origin, transit, and destination locations. These locations can be seen as "neighbors" in the transit network. One important factor that the previous paper does not consider changes over time and as a result of activities taken by the decision maker, rightfully so since oil fields don't jump up and move once they are discovered. [108] investigate a multi-armed bandit when environmental changes are occurring throughout the exploration process. This is highly likely for IWT interdiction efforts as traffickers are highly adaptive, and increasing observation and enforcement in a specific area may take time to implement. [109] look at a multi-armed bandit problem from a robust optimization approach which takes into account the likelihood of misspecifying, or not knowing, the problem parameters.

The laundering of illicit products into licit supply chains, sometimes called greenwashing, is also a subject of concern in wildlife trafficking. Operations researchers have published a number of papers in recent years focusing on supplier evaluation and inspection. Several of these works derive mechanisms for firms to respond to product adulteration by their suppliers [110–112]. These works are similar to the plight faced by firms purchasing products that are difficult to distinguish from illegally sourced ones, such as timber or fish. However, many of the mechanisms in these works rely on the consumer eventually realizing that the product has been adulterated even if it is not obviously defective at first. This is unlikely to be the case for laundered wildlife products, and even if a customer was later able to identify the illicit nature of the product and demand a refund, the environmental destruction would have already occurred. This highlights the need for firms that purchase products likely to be substituted with illicitly obtained wildlife to ascertain the legality and sustainability of their supply before purchasing and receiving shipments of goods. Other works in the literature focus on supplier inspections to ensure sustainability and safe working conditions [113–117]. Many of these studies include game theory models in their analysis and consider suppliers' motivations to avoid or deceive inspections by their customers [118]. For illicit products where there are known processing facilities and the unprocessed product is more easily identified, inspections may be a valid approach. However, the illegal harvesting of wildlife mostly occurs in rural areas, and it may not be possible to inspect those processes. In addition, inspections would not be random or unannounced if harvesting locations are constantly changing. These issues highlight the need for new work in supplier evaluation that reduces the focus on facility inspection to limit the risk of supplier deception. [112] study product adulteration in farming supply chains and discuss strategies for scenarios where end product testing and inspection is the only option. This can be effective for IWT because some products can be tested using DNA to determine the species, but these methods alone may not show the country of origin or if a legal permit existed for the harvesting of those materials. Multiple methods must be considered in conjunction to truly prevent illicit supply from entering licit supply chains. Blockchain technology may have some benefits for reducing opportunities for corruption and the introduction of illicit goods into supply chains [1]. However, there are challenges such as suppliers being unwilling to adopt the technology and "garbage in, garbage out [119]".

4.4. Effectively Utilizing Limited Resources and Reducing Corruption

The effective use of limited resources is a key characteristic of operations research problems. [120] states many areas use traditional operations approaches in addressing community problems, including urban services, crime, drugs, violence, and public health. He also notes that there are other areas OR researchers could contribute. Organizations and governments dedicated to reducing IWT often have to choose between multiple competing proposals and projects to allocate funding and resources. Optimization models are the primary solution approach when considering resource constraints. Specifically, in the illicit domain, two types of formulations appear to be the most useful in handling various limitations of the problem environment. The first type of formulation includes knapsack problems (KS) that can be used to choose which subset of activities will yield the greatest reduction in harm (or maximize the benefits) subject to resource and time constraints. Network interdiction problems often have a total budget or a maximum number of arcs that can be removed [89]. The second type of formulation is multi-armed bandit (MAB) problems which can also be subject to resource constraints in addition to limited information. MAB problems are typically used to learn effective strategies while balancing exploitation and exploration. In an illicit domain, a defender dedicates limited resources to several possible actions to defend against an attacker's activities. Next, the defender learns the optimal resource allocation strategy based on observations of loss and reward coming from historical data and multiple rounds of exchange. MAB problems have multiple variants that can be explored in different problem contexts. Recently, some mixed integer optimization models have been used to create wildlife corridors and for reserve design in conservation planning [121–123]. Another recent example is related to reducing poaching risk through the optimization of land use and routes [124].

The first two of these problem formulations have received recent interest in illicit domains. In a human trafficking context, [125] consider a generalized KS problem to allocate a budget for locating residential shelters to maximize societal impact. In addition, [126] uses a KS-based formulation to design human trafficking awareness campaigns. [80,127] consider MAB models to account for imperfect data for poaching. [128] addressed perimeter surveillance using a combinatorial MAB model with Poisson rewards [129] developed a framework for land managers to allocate resources against multiple conservation threats. Yet, for IWT, there are still many open problems that depend on allocating or rationing limited resources where operations research tools could be useful. One such open area of investigation is incorporating corruption considerations while allocating resources since IWT problems are interlaced with bribery and corruption. Another possible area of investigation is to expand the outcomes of various MAB solutions into policy determination. The final opportunity for optimization models is related to assignment problems for the deployment of scarce resources for inspections and poaching, such as inspector deployment.

5. Example Wildlife Trafficking Problems

In this section, we discuss three different operational problems in combating IWT. We present these problems in the context of three different trafficking supply chains and discuss their unique characteristics. First, we present the network prediction problem to discuss potential methodological advances that can assist in determining the true scope and scale of IWT. Second, we introduce the network interdiction problem and discuss important adaptations to existing formulations that would contribute to the literature. Finally, we introduce the problem of supplier investment for social responsibility with incomplete information and interacting intervention types to model the problem faced by firms that source wildlife products.

5.1. Network Prediction Problem

Although some information about IWT network structures is available through seizure data and previous research, data that characterizes the specific operations of IWT networks is still not available for many species. Seizure data is often biased and can mislead authorities to focus resources in regions that are already investing in wildlife trafficking interdiction. Figure 1 shows the seizures of a wide array of animal products on an airport network since 2010 [9]. Note that the blue dots represent the available airports and red circles represent the known seizures. Despite the cumulative nature of data, there are a larger number of airports where no seizures are reported. This is not necessarily due to a lack of wildlife trafficking in those areas but rather a lack of enforcement resources and data sharing. Implementation of data-driven network prediction can highlight new regions for enforcement efforts that were previously unknown to authorities and underrepresented in existing seizure data. The availability of the data standards [47] makes it easier to address data-driven network prediction problems.

For interdiction and prevention efforts to be successful, it is important that researchers and officials have a deep understanding of the different transit routes used by traffickers, their prevalence, and the benefits and costs (to the traffickers) associated with them. This data will enable researchers to develop tailored strategies that minimize displacement effects and effectively disable IWT networks. There are four main segments of IWT supply chains where detection may be possible: sourcing, processing/manufacturing, transit, and sales/delivery. There are often varying levels of concealment at each stage in the supply chain.

Radiated tortoises, for example, are harvested from a very small region in the south of Madagascar. While this harvesting is not condoned, it is also not actively prosecuted, and so traffickers are not as covert. Network prediction is very difficult for this stage of the radiated tortoise supply chain because of extremely limited data, on both the terrain and past enforcement efforts, and a wide array of potential transit paths (e.g. rivers, roads, and oceans). This makes predicting likely routes of traffickers highly complex and prone to error. Since radiated tortoises are often sold alive, there is little processing to be done in the early phases of the supply chain.

In the transit phase, the tortoises are hardy and can be pushed into their shells and taped up. They are then hidden in luggage and otherwise concealed. Faster methods of transit such as passenger air are often used because these tortoises are sold as exotic pets and need to be kept alive. In this manner, the transit phase of the supply chain is more directly covert. However, data is also more readily available through air seizures, particularly at international borders. There are also more defined transit paths, especially across continents and large bodies of water where driving is not possible. The availability of data on transit paths and enforcement efforts makes network prediction in this phase more tractable for researchers. Efforts to understand the transport phase of the supply chain can be made using an arc prediction or multi-armed bandit framework. Arc prediction can be used in cases where certain arcs along a network are known to be used, but other arcs have received little enforcement effort. By understanding which characteristics of the known arcs make them attractive, researchers can then predict what other, previously unknown, arcs might be popular with traffickers.

As mentioned earlier, multi-armed bandit (MAB) frameworks are often used to choose between multiple options. One previous application of MABs in the literature is for discovering new oil fields [107]. This example is particularly applicable to wildlife trafficking because of the correlation between the probabilities of discovering oil in neighboring locations. In a wildlife trafficking con-

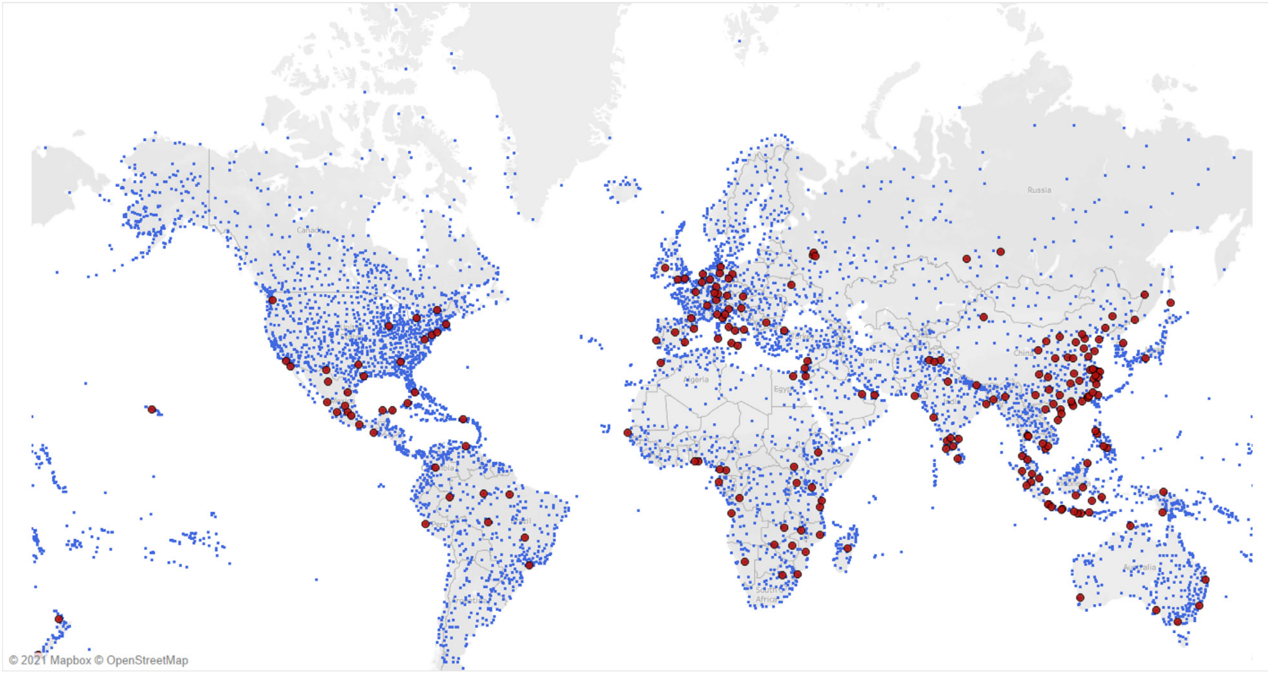

Fig. 1. Airport seizures for a wide array of animal products. Blue nodes indicate airports, while red nodes indicate seizures.

text, finding trafficking in one airport can indicate other airports as trafficking locations along popular flight routes. Both of these contexts consider sequential exploration problems similar to multi-armed bandits with dependent arms. However, these models lack the added complications of potential false negatives on inspections, due to failure by authorities to correctly identify illicit products, and the adaptability of traffickers. There is an opportunity for new models to be developed that incorporate the value of correlation between network locations with the unique challenges of IWT to improve our understanding of the structure of transit networks.

In the final segment of the supply chain, sales and marketing are often not well concealed for radiated tortoises because much of the marketing takes place online, through social media channels [1]. This makes data collection through social media a possibility and opens up new data sources for network analysis and prediction. In this stage of the supply chain, it can also be difficult to predict a physical transit network because of the large array of potential paths and locations for sales between individuals, similar to the sourcing phase. However, this stage presents a good opportunity for researchers to predict the network of individuals who may be involved with trafficking. The financial flows associated with the trafficking and sale of exotic pets can also provide clues about the network of individuals involved. Analysis of financial flows can enable the discovery of individuals who are heavily involved with criminal organizations. Machine learning has previously been used to identify money laundering activities but this research has not extended to characterizing networks of individuals involved in illicit activities. We refer our readers to [130] for a detailed review of machine learning techniques for money laundering. As this review points out, most of the research in this arena focuses on data collected from banking transactions to detect the behaviors of banking customers. Not necessarily to understand the relationships between individuals in a network and identify new members through financial transactions. This presents an opportunity to utilize the wealth of financial data available to determine the individuals who are most central to the network and understand more about the profitability of IWT at various stages in the supply chain.

5.2. Network Interdiction Problem

Law enforcement interdiction and seizures of trafficked goods are important tools in the fight against IWT. Seizures reduce the profitability of trafficking organizations, and the data that is obtained from them is currently one of the primary sources of information about IWT operations. Current seizures only interrupt a fraction of IWT and increased interdiction efforts are needed to effectively curb IWT activity. Many works in the OR discipline have studied network interdiction problems; but, IWT brings up several new challenges that previous papers have not considered [89].

In recent years, pangolins have quickly become one of the most trafficked species. Since 2014, the number of whole pangolin equivalents seized globally has increased to more than 10 times the previous amount [1]. Pangolins are hunted for their meat and scales, but most meat consumption occurs locally. Pangolin scales are primarily trafficked to Asian countries and, more specifically, China where they are used in traditional medicine. Prior to 2013, most shipments originated in Southeast Asian countries such as Thailand, Indonesia, and Malaysia. In 2013 the main supply of pangolin shifted, likely due to severely declining populations of Asian pangolin species and increased protections, to West and Central Africa. Countries including Nigeria, Cameroon, and the Democratic Republic of the Congo have become popular locations for illicit pangolin harvesting. Estimates on the number of shipments of pangolin through various transportation modes are unreliable, and it is unclear what the costs and profits are for traffickers at the transit stage of the supply chain [1]. Figure 2 presents a well-known pangolin trafficking network from Kinshasa, Democratic Republic of Congo to Kuala Lumpur, Malaysia. The other nodes are all known transit or destination locations, including Nairobi, Kenya; Dubai, United Arab Emirates; Istanbul, Turkey; Marrakesh, Morocco; and Guangzhou, China. While this network is considered to be established, there is still limited information regarding shipment volume, shipment frequency, number of transportation agents, and overall cost and value of shipments. Pangolin trafficking occurs across multiple modes of transportation, including sea, air, land, and parcel post. Pangolin scales are often concealed in passenger

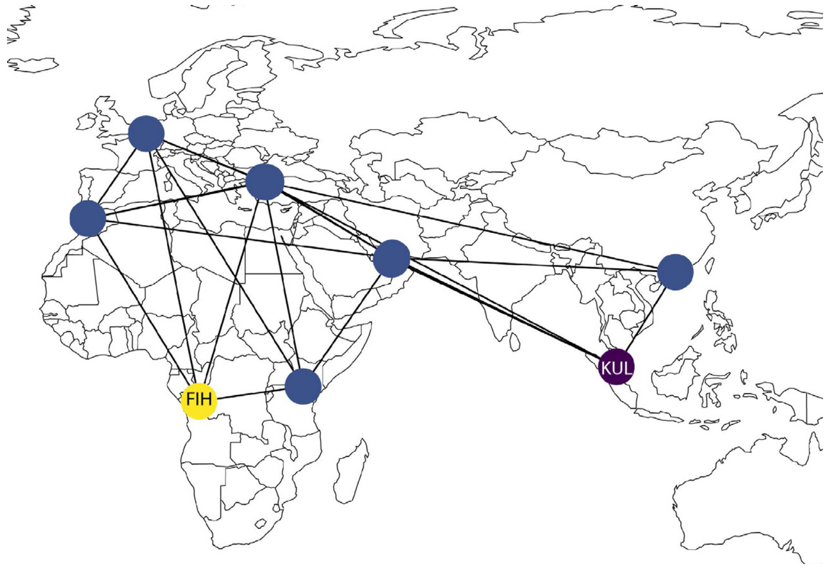

Fig. 2. A well-known pangolin trafficking network from Kinshasa, Democratic Republic of Congo to Kuala Lumpur, Malaysia

luggage in small amounts for air travel and under large shipments of plastics or other materials for ocean travel. The variety of concealment methods makes identifying illicit shipments more difficult and requires more training for enforcement officials to successfully identify illicit shipments and products. In addition, the variety of ways the animal parts can be prepared can make them difficult for untrained officials to identify, especially in countries where the animals are non-native. For example, Turkey is a known transit country for pangolin scales but there are no native pangolin populations there.

[89] introduce a general notation for the network interdiction problem that we will reiterate here. Let $\Theta(x)$ be the objective of the interdictor and represent the value of an interdiction decision x. The general form of the interdiction problem is given by:

$$\begin{aligned} \max \quad & \Theta(x) \\ s.t. \quad & x \in X. \end{aligned}$$

$\Theta(x)$ is defined as:

$$\begin{aligned} \Theta(x) \quad & = \min f(x,y) \\ s.t. \quad & y \in Y(x), \end{aligned}$$

and $f(x,y)$ is the traffickers objective function. Interdiction problems in IWT are dynamic with traffickers adapting to law enforcement efforts through geographic displacement and the development of new transportation pathways. Traditional interdiction models often focus on traffickers who minimize the probability of detection or their cost, where cost is some combination of a fixed value and a penalty applied via interdiction. In practice, the impact of interdiction decisions on $f(x,y)$ is unknown and dependent on the relative importance of other factors and the ability of the traffickers to observe enforcement actions. In contrast to traditional network interdiction problems, the relative importance of different factors that impact traffickers' chosen paths are often unknown to enforcement authorities. While transportation costs and interdiction efforts will undoubtedly impact traffickers' utility from various paths, more detailed considerations, such as corrupted officials, legal penalties, time (for perishable products), and species awareness, may also impact transit decisions. For the pangolin trafficking routes shown in Figure 2, the choice between traveling through Paris, Istanbul, or Dubai can be heavily influenced by the awareness of pangolin scales in those countries and the presence of local laws prohibiting their trade. In addition, penalties for detection may vary between countries which motivates a new form of $f(x,y)$ that focuses on minimizing the expected penalty to the trafficker from detection. In contrast, time is unlikely to be an important consideration for pangolin because meat consumption is often local and scales are not perishable. Models need to accurately predict these adaptations and help enforcement officials minimize displacement effects. Network interdiction models applied to IWT must capture the uncertainty around the problem parameters and the impact of interdiction methods on the traffickers' costs. In addition, although traffickers may notice if more seizures begin to occur on certain paths, increased inspection for wildlife products can be indistinguishable from other forms of inspection. This creates information uncertainty around traffickers' level of awareness of interdiction activities and detection probabilities in various countries, which is another potential area of expansion for researchers.

The form of $\Theta(x)$ is also unique for the wildlife trafficking interdiction problem because the benefit of capturing traffickers in various countries (for law enforcement) is often uneven and species-dependent. Some items, such as pangolin, are the focus of substantial amounts of resources and attention. However, other species may only be seized in countries where they are native or recognized as endangered. Legal and political differences across countries make it so that seizure in specific countries is far more impactful, depending on the species. More investigation is needed to accurately characterize $\Theta(x)$ and $f(x,y)$ so that interdiction models accurately capture incentives and predict trafficker activities.

Network interdiction and prediction problems are often intertwined and can be solved simultaneously or individually depending on the goals of the study. Recent advances in the literature have focused on combining the two problems and capturing the explore versus exploit trade-offs that these problems create [131–133]. Whether an individual or combined approach is preferred is heavily dependent on the goals of the authorities implementing the solution and the resources available for implementation. Regardless of whether these problems are approached independently or jointly, the factors highlighted in this section are critical to the successful application of IWT networks.

5.3. Supplier Improvement Problem

Another concern that arises within IWT is the laundering of illicit wildlife products into licit supply chains. There is ample ev-

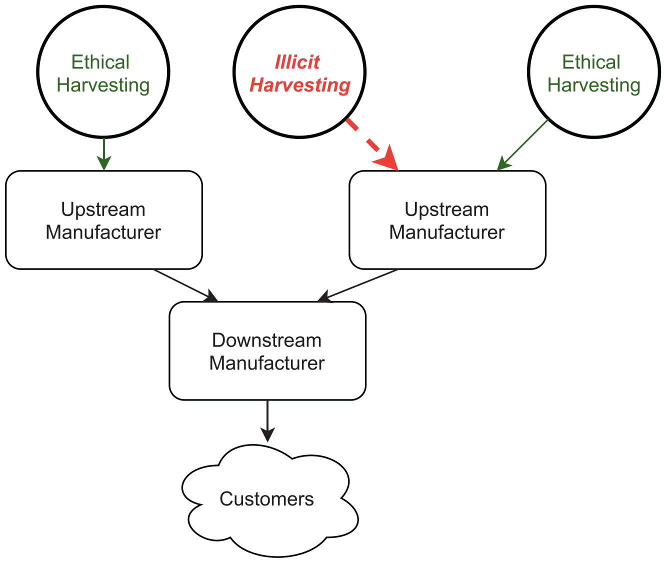

Fig. 3. IWT proliferation into regular supply chain

idence of connections between illicit and licit supply chains, and many illegally obtained products are indistinguishable from their legally obtained counterparts [1]. For instance, Figure 3 depicts a supply chain where one of the upstream manufacturers is procuring from an ethically harvested source, and the other one is using an illicit source along with the ethical harvesting. This example highlights the overlap between IWT and the need for supply chain transparency and corporate social responsibility. If firms are not transparent or socially responsible, it is incredibly difficult for consumers to distinguish between ethically sourced products and illicit ones, especially in the presence of greenwashing. Illicit harvesting can take the form of products harvested from protected areas, products harvested in excess of legal limits, or product substitution where protected species are harvested and passed off as legally harvested species. There are many wildlife products used in consumer goods that may be illegally harvested. Popular examples are various tree species used for furniture, animal skins and furs used for fashion products, and seafood products sold for consumption [1,134]. Illegal logging and harvesting and illegal, unreported, and unregulated (IUU) fishing present substantial threats to protected species and highlight the need for increased supply chain transparency. In some cases, trafficked wildlife products that enter licit supply chains may also have been handled or harvested by victims of labor trafficking [34]. For illustration purposes, we will discuss these issues in the context of illicit rosewood harvesting for the remainder of this section.

Rosewood does not refer to any specific botanical category but rather a “wide range of tropical hardwoods” [1]. There is evidence that illicitly obtained tropical hardwoods are entering legal supply chains, particularly in the furniture industry. Tropical hardwood harvests can be illicit because of their location or the species harvested [1]. In cases where the harvesting is illicit because of the country or region of origin, it can be extremely difficult to distinguish from legally harvested wood. As an example, note the Gibson Guitar case that took place in the United States in 2011-2012. Gibson ended up paying $350,000 and forfeiting over $200,000 worth of wood fingerboards as part of the inquiry around their import of ebony and rosewood from Madagascar and India [135]. Gibson’s supplier was using wood from Madagascar which was illegal to export to construct the fingerboards that Gibson was purchasing, and as a result, Gibson was investigated by the United States Department of Justice. It is necessary that firms understand the sourcing practices of their suppliers and ensure that all components are legally obtained. Unfortunately, for many wildlife products inspections of harvesting operations are difficult, and it may not be possible to do covert or surprise inspections due to the remote and changing locations. Firms have better visibility for manufacturing and processing locations but products may not always be distinguishable on inspection, especially when the only distinguishing factor is the country of origin. Some products may be identifiable before they are processed and others may require forensic analysis or testing to ascertain their legality. These special characteristics make the problem an interesting application for quantitative supplier selection, intervention, and inspection problems.

For example, the chocolate industry faces many of the same problems as downstream manufacturers who utilize wildlife products: many suppliers, low visibility, and difficulty of inspection. The chocolate industry has been tied to child labor and human/labor trafficking concerns for many years [136]. Tony’s Chocolonely, a chocolate company, is well known for its commitment to ethical sourcing practices [137]. Their strategies combine a digital bean tracking platform, a child labor monitoring system, and GPS mapping of plantations to make their beans traceable. They also pay higher prices, develop farmer cooperatives, make longer-term commitments to their suppliers, and invest in quality and productivity initiatives [138]. Some of these strategies may also be applicable to illicit rosewood harvesting. However, because the types of restrictions on harvesting can vary wildly, some strategies may not be effective for certain regions and species. Investment in initiatives like these is supported by existing research, but there is still a need for more empirical research on the effectiveness of the various strategies and any synergistic effects of utilizing them simultaneously [139]. Some research has been done on the optimal investment in a supplier, given a signal about the supplier’s social responsibility [140]. However, because of the multifaceted nature of ensuring sustainability, and legality, in wildlife supply chains, models must also capture trade-offs between investments in various initiatives to determine optimal investment amounts. A knapsack model with stochastic rewards to capture the expected impact of various policies subject to a budget constraint may be appropriate in this scenario. Knapsack problems with stochastic rewards, in both static and dynamic forms, have already been studied in the literature [141]. They model the static stochastic knapsack problem as follows:

$$\max \quad P\left(\sum_{i\in N}\sum_{j=1}^{N_i} X_i^j y_{ij} \geq r\right)$$

$$s.t. \quad \sum_{i\in N} w_i \sum_{j=1}^{N_i} y_{ij} \leq W$$

$$y_{ij} \in \{0,1\} \qquad j = 1, 2, \ldots N_i, \forall i \in N.$$

Where y_{ij} is equal to one if the jth item in set i is selected, and zero, otherwise. X_i^j is the random variable for the reward from selecting item j from set i, w_i is the cost of selecting an item from set i, and W is the overall budget. The objective is to maximize the probability that the total reward exceeds some threshold value. This model captures some key characteristics of the problem that firms face when choosing to invest in a variety of supplier interventions. However, assumptions about the independence of the reward values are limiting when certain practices have synergistic impacts, and others, such as productivity initiatives, may have negative impacts when not combined with other initiatives. Further research into the problem of supplier investment for social responsibility with incomplete information and multiple interacting intervention types can increase applicability to IWT contexts.

6. Conclusion and Future Research Directions

Over the last decade, especially in the last two years, wildlife trafficking has received increased attention, partially due to the COVID-19 pandemic potentially originating via the wildlife trade. However, despite this attention, there is a shortage of technical methods to map, analyze, and interrupt wildlife trafficking activities. Furthermore, while methods to counteract other illicit supply networks have been developed, due to the special characteristics of IWT and other socio-economic challenges, existing technical models require further research and adaptation. Operations research and other analytical approaches have the potential to greatly improve solutions and provide recommendations to decision-makers, policy developers, and law-enforcement agents.

With this review, we highlight the challenges and key characteristics of IWT to inform OR/analytics professionals and inspire them to get involved in this line of research. We discuss the overlap between IWT and other illicit supply chains and highlight the areas where IWT presents distinct challenges. The opportunities section presents a number of ways in which OR methods can be leveraged to address IWT issues. We highlight several key problems of interest and research directions in Section 5. Additionally, in the appendix, we provide a list of agencies and data sources for those who would like to partake in this research. While we provide a number of research directions, there are still many other outstanding challenges waiting to be addressed.

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Appendix A. Appendix and Additional Resources

A1. Data Sources

The CITES Trade Database is a publicly available dataset intended to record information regarding the international trade of wildlife, both legal and illegal. It contains more than 15 million records of both legal and illegal wildlife transit events with columns that can describe the importing and exporting countries, animal, sourcing, and purpose of the trafficked material [77,142]. The database can be accessed at: https://trade.cites.org.

The C4ADS Widlife Seizure Database C4ADS maintains a database of illegal wildlife seizures and generates many reports and analyses from the data, which are publicly available. Their data contains information on seizures of ivory, rhino horn, and pangolins and their scales. The Wildlife Seizure Database is large and updated on a daily basis with new seizures. A description of the database is available at: https://c4ads.org/blogposts/2020/6/1/wildlife-seizures.

LEMIS Wildlife Trade Data The United States Fish and Wildlife Services (USFWS) Law Enforcement Management Information System (LEMIS) contains data on live organisms and wildlife products that have been imported to (or exported from) the United States. This data contains information on a large number of species, in comparison to other data sets that may focus on specific subsets of species. Eskew, E.A., et al. (2020) provide a descriptor of 14 years of LEMIS data that has been cleaned and processed [143]. Their data and analysis are publicly available at: https://github.com/ecohealthalliance/lemis.

Wildlife Trade Portal The Wildlife Trade Portal is built from TRAFFICs open-source wildlife seizure and incident data. The portal allows users to filter on a variety of factors and also generates some standard visualizations of the selected data automatically. Data can be exported in csv format and detailed information about the species involved and the transit locations is available. Data on a wide range of species and geographical regions is available through the portal. It can be accessed at: https://www.wildlifetradeportal.org.

UNODC Dashboard The UNODC website provides data on a variety of topics and maintains a section on wildlife crime. There are a number of visualizations shown on the dashboard and data is broken down by species and country for analysis. The dashboard can be accessed at: https://dataunodc.un.org/content/wildlife.

IWT Data standards Geospatial data standards are important for combating IWT since knowledge about crime patterns and trends is required for crime prevention and response, including non-law enforcement-oriented response. The datasets generated by [47] are available at https://zenodo.org/badge/latestdoi/444480619 without any restrictions on access or use.

Appendix B. Organizations Against IWT

- The Alliance to Counter Crime Online (ACCO): www.counteringcrime.org
- Center on Illicit Networks and Transnational Organized Crime (CINTOC): www.cintoc.org
- Chengeta Wildlife: www.chengetawildlife.org
- CITES: www.cites.org
- Earth League International: www.earthleagueinternational.org
- ROUTES: www.routespartnership.org
- UNODC: www.unodc.org
- TRAFFIC: www.traffic.org
- U.S. Fish and Wildlife Service: www.fws.gov
- Wild Life Fund (WWF): www.worldwildlife.org
- Wild Aid: www.wildaid.org

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