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RESEARCH

Comparative Analysis of Illicit Supply Network Structure and Operations: Cocaine, Wildlife, and Sand

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Illicit supply networks (ISNs) are composed of coordinated human actors that source, transit, and distribute illicitly traded goods to consumers, while also creating widespread social and environmental harms. Despite growing documentation of ISNs and their impacts, efforts to understand and disrupt ISNs remain insufficient due to the persistent lack of knowledge connecting a given ISN's *modus operandi* and its patterns of activity in space and time. The core challenge is that the data and knowledge needed to integrate it remain fragmented and/or compartmentalized across disciplines, research groups, and agencies tasked with understanding or monitoring one or a few specific ISNs. One path forward is to conduct comparative analyses of multiple diverse ISNs. We present and apply a conceptual framework for linking ISN *modus operandi* to spatial-temporal dynamics and patterns of activity. We demonstrate this through a comparative analysis of three ISNs – cocaine, illegally traded wildlife, and illegally mined sand – which range from well-established to emergent, global to domestic in geographic scope, and fully illicit to de facto legal. The proposed framework revealed consistent traits related to geographic price structure, value capture at different supply chain stages, and key differences among ISN structure and operation related to commodity characteristics and their relative illicitness. Despite the diversity of commodities and ISN attributes compared, social and environmental harms inflicted by the illicit activity consistently become more widespread with increasing law enforcement disruption. Drawing on these lessons from diverse ISNs, which varied in their histories and current sophistication, possible changes in the structure and function of nascent and/or low salience ISNs may be *anticipated* if future conditions or law enforcement pressure change.

Keywords: global commodity chain; complex adaptive systems; spatial dynamics; environmental crime; cocaine trafficking; illegally traded wildlife; illegal sand mining

1. Introduction

Globalization has concurrently expanded connectivity among the world's economies and increased the ease and speed with which goods, people, capital, viral pandemics, and information move across national borders. As of 2017, international trade constituted a global average of 58% of national gross domestic products (GDPs) (World Bank & OECD 2019). Domestic and transnational illicit economic activities – including trade in people, arms, drugs, and natural resources – have grown alongside legal economies. Illicit activities and the networks that connect suppliers and consumers of illicit goods and services, henceforth illicit supply networks (ISNs), generate an estimated US\$1.6 to \$2.2 trillion annually (Nellemann et al. 2016) – larger than the reported 2018 GDP of all but twelve of the world's economies (World Bank & OECD 2019). An understudied and poorly understood dimension of many ISNs, however, is their dependence or impacts on the environment. As a specialized type of crime directly exploiting the environment, environmental crimes (Gibbs et al. 2010) have grown in scope and reached an estimated global economic value of US\$91 to \$259 billion per year (UNEP 2018). These ISNs have emerged in part to meet unprecedented demand for natural resources. From 1970 to 2017, the annual global extraction of material grew from 27 billion tons to 92 billion tons (OECD 2019). Consequently, environmental crime ISNs are associated with widespread social and environmental harms (Gore et al. 2019a; McSweeney et al. 2014; Sesnie et al. 2017; UNEP 2018). ISNs also inject exorbitant amounts of illicit capital into already socially and/or economically unstable places (Gore et al. 2019a), fueling corruption, violence, environmental degradation, and dispossession of land and/or livelihoods of local communities (Devine et al. 2018; Hübschle & Shearing 2021; McSweeney et al. 2017; Rege & Lavorgna 2017).

ISNs may also impact the environment in ways not directly associated with their focal illicit activity. The environment may be exploited as a means to support or facilitate the focal illicit activity, as in the case of deforestation for purposes of territorial control and money laundering associated with cocaine trafficking in Central America (Dávila et al. in press; McSweeney et al. 2014, 2017, 2018; Sesnie et al. 2017; Tellman et al. 2020a). Combined with instances of direct reliance on natural resources as the primary illicit good for profit generation (e.g., illegally traded wildlife), ISNs associated with environmental harms and/or crimes leave distinct spatial footprints that can be used to understand their structure and *modus operandi*¹ through unique means unavailable for other ISNs not linked to the environment (Tellman et al. 2020b). Environmental impacts, either direct or indirect, can occur at any stage of ISN operations, and often lead to significant social harms, including violence, erosion of governance norms, and exploitation of vulnerable populations (Gore et al. 2019b; Wrathall et al. 2020). Environmental impacts during the production stage, such as illegal extraction (e.g., mining) or harvesting (e.g., wildlife poaching), have received the most attention from scholars, popular media, and law enforcement (Bernal et al. 2020; Nellemann et al. 2016; Rege 2016; UNEP 2018). Environmental impacts in the spaces through which illicit goods are transported, or 'transit zones', remain understudied or unrecognized (Hübschle 2016, 2017a), and can include deforestation as a means of territorial control and/or money laundering (McSweeney et al. 2014, 2018; Tellman, Sesnie, et al. 2020). Understanding the spatial dynamics of ISN activities is necessary to anticipate the spread and intensity of social and environmental harms (Williams & Godson 2002).

Despite the documented scope of ISN economic activities and associated harms, efforts to understand and disrupt ISNs remain insufficient due to the persistent lack of knowledge connecting a given ISN's *modus operandi* and its patterns of activity in space and time (Hall 2013; Hudson 2014; Nellemann et al. 2016). Like other illicit activities, the clandestine nature of environmental crimes poses difficulties for monitoring and research, and data about illicit flows, actors, and locations are inherently incomplete (Banister, Boyce & Slack 2015; Siriwat & Nijman 2018). Yet, taken as a whole, there is an abundance of data available ranging from ad hoc, place-based investigations, such as media reports (Belhabib et al. 2020; Siriwat & Nijman 2018; Tellman et al. 2020a) and ethnographic case studies (Singh 2014), to large-scale databases and research initiatives, such as TRAFFIC (East Asia and Pacific World Bank 2008) and UNODC (2016, 2020). The core challenge is that this data – and the knowledge needed to integrate it – can vary substantially across ISNs,

¹ While the term *modus operandi* is typically used to describe qualities of an actor, we expand its usage to refer to network-level spatial and temporal patterns of illicit activities that arise from the coordinated actions of ISN actors. These include, for example, typical modes of conveyance or concealment methods for illicit goods, spatial locations of ISN operations to avoid detection (e.g., remote landscapes), or strategies for maximizing profit.

and the data remains fragmented and compartmentalized across disciplines, research groups, and agencies tasked with understanding or monitoring one or a few specific ISNs (Tellman et al. 2020b). Moreover, current knowledge about most ISNs is primarily descriptive and compartmentalized. For instance, efforts to investigate illegally traded wildlife (e.g., rhino horn, pangolin scales, tiger parts) focus on poaching and consumption markets, yet comparatively little is known about the transit stage. Such knowledge gaps lead to a spectrum of ineffective programming across ISNs, including duplicated research efforts, counterproductive intervention or conservation strategies (Bocarejo & Ojeda 2016; Lu 2017), and unintended consequences of law enforcement (Magliocca et al. 2019). This article is an effort to begin building knowledge across ISN operations from production/source locations through to consumption markets.

One way forward is comparative analyses of multiple, diverse ISNs that impact the environment (Rege & Lavorgna, 2017; Reuter & O'Regan, 2017; South & Wyatt 2011; Wyatt et al. 2018). Comparative analysis of ISNs is generally considered an overwhelming challenge because 1) knowledge and data availability vary widely across different ISNs (South & Wyatt 2011), and 2) ISNs trafficking in different goods, regions, and/or geographic scopes often appear to be categorically different. However, exploiting key similarities and differences among ISNs with generalizable traits can provide compelling avenues for understanding the nature and functioning of those networks (Banister, Boyce & Slack 2015; Mackenzie & Yates 2015; Wyatt 2016). Initial efforts toward comparative research from the criminogenic asymmetry perspective have established the importance of deriving indicators to better target and intervene in illicit markets (Albanese 2020). However, proposed indicators remain descriptive and non-spatial, and further empirical research is needed to formalize metrics that can link criminogenic conditions with the spatial structure and operations of ISNs. Moreover, comparing ISNs can advance individual research communities by transferring knowledge across research and practice community boundaries (e.g., criminology, other social sciences, or land system sciences), and by developing a common conceptual framework and vocabulary to facilitate knowledge accumulation.

Our main objective in this work is to develop a generalized conceptual framework for linking the *modus operandi* of diverse ISNs to their spatial structures and patterns of activity. By doing so we demonstrate the feasibility and potential value of comparative ISN analysis with three examples – cocaine, illegally traded wildlife, and illegally mined sand. We chose these three precisely because of their apparent differences: they range respectively from well-established to emergent, global to domestic in the scale of their trade, and fully illicit to de facto legal at various supply network stages. The next section articulates important definitions (e.g., illegal versus illicit) and sets the scope of the paper. This is followed by the presentation of our proposed conceptual framework and a logic model for leveraging common ISN attributes to generate comparative insights. We then use examples of ISNs for cocaine, illegally traded wildlife ranging from rhino horn to plants, and sand to illustrate the application of the framework. We conclude with a discussion of generalizable and contingent insights gleaned from comparative analysis, and an identification of future research directions.

2. Defining Illicit Supply Networks

ISNs have recently become a salient topic in both social and political discourses, as well as an emergent research priority (National Science Foundation 2020). We provisionally define the term ISN as representing *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*. How, when, and where a good is termed 'illegal' or 'illicit' is always contingent on societal norms and political expediency and depends on the origin of the authority that aspires to regulate the good: political (what is legal vs. illegal) or social (licit vs. illicit) (Van Schendel & Abraham 2005). Illicitness is not an inherent property of a good, but rather a condition rooted in culture, history, and power differentials that is dynamic across space and time (Brisman & South 2014; Conrad 2016; Ferrell 1999; Van Schendel & Abraham 2005). Prohibition may only apply to one stage of an ISN, and a changed legal status of a good further downstream or upstream may be unknown to market actors (Beckert & Wehinger 2013). Economic exchanges that occur across multiple (e.g., transnational) or beyond (e.g., virtual marketplace) political boundaries further complicate jurisdictional considerations. Defiance or contestation of the state-sponsored label of illegality may also serve as a legitimizing mechanism for economic actors to participate in illegal economies (Hübschle 2016).

Figure 1 proposes a matrix (inspired by Van Schendel & Abraham 2005) that summarizes how tensions between the two forms of political and social regulation create particular typologies of goods *in a given spatial, social, and historical context*. Consistent with the distinction made by Van Schendel and Abraham (2005), 'legal' and 'illegal' are the results of the political sphere, because changing political sentiments

		Social Regulation	
		High	Low
Political Regulation	High	Illicit (A): both illegal and socially shunned; invites high degree of social and political enforcement	Illegal (B) but socially tolerated; enforcement contingent on local context
	Low	Politically legal but not socially accepted; results in ad hoc forms of social regulation (C)	Informal, legal, or tolerated (D); enforcement lax

Figure 1: A typology of goods ranging from illicit to legal given political and social regulations. The dashed lines indicate that there is no ‘hard’ boundary between the categories, and informal/formal and illicit/illegal all occur along a spectrum.

or priorities can change laws. Thus, we use the term *political* to refer to and emphasize the fluidity of the underlying process and resulting policies that render something legal or illegal. Importantly, this typology focuses on the implications of political and social regulation of a good for the means of its *supply* through ISNs. While consumption can be politically or socially regulated, supply often remains little affected by such regulation precisely because of the existence of ISNs. Thus, we focus on how goods are supplied under varying conditions of political and social regulation. For example, cocaine production and trade in most contexts (with the exception of scientific and medical purposes) is considered illegal and illicit (A); such goods are typically the target of strong state regulatory and law enforcement responses and negative social messaging. Marijuana in the U.S. would be an example of (B), with a resulting patchwork of state enforcement depending on the localized legal regime. Alcohol in the U.S. is an example of (C), whereby it is a legal good but is not socially tolerated in all contexts. Finally, there are goods that are considered both socially distasteful and technically illegal (D) – counterfeit handbags, or illegally-mined sand, for example – but insufficiently so in either time or space to manifest a strong social or political response.

This typology makes clear that many goods are not ‘fixed’ within these categories in all historical moments, locations, nor phases of the supply network (Abraham & von Schendel 2005). Thus, despite the attractiveness and efficiency of the term ‘illicit supply network,’ this typology recognizes that there can be tremendous heterogeneity within each of these categories across commodities, as well as considerable spatio-temporal variability in the same commodity’s social and political identities at different times and/or contexts. That variation – however messy – must be acknowledged as a first step towards meaningful inter-commodity comparison. Moreover, this typology is a useful heuristic for comparing how a given commodity moves along the informal/formal and illicit/illegal spectrum at different supply network phases, the implications those changing identities have for supply network structure and *modus operandi*, and how those characteristics compare with other commodities and their supply networks.

3. A Conceptual Framework for Comparative ISN Research

The following conceptual model and its applications to selected ISN examples are based on expert opinion synthesized during the convening of an international, collaborative workshop at the University of Alabama in August 13–15, 2019, with the expressed purpose of advancing comparative ISN research. The elements included in the final conceptual framework were those represented in one form or another across all ISNs, and which provided a means for meaningful comparisons across ISNs. Applications of the framework to each ISN in sections 4 and 5 are based on the synthesis of research of the workshop participants and sources from peer-reviewed literature.

3.1. Theoretical Foundations

The proposed conceptual framework is informed by the theoretical foundations of global commodity chains (GCC) and complex adaptive systems (CAS). Rooted in world-system theory, GCC deals with the commodity supply chain structures needed to move and accrue value from production to consumption locations

(Gereffi, Humphrey & Sturgeon 2005). GCC recognizes that commodities are no longer contained and controlled within single firms (Elliott 2016), necessitating coordination among dynamic supply networks of distributed actors at various stages of production, transport, and sale in consumption markets. Starting with spaces of production, GCC analysis follows the commodity, noting how, where, and by whom value is captured until the moment of its consumption (Neimark et al. 2016). Nodes are locations where supply, exchange, production, or transformation in a commodity takes place, and GCC is particularly useful for attending to how a commodity embeds socially and ecologically within those spaces (Bair & Werner 2011; Elliott 2016; Hartwick 2012). Central to the coordination challenge of supply networks are transaction costs that influence value captured at each node, and which vary with diverse actors, with varying risks of supply disruption, and according to the characteristics of the commodity (Dávila et al. in press).

A typical structure for a legitimate agricultural commodity supply network is analogous to an hourglass shape – wide at the top and bottom and narrow in the middle – corresponding to many actors at the production stage; a contraction of actors at the export, import, and transportation stage; and an expansion of actors in the consumption market's distribution and retail stage (Dávila et al. in press). In contrast, the commodity volume per shipment typically follows the opposite shape. Relatively small volumes are transported from many producers, aggregated into larger volume shipments in the transportation stage, and then disaggregated and distributed in gradually smaller volumes to consumption market actors (e.g., processors, distributors, retailers). Finally, the value per shipment and value captured per actor continually increase the closer the commodity gets to the point of consumption, typically with the majority of value being captured in the last stages in the consumption market (Rueda & Lambin 2013).

Similar to legitimate supply networks, ISNs derive earnings based on their logistical abilities to maximize profit and efficiency while managing risks to supply disruptions (Bright and Delaney, 2013; Caulkins, Crawford & Reuter 1993; Morselli & Petit 2007). A key difference between legitimate and illicit commodity supply networks is the disruption they face from regulatory sanctioning and/or law enforcement. All else being equal, vertical integration minimizes transaction costs associated with incomplete price information and labor supply, identifying reliable transaction partners, and enforcing transaction agreements (Allen 2005; Basu 2014; Kenney 2007). However, the need to evade detection of illicit and/or informal activities disrupts vertical integration, forcing decentralization of logistical decisions (Allen 2005; Bagley 2013; Dávila et al. in press; Dudley 2010; McSweeney et al. 2018). Consequently, governance structures of ISNs also deviate from legitimate counterparts with clandestine transactions based on actor-to-actor trust and/or enforcement through threats and coercion (Tellman et al. 2020b), rather than formal institutions and exchange mechanisms.

As a compliment, CAS enables analysis of ISN spatiality as a result of adaptive modifications to supply network structure and *modus operandi*, as predicted by GCC, in response to disruption. ISNs either adapt to increased transaction costs by modifying network structure and/or *modus operandi* at one or more stages, or they are critically disrupted by law enforcement or displaced by rival ISNs. Evidence shows that such adjustments are *primarily spatial in nature*: active ISN nodes will emerge in locations with lower perceived transaction costs (Basu 2014; Magliocca et al. 2019). The spatial manifestations of ISN adaptive behaviors reflect an ISN's internal structural characteristics (e.g., transport requirements of commodity, value accrued at each node) and impacts from methods for minimizing transaction costs (e.g., violence and/or corruption to enforce agreements). Comparison of spatial organization and dynamics across diverse ISNs can reveal key differences in how they operate, how they might respond to disruptions, and where and when harms associated with their operation might manifest.

3.2. Analytical Framing and Common ISN Attributes

A useful starting point is to distinguish between the production (source or supply), transit, and consumption (distribution and retail sale) stages of the supply network. Although particular expressions might differ for any ISN, all ISNs operate to some extent through these stages, which are defined by the flow of the commodity/product through the system. Nevertheless, the boundaries between these stages can become blurred. For example, opium poppy/heroin is produced and consumed in Peru, Colombia, Guatemala, and Mexico as well as trafficked to the U.S. However, these imposed demarcations are a useful lens through which to compare a core set of supply network attributes that we propose are common to all ISNs.

We propose two categories of attributes that are observable at each stage of ISN activity and reflect key indicators of ISN organization and function (**Table 1**). Attributes of *supply network structure* describe the overall configuration and important logistical characteristics of the ISN at each stage. For example, high

Table 1: Common structural and operational attributes of illicit supply networks (ISNs).

	ISN Attributes	Description
Supply Network Structure	Number of actors	Total number of participants in various roles (e.g., producer, miner, poacher, transporter, smuggler, importer, distributor, etc.) at each stage of the supply network.
	Volume per shipment	Mass of discrete commodity units (e.g., kilos, specimens) per shipment at each stage of the supply network.
	Value per shipment	Monetary value per shipment at each stage of the supply network.
	Value capture per actor	Distribution of illicit profits per actor at each stage in the supply network.
Modus Operandi	Environmental harms	Detrimental impacts to the natural resource and/or supporting ecosystems that harbor, produce, are transited through, or receive/consume illicit commodities. Harms range from direct resource exploitation to indirect impacts from illicit activity and/or law enforcement at each stage of the supply network.
	Social harms	Detrimental impacts to social systems that produce, are transited through, or receive/consume illicit commodities. Direct harms range from violence or exploitation of local communities in commodity production to addiction, corruption, or otherwise undermining institutions at each stage of the supply network. Indirect harms might include adverse impacts to livelihoods from environmental harms (e.g., exacerbated erosion from illegal sand removal; ecosystem destabilization from poaching of keystone species), and/or financial costs related to law enforcement expenditures, social services, or lost revenue from legitimate trade.
	Saliency of harms	Perceived urgency or priority to authority and/or society (severity, proximity, or perceived importance motivate response/enforcement).
	Disruption intensity	Volume and/or value of illicit commodity directly seized or disrupted by law enforcement or modified profitability of commodity affected by policy or market changes.

value capture at a particular stage attracts more numerous and diverse supply network actors (e.g., smugglers). Attributes of *modus operandi* describe the processes through which ISNs operate (e.g., exploitation of specific natural resources, locations, and/or social strata) or are disrupted (e.g., law enforcement intervention), and associated social and environmental harms that are consequences of their operation. All attributes can be qualitatively or quantitatively measured at each supply network stage. Changes in attributes across stages of the same ISN or the same stage across different ISNs provide comparative insight into processes influencing the spatial extent, structure, and dynamics of supply networks.

3.3. A Logic Model for Comparing ISNs

Generating comparative insights across diverse ISNs faces at least two challenges. First, the illicit nature of ISN activities translates into incomplete, fragmented, and/or unreliable data about ISN structure or operations, which renders most analytical methods based on direct observation ineffective (Tellman et al. 2020b). Second, ISN research tends to be commodity-centric, resulting in ISN observations/metrics defined in relation to unique commodity characteristics. ISNs are studied as highly contingent, idiosyncratic phenomena due to their unregulated and often informal organization and emergence in response to demands outside of formal economic systems (South & Wyatt 2011; Wyatt 2016). As a consequence, efforts to shift away from the commodity to the supply network as the object of analysis are often stifled by incomparable bodies of commodity-dependent knowledge.

We propose the logic model presented in **Figure 2** to navigate the intermediate steps needed to overcome these comparability challenges and develop insights into general causal mechanisms across diverse ISNs. First common and observable attributes of diverse ISNs are identified. Explanations of the particular manifestations of these attributes for each ISN are based on ISN-specific knowledge and existing research. Depth of knowledge for each ISN is needed to explain linkages among observable attributes (e.g., commodity characteristics, nature of production/supply and demand) and the ISN's unique network structure, *modus*

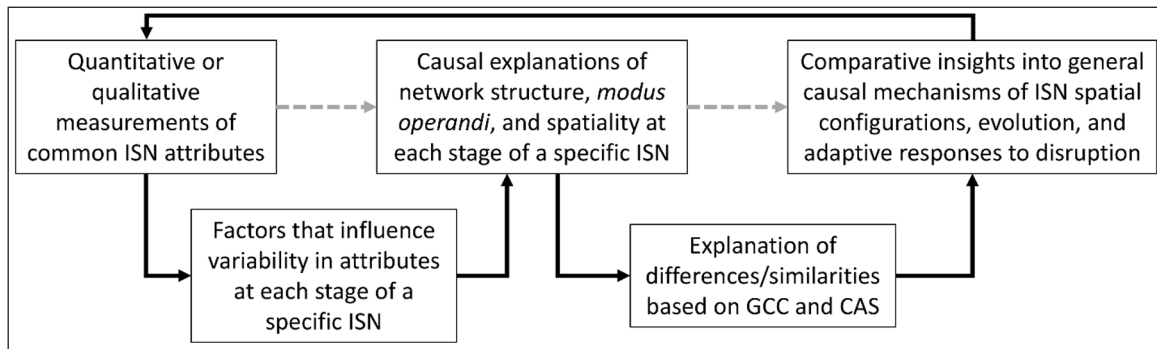


Figure 2: Logic model for operationalizing the conceptual framework and drawing insights into the spatial and operational evolution of different ISNs. Intermediate steps (solid lines) are needed between comparing a common set of attributes and gaining comparative insights into the general causal mechanisms using global commodity chain (GCC) and complex adaptive systems (CAS) frameworks. Comparative insights can feedback to modify and/or add common ISN attributes to measure for future inquiry.

operandi, and spatial expressions of those characteristics at and across each supply chain stage. Differences and similarities in these explanations among different ISNs are then compared based on GCC and CAS theoretical lenses. Specifically, how transaction costs at each supply chain stage shape the overall network structure; how supply networks locally embed and capture value; how ISNs adapt their structure and/or *modus operandi* to disruption; and how each of the former translate into varied spatial manifestations of ISN operations. Using these common theoretical frameworks, linked to shared and measurable ISN attributes, conclusions can be drawn about specific causal mechanisms and processes underlying operations and spatial configurations of diverse ISNs. Finally, comparative insights can feedback to modify and/or add common ISN attributes to measure for future inquiry.

4. Application of the Comparative Conceptual Framework

Three diverse types of ISNs were chosen for comparative analysis: cocaine, illegal wildlife trade (IWT), and illegal sand mining. These ISNs were selected because they span the topology of social and political regulation (**Figure 1**): cocaine is illicit in all supply network stages; there are both legal and illegal wildlife trades with varied social acceptability; and sand mining is socially tolerated and ranges from largely legal to largely informal depending on the country and region. In addition, each of these ISN types vary considerably in their maturity and research knowledge base. Cocaine trafficking between the U.S. and South American production regions is at least five decades old, and consequently is the best understood and has the most reliable data among the three ISNs types (McSweeney 2020). Knowledge and maturity of ISNs for wildlife vary greatly depending on the species: ISNs for rhino horn, for example, are long established and well-studied, whereas illegal trade for pangolin or succulent plants is relatively new (Margulies et al. 2019a). ISNs for sand are similarly new and an emergent research topic (Duan et al., 2019; Torres et al. 2017; UNEP 2019). These diverse ISNs test the robustness of the proposed conceptual framework and provide an opportunity to identify transferrable insights from research of more developed ISNs to emerging ISNs.

4.1. Cocaine

Cocaine trafficking through the Central America ‘transit zone’, including over-land and maritime routes in the Caribbean and eastern Pacific, has risen significantly over the past decade, including an unprecedented 2,976 metric tons in 2016 (USIC 2019). The value of the U.S. cocaine market is estimated at \$37 billion per year, while other markets are growing with the transatlantic cocaine market nearly reaching parity estimated at \$23.7 to \$33.6 billion in 2017 (McDermott et al. 2021; UNODC 2011). The source stage for cocaine is unusually spatially concentrated in Bolivia, Colombia, and Peru (UNODC 2018). Despite significant international efforts at coca eradication, the amount of cocaine produced does not appear to be sensitive to regulation of coca cultivation (UNODC 2018). The transit stage for cocaine is characterized by a collection and processing phase, followed by primary, secondary, and tertiary movements. In the first phase, coca leaves are processed into coca paste, which is further consolidated then processed into refined cocaine. Large stocks of cocaine are then moved into the transit network in primary movements. In some cases, a transshipment point is used where the shipment is parcelized into smaller secondary shipments after arrival. Tertiary movements of cocaine occur as distribution within the consumption market (e.g., among and within European and U.S. cities).

The U.S. government has prioritized supply-side approaches to cocaine trade for fifty years, resulting in an unusually robust government record of those actions plus an equally robust record of critique, which combined allow this to be among the most well-understood ISNs in the world. Counterdrug interdiction efforts in the transit zone have rarely intercepted more than 10% of the known flow (Faller 2019; McSweeney 2020), and the amount of cocaine seized does not have a significant or sustained impact on cocaine prices in the U.S., or on traffickers' profits (Magliocca et al. 2019; Pollack & Reuter 2014).

4.2. Illegal Wildlife Trade

Illegal trade in wildlife is a globally distributed phenomenon (UNODC 2016, 2020). Illegality of traded wildlife varies across supply network stages, according to different species, locations, and methods of take. For example, international trade in rhino horn is illegal, but domestic trade is legal in South Africa. The legal status is unclear and even more complex for different stages of trade in regulated plant species with regard to whether the trade is international versus domestic, or in the form of seeds, live plants, or a derivative. There are very diverse types of actors involved at each stage, ranging from opportunistic to corporate to professional (Phelps et al. 2016). In the case of rhino poaching, both transnational criminal networks and private wildlife suppliers are involved in supplying consumer markets, whereas enterprising actors and existing trafficking networks may facilitate trade opportunistically (Hübschle 2016, 2017a; Rademeyer 2016; Titeca 2018). IWT in less-high profile species (e.g., succulent plants, cacti, lizards) often involves non-violent small groups or individual actors involved in illicit collection and transfer (CapeNature 2015; Margulies et al. 2019a) forming a 'disorganized criminal network' (Wyatt et al. 2020).

The majority of IWT research, policy, and intervention is biased towards charismatic megafauna (e.g., large cats, rhinos, elephants) and focused in source areas in the Global South (specifically Sub-Saharan Africa and parts of Asia) and demand in East Asia (Arroy-Quiroz & Wyatt 2019a, 2019b; Margulies et al. 2019b; UNODC 2016, 2020; Witbooi et al. 2020). However, the United States and Europe also represent major source, consumer, and transit destinations for much of the world's illegally traded wildlife (Margulies et al. 2020; Sina et al. 2016). Poaching, or illegal taking of a plant or animal, differs from trafficking in that it is often considered a 'local' issue occurring within the confines of a country. Source-based interventions include militarized anti-poaching, support for livelihood alternatives, education and communication, policy and regulatory levers, and community-policing (Massé & Margulies 2020). In contrast, transit might cross one or more borders, and interventions, such as coordinated shipment seizures, are relatively limited. Comparatively little inquiry has focused on the transit dimensions of IWT networks. Instead, the focus is on destination interventions (e.g., education, marketing) to reduce demand and the growing application of consumption reduction science (e.g., Hinsley & 't Sas-Rolfes 2020; McNamara et al. 2016; Veríssimo & Wan 2018).

4.3. Illegally Mined Sand

Sand and gravel have become the most widely extracted solid materials on Earth due to infrastructure development and urbanization (Torres et al. 2017). In developing countries, the aggregates industry is dominated by informal artisanal and small-scale mining operations (e.g., with rates of 25–90% of the total sand mining in Fiji, Colombia, Morocco, or Uganda; ACP-EU 2018a, 2018b; Asogravas 2019; UNEP 2019). This sector can employ a large number of workers for whom sand mining can be an alternative or complementary income source. However, the informal nature of the sector might bring challenges such as child labor and environmental degradation (Frank 2020; Hilson 2016). With increased demand and profits, informal mining might turn into illegal/illicit mining operations characterized by higher levels of criminality and sophistication, and tension between illegal miners and local communities. Conflicts due to illegal or illicit mining have emerged in several countries including Morocco, India, Bangladesh, China, Italy, and Cambodia (UNEP 2019). The highest level of sophistication of sand ISNs has been observed among India's multiple, independent 'sand mafias' (Rege 2016), each with their own complete ISN. The processes and parties involved in each ISN stage exist along a continuum of (il)legality (Rege 2016; Rege & Lavorgna 2017). The ISNs are loosely structured around interactions among contractors, politicians, trade union leaders, local officials, and corrupt policemen in a transactional relationship (Mahadevan 2019). However, legal sand mining corporations with permits and equipment can also engage in illegal mining as they try to compete with the sand mafias. Another example where sand ISNs have emerged is in China (Zhu 2020a), where high demand and tight supply coupled with increased mining restrictions have led to price increases of river sand; up to 600% in some cases (Tian 2018). Likewise, numerous cases of illegal dredging by Chinese vessels along the coast, in the South China Sea, and North Korea have been recently reported, with possible links with land-reclamation projects and transnational crime (Lucas & Sung 2020; Sutton 2020).

There are myriad types of sand end uses, but here we focus on natural sands and gravel for construction, representing the vast majority of the volume traded. Local supplies are becoming constrained in densely populated and high-growth regions due to the depletion of resources or mining restrictions, which have led to increasing prices making illicit sand mining highly lucrative. The main stages of the supply network are the source (mining sites), transit (e.g., by trucks or barges), and consumption (e.g., urban construction sites). Demand hotspots are mostly located in rapidly expanding regions with significant new housing and/or infrastructure construction. In contrast, hotspots of extraction extend from peri-urban to rural areas near their markets with lower restrictions or perceived transaction costs. Sand is excavated in pits in river floodplains or beaches, produced from crushing stones (e.g., sandstone, granite), or dredged from shallow coastal waters and active riverbeds. Sand deposits from river and coastal systems are particularly vulnerable to over-exploitation due to its intrinsic characteristics as a common-pool resource: widespread, easy to extract and transport, and difficult to regulate (Torres et al. 2017). Once excavated, the sand is loaded on trucks, each with a typical carrying capacity of 2.5 tons, or barges that can carry significantly larger amounts. Sand can also be stored to manage supply better and adapt for seasonal variations in construction demand (Rege 2016). Regulation and law enforcement focus mainly on the source stage (via patrols, raids, remote sensing, drones), less in the transit stage (e.g., checkpoints), and are almost absent in the demand stage, mainly due to difficulties in distinguishing illegally from legally mined sand. Research on sand ISNs is emerging but still scarce, with studies focused on social and environmental harms (Duan et al. 2019; Hackney et al. 2020; Mahadevan 2019; Rege 2016; UNEP 2018, 2019), describing the *modus operandi* of an ISN (Mahadevan 2019; Rege 2016; Rege & Lavorgna 2017), and testing the response of an ISN to disruption methods (Duan et al. 2019).

5. Comparative Analysis of Diverse ISNs

The following section examines each of the common ISN attributes presented in **Table 1** and identifies commonalities or uniqueness in their manifestations for each type of ISN. Moreover, differences in structural characteristics of each ISN are linked to distinct spatial patterns of activity and *modus operandi* at each stage of the ISN.

5.1. Supply Network Structural Attributes

5.1.1. Number and diversity of supply network actors

Extreme profit potential at each ISN stage, often paired with the disadvantaged socioeconomic conditions in which ISNs operate, ensures a diverse and abundant (and expendable) labor force at each stage. In the source stage, geographic distribution of the commodity's origins and any specialized required skills (e.g., in processing) for sourcing it may constrain the number and/or diversity of supply network actors involved. In the case of cocaine, the number and diversity of actors at the source stage resembles that of a licit agricultural commodity (**Figure 3a**). The majority of coca cultivation is performed by smallholders throughout the growing region. Illegal trade in endangered, charismatic megafauna offers a contrast. Rare, high-value products, such as rhino horn, are concentrated in protected areas, which attracts a large number of actors to geographically constrained locations (**Figure 3b**). On the other end of the spectrum, sourcing for lower profile species that may exist outside of protected areas typically occurs more discretely and opportunistically among many individual actors rather than professional hunters across species' ranges (e.g., live reptile or succulent plant trade, **Figure 3c**; Arroyo-Quiroz & Wyatt 2019a, 2019b; Krishnakumar et al. 2009; Vanderpool 2016). Much of the illegal international trade for cacti, for example, is not in wild collected plants being sold internationally directly from source countries. Rather, plants are reproduced from wild collected material in greater volumes elsewhere, oftentimes in countries with large and legal greenhouse industries (which themselves may also be implicated in illegal trade), which expands the potential number of actors at the source stage (Margulies et al. 2019a). Similarly, natural sands and other aggregates for construction are widely distributed (**Figure 3d**), and mining is done with large amounts of local and/or migrant workers. Furthermore, little or no specialized skill requirements for participation in sand ISNs, making the trade an attractive option relative to other livelihoods, which increases the potential number and diversity of actors in the source stage.

The number and diversity of actors in the transit stage also depends on the potential for parcelization of the illicit commodity. Parcelization is the division of large into smaller quantities of the illicit commodity for the purposes of reducing the risk of lost shipments, evading detection from law enforcement, and/or maximizing profits (Allen 2005). Parcelization potential depends on physical characteristics of the illicit commodity, value to volume ratio, and ease of concealment. Increased parcelization potential increases the

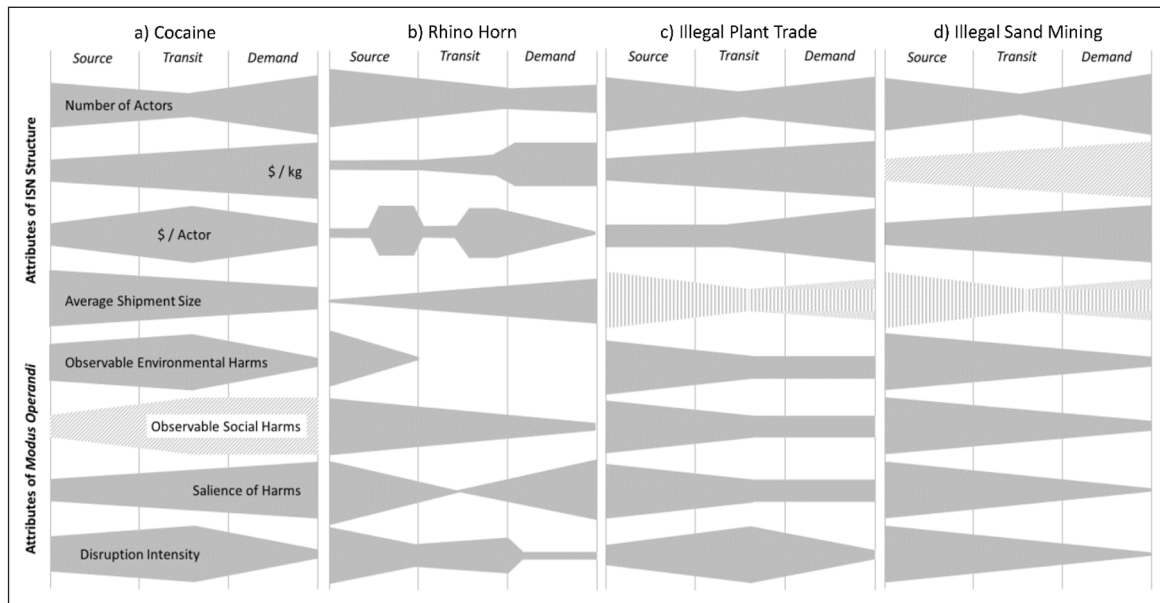


Figure 3: Graphical representation based on expert opinion of illicit supply network (ISN) structure and *modus operandi* attributes at each supply chain stage for cocaine **(a)**, illegally traded wildlife, specifically rhino horn **(b)** and plant trade **(c)**, and sand **(d)**. Thicker sections of the polygons represent higher amounts and vice versa. Polygons filled with solid color indicate higher confidence in attribute descriptions, whereas polygons with cross-hatching indicate lower confidence and higher uncertainty. Inspired by Allen (2005).

number of possible shipments, and thus the potential number and diversity of actors involved in and geographic scope of transit stage operations. For example, far smaller volumes of cocaine can achieve a given level of profit than marijuana, which is much bulkier and lower value, and can be more easily concealed (Magliocca pers. comms.). Thus, the number of ‘mules’ involved in primary movements of cocaine shipments is larger than the number of actors involved in receiving shipments further along the supply chain. For example, secondary shipments through Central America are coordinated by a smaller number of actors in regional drug trafficking organizations (DTOs), known as ‘transportistas’ (Dudley 2010; Magliocca et al. 2019), after which the number of actors further decreases entering Mexico where highly-organized criminal networks control trafficking into consumer markets (**Figure 3a**).

ISNs for wildlife and sand offer a range of congruent and counter examples. Much like cocaine, the high value of some wildlife products (e.g., rhino horns, totoaba bladders, west and south coast rock lobster and abalone) (UNODC 2020; Witbooi et al. 2020) supports export of small quantities, improves concealment, and increases the potential modes and number of actors involved in and geographic scope of smuggling (**Figure 3b**). For example, rhino horn sells for US\$ 12,000 and US\$ 18,000 per kilogram in Vietnam in 2020 (Hübschle & Shearing 2021). Given this high value per volume, rhino horn consignments are usually small, ranging from a few horns up to one or two suitcases of well-concealed horns (Hübschle 2016). However, some instances of convergence with criminal networks with expertise in illicit drug, arms, and timber markets have been moving illegal wildlife products (Hübschle 2016; Hübschle & Shearing 2021), which constrains the number of actors that can be involved. In contrast, much of the value per unit volume in illegal plant trade is highly variable (based on current species trends as well as supply/demand) but generally low, which does not draw as many actors to the transit stage as more high-profile forms of IWT (**Figure 3c**). Many illegally traded yet threatened species do not cost more than US\$ 30–50 dollars per plant, though there are exceptions where prices reach thousands of dollars (Margulies pers. comms.). For the illegal plant trade, parcelization potential is a function of physical characteristics, rather than concealment needs or value per volume ratio. Actors can often successfully move plant products through pre-existing transport channels such as the registered post, parcel couriers, or via personal luggage in air transit at relatively low cost, and much of the illegal plant trade occurs in open online market places and social media platforms connecting international suppliers and buyers (Hinsley et al. 2016; Lavorgna 2014). Finally, parcelization of sand is not common, as the volumes moved are large and difficult to distinguish from licit sources, and there is little need for concealment once the shipment leaves the extraction point. Consequently, the number of actors and value per shipment of illegally mined sand in the transit stage is limited (**Figure 3d**).

At the demand stage, the number and diversity of actors primarily depends on the physical characteristics of the commodity, particularly related to parcelization and storage potential. Once in consumer markets, parcelization of cocaine continues and the number of distributors and retail sale actors increases (**Figure 3a**). Consequently, physical cocaine distribution networks have wide geographic reach. The market for rhino horn is similarly global. Local couriers smuggle rhino horns from the poaching site to major urban centers in southern Africa. From there, international exporters channel rhino horns to seasoned traffickers who move the horn on airplanes to major consumer markets (Hübschle 2016). Distribution of lower-profile IWT may involve a greater diversity of actors (**Figure 3c**), particularly when species or wildlife products are sold in urban and rural locations through physical markets with little law enforcement (Sánchez-Mercado et al. 2016). For example, captive breeding facilities illegally sell wild caught turtles claimed to be captive bred (Mali et al. 2014). For illegally traded plants, which can be propagated by individuals, in-person conventions and trade shows of plant enthusiast groups frequently host illegal transactions, occurring outside the formal confines of the legal gathering or even within it 'under the table' (Flores-Palacios & Valencia-Diaz 2007; Hinsley et al. 2015; Phelps & Webb 2015). In contrast, natural sand and gravel for construction are common bulk commodities with a low value-to-volume ratio and high transport costs (**Figure 3d**), and therefore the source tends to be as close as possible to demanding markets and/or with good transport links (Franks 2020). Consequently, most sand ISNs tend to be domestically oriented with small spatial footprints. However, trade among neighbor countries has also been reported, such as illicit trade between Singapore and countries like Cambodia and Indonesia, which have been widely covered in the media and supported by mismatches in reported exports and imports (Lamb et al. 2019).

When the physical characteristics of the illicit commodity allow for parcelization and concealment in legitimate modes of distribution (e.g., parcel services), ISNs are no longer constrained by direct contact between supplier and consumer. Increasingly, virtual marketplaces are expanding the geographic scope of and number and diversity of actors in the demand stage. For example, virtual drug marketplaces operating on the TOR Network link suppliers and consumers directly, and in some cases, reach beyond the geographic scope of physical supply networks (Dolliver, Ericson & Love 2018). Wildlife ISNs are similarly global in scope in the demand stage and sales are increasingly conducted in virtual spaces. Many illegally sourced and traded wildlife species are sold on the internet via legal auction and marketplace platforms such as Ebay and Etsy or facilitated through social media and peer-to-peer encrypted platforms like Facebook, Instagram, WeChat, or WhatsApp (Harrison et al. 2016; Hinsley et al. 2016; Lavorgna 2014). The 'dark web' is not used as often because illegal trade is easy enough to accomplish in plain sight under different names (Harrison et al. 2016).

5.1.2. Illicit commodity value

The value of ISN commodities derives from the nature of their prohibition and demand. Demand for an illicit commodity may be based on broader economic growth (e.g., sand for construction), luxury or status consumption (e.g., many wildlife products), or cultural importance (e.g., coca, tiger bones). The value of some illicit commodities appreciates over time due to its durability and rarity (e.g., ivory or rosewood) and is thus demanded as an investment (Zhu 2020b). With living illicit commodities, such as reptiles or plants, consumers may pay a premium for live wildlife, which places additional demands on the capture and transport of specimens that can increase their value. On the other hand, if the commodity can be reproduced from original illicit material after the initial sale (e.g., wild plants), then supply can be modified independent of the ISN and depress its value. The nature and persistence of demand will have implications for profit potential, opportunistic versus established ISN organizational structures/actors, and intensity and salience of social and environmental harms. Similarly, the more diverse the buyers or demand sectors for an illicit commodity, the more consistent demand will be in the face of disruptions affecting buyers (e.g., policy or market disruptions). All other contributors to demand being equal, a commodity will fetch a higher price as political and social regulation increase (**Figure 1**) to cover increased risk of law enforcement in production, transportation, and distribution stages (Caulkins et al. 1993; Caulkins & Reuter 1998). For example, increased risk of interdiction leads to a 'risk premium' paid to individual traffickers (Caulkins, Crawford & Reuter 1993; Magliocca et al. 2019), which increases the profits that can be captured in the transit phase.

Similar to legitimate commodities, value is also related to supply and the availability of substitutes. For many IWT commodities, value is directly related to rarity of the species (Courchamp et al. 2006). Hobbyists or collectors typically want the rarest species, and thus value is directly related to the number of individuals remaining in the wild. However, geographic substitutes can somewhat moderate prices. For example, as

rhinoceros numbers decreased north of South Africa, criminal networks started moving south and exploiting different populations (Hübschle 2016). Cocaine provides an even more extreme example. Although the production of coca is relatively limited to a few countries and eradication can be extensive, production locally has a small footprint and can be easily relocated to additional suitable locations if disrupted by law enforcement. In fact, wholesale cocaine prices in the United States have dropped significantly since 1980 despite increased counterdrug interdiction and crop eradication efforts (Rydell et al. 1996; Office of National Drug Control Policy 2001; Pollack & Reuter 2014). Independent of the illegality or illicitness of the commodity, the long-term value of rare commodities can be moderated if there are more source areas than can be effectively policed.

5.1.3. Value captured per actor

Although the demand and consequent value of the illicit commodity contributes significantly to the intensity of its trade, the overall structure and operation of the ISN is more directly related to how the value generated at the point of sale is differentially captured at each stage of the supply network. Value is captured at different stages of the ISN according to control of the means of (re)production and/or distribution, risk of capture by law enforcement, and value-added processing.

In the case of cocaine, value capture per actor is highest in the transit stage where there is a large increase in value and relatively few actors (Allen 2005) (**Figure 3a**). Successful evasion of counterdrug interdiction is the principal way a cocaine shipment increases value, and represents accumulated transit costs (labor, fuel, services) and 'taxes' to move the product through Central America (Dávila et al. in press). Every time a shipment changes hands a trafficker extracts rent by increasing the wholesale price (Allen 2005); the price for a kilogram of cocaine at the Panama-Colombia border is about US\$4,500 (Pearson et al. unpublished data) and about US\$24,000 at the US border. Similar value capture is observed in many IWT commodities, although price structures vary widely depending on the commodity characteristics (e.g., UNODC 2020: 109–134). Although a rhino poacher can earn more than the average annual income in southern Africa through one successful hunting expedition, the final price per kilogram for rhino horn in consumer markets is seven times more than what rhino poachers are paid on average in source countries (Hübschle pers. comm.).² There are relatively few people who have the needed infrastructure and political leverage to transport rhino horn at key points, and the value captured per actor increases at key nodes along the rhino horn ISN (**Figure 3b**). These points involve kingpins that amass rhino horn near the source from hunters for export into consuming countries and distribution to domestic sellers.

In contrast, sourcing of plants for illegal cactus and succulent trade often takes place by foreigners from the global North who may at times pay proportionally small fees to locals able to identify and source target species, which the sellers will then sell for far higher prices abroad (**Figure 3c**) (Margulies et al. 2019a). On the other end of the spectrum, the price structure and value capture of illegally mined sand resemble that of licit commodities with value per shipment and value capture per actor increasing closer to the point of demand (**Figure 3d**). For example, in India profits from sales increase fourfold from source to selling. The actors involved in the mining at the source get very little of the sale profits, with those mostly going to a much narrower number of actors in the points of sale, who buy the sand from transporters and re-sell it to construction companies (Mahadevan 2019). The price increases due to the cost associated with transportation, storage, and bribes to local police and administration officials.

Value-added processing also provides an opportunity to capture value by additional actors. For cocaine, the coca base produced by farmers is processed in hidden and defended processing facilities, which require both capital investment and actors with technical expertise (Dávila et al. in press). Compared to the US\$4,500 per kilogram at the Panama-Colombia border, Peruvian coca farm workers, for example, earn only US\$30 per day (Carranza 2019), indicating a large increase in value at the processing and transit stages. Similarly, value is added to many IWT commodities by transforming the raw product into a consumer good. Rhino horn is often transformed into elaborate artworks, status products, investments, and/or traditional medicine (Gao et al. 2016). The value capture of illegally traded plants, on the other hand, is in part tied to their potential for reproduction post-transit, which differs significantly from many other ISNs. A wild collected individual cactus, for instance, may provide far more value for its capacity to propagate new plants to sell (especially if they are very rare) in comparison to the potential value of selling the original individual alone (Margulies et al. 2019a).

² In 2013, the final price of rhino horn was forty times more than what poachers were paid at the source.

5.2. Supply Network *Modus Operandi*

5.2.1. Social and environmental harms

Illicit commodities that are extracted (e.g., wildlife poaching) or cultivated (e.g., coca) tend to concentrate social and environmental harms in the production/source stage (**Figure 3**). Harms often arise around the extraction and transportation of resources by actors without legitimate user-rights to the resource (e.g., illegal mining in rivers), or when user-rights are granted by corrupt methods (Gore et al. 2019a). Poaching of wildlife leads to immediate declines in populations of already pressured species, loss of biodiversity, and cascading impacts on ecosystems (Nellemann et al. 2016; UNEP 2018). Loss of species to IWT can also translate into loss of income to local communities that rely on subsistence practices (Cooney et al. 2018; IIED & IUCN-SULI 2019; Witbooi 2020), such as hunting, fishing, and/or eco-tourism. Additionally, the militarization of anti-poaching, particularly for high-value and endangered species, such as rhino, has negatively impacted local community and protected area relationships, leading to perceptions that wild animals are more valued than local people and even instances of human rights abuses that further undermine conservation's sustainability in its local context (Duffy et al. 2015; Hübschle 2017b; Hübschle & Shearing 2021; Kahler & Gore 2012; Roe et al. 2015). Rampant illegal mining of sand in rivers, lakes, floodplains, and coastal areas also has adverse effects on the health of aquatic ecosystems, for example by lowering the water surface and groundwater table, increasing suspended sediments and water turbidity, or damaging benthic habitats and fish spawning sites (Cao et al. 2017) (**Figure 3d**). Illegal mining also increases the risk of damages to infrastructure, such as houses, bridges, dams, or roads, due to over-excavation (Hackney et al. 2020). For example, illegal dredging in Lake Hongze, China posed a severe threat to dam integrity and endangered the safety of the 20 million residents and the productivity of the 2000 km² of farmlands in the five cities downstream of the lake (Duan et al. 2019). In addition, illegal sand mining often leads to the displacement of or conflicts with competing land uses, typically fishers (due to declining populations of fish and shrimp) and farmers who cultivate crops in floodplains (Adesina & Adunola 2017; Tetsopgang et al. 2019). Social conflicts have also been observed, such as violence against protestors, environmental activists, or journalists (Beiser 2019). In the case of cocaine, deforestation and negative ecosystem and human health consequences of eradication efforts have been well documented in coca production areas (Bernal et al. 2020; Dávalos, Bejarano & Correa 2009; Dávalos et al. 2011; Rincón-Ruiz & Kallis 2013). In all cases, the corruption of officials and/or law enforcement that accompanies the presence and operation of ISNs undermines social and political institutions, exacerbates existing inequalities, and enables ISN actors to operate with partial to full impunity (Devine et al. 2018; Mahadevan 2019; McSweeney et al. 2018; Wrathall et al. 2020).

Social and environmental harms beyond the source stage have been documented for the cocaine ISN but are less visible for IWT and illegal sand ISNs (**Figure 3**). Social harms associated with cocaine consumption are extensive, including disproportionate incarceration rates (Patten 2016) and overdose rates in the U.S. second only to opioids (Frankt 2018). Social and environmental harms of the cocaine ISN in the transit stage are also extensive. 'Narco-deforestation' has been documented across Central America (Devine et al. 2020; McSweeney et al. 2014; Sesnie et al. 2017; Tellman et al. 2020a) related to trafficking node establishment, territorial expansion of local trafficking groups, and money laundering. This deforestation is often preceded by land-grabbing, which leads to the displacement of smallholders and other community members (McSweeney et al. 2017, 2018). Violence, intimidation, and corruption are used to secure impunity for traffickers, particularly when cocaine trafficking is utilizing protected and conservation landscapes (Magliocca et al. in review; Wrathall et al. 2020). Such features of the cocaine ISN *modus operandi* are also sources and strong predictors of the scope and location of associated social and environmental harms.

5.2.2. Salience of harms across ISNs

The salience, or perceived need for a policy and/or law enforcement response, of social and environmental harms relates to their perceived severity by and proximity to society and cognizant authorities. In the case of cocaine, salience to authorities is highest in the demand/consumption stage (**Figure 3a**). The public health threat and moral hazard associated with cocaine consumption continues to have high salience as a part of the U.S. 'war on drugs', which has motivated military-backed law enforcement efforts – and annual government spending to match – to disrupt cocaine trafficking (McSweeney 2020). IWT has garnered significant attention from the public and conservation organizations in the source stage when endangered charismatic megafauna are involved (**Figure 3b**), due to the genuine threat IWT poses to species survival as well as the visceral images of rhino and elephant carcasses, for example. Recently, IWT has become especially salient with links between zoonotic diseases and human health impacts (e.g., COVID-19) (e.g., Cantlay et al. 2017;

Greatorex et al. 2016; UNODC 2020; World Bank 2019). Both cocaine and IWT ISNs have achieved high levels of salience among the public, policy-makers, and funders through their linking with national security concerns, including proposed links to funding terrorist organizations (Duffy 2016; Gore et al. 2019b; Massé & Margulies 2020; Reuter & O'Regan 2017; Witbooi et al. 2020). Even the illegal mining of sand has reached high levels of salience when linked with organized criminal groups (Rege 2016; Rege & Lavorgna 2017).

In contrast, illicit commodities with decreased visibility of social and environmental harms have lower salience to authorities. For example, the illegal plant trade is not prioritized by enforcement agencies in part due to privileging of animal life over plant life as matter of ethical concern (Margulies et al. 2019a). Additionally, detection in plant trade is made difficult by the inability of customs and border patrol to correctly identify plants and discern between legal and illegal plants in shipments (Hinsley et al. 2015; Lavorgna et al. 2020; Phelps & Webb 2015). Illegally harvested timber, mined sand, and lower profile wildlife species are easily co-mingled with legal sources beyond the source stage (**Figure 3c, d**), which masks the scope of ISN operations due to either limited awareness or difficulties in distinguishing illicit from licit sources (Nellemann et al. 2016). Whether due to value judgements or detection difficulties, low visibility of social and environmental harms translates to low salience among authorities, which influences the scope and intensity of law enforcement efforts to disrupt ISN operations.

5.2.3. Intensity of and response to disruption

Of the three ISNs, cocaine has the longest history of law enforcement disruptions focused on source and transit stages (**Figure 3a**). Given the high salience of cocaine trafficking, investments in counterdrug interdiction efforts have been substantial; for example, US\$4.7 billion was allocated to interdiction in fiscal year 2016, or about 18% of total federal drug control spending (GAO 2017). This pressure has had two main effects on cocaine ISNs. First, increased risk of interdiction leads to a 'risk premium' paid to individual traffickers (Caulkins, Crawford & Reuter 1993; Magliocca et al. 2019), which increases the profits that can be captured in the transit phase. When interdiction risk is lower, longer and fewer cocaine shipment movement and transactions are more profitable, resulting in 'cutting out middlemen' and higher individual value capture. When interdiction risk is higher, more transactions may be required to evade detection (i.e., shorter movements), which depresses individual value capture but increases the number and diversity of actors and geographic extent of the transit stage. The high levels of value captured overall and per actor in the transit phase makes a dynamic and fluid spatial structure financially feasible, which promotes greater modularity and ability to reconfigure network structure when needed.

Second, interdiction has also prompted innovation in and geographic displacement of trafficking methods and routes (Magliocca et al. in review; Magliocca et al. 2019). Innovations in the conveyance methods used by cocaine traffickers to evade detection is well documented, progressing from early uses of fishing vessels and small aircraft (McSweeney et al. 2014; USIC 2015), to more sophisticated self-propelled semi-submersibles, or 'narco-subs' (Insight Crime 2012), and the more recent surge in trafficker exploitation of container ships (Allyn 2019). Such innovation has coincided with the unintended geographic displacement and fragmentation of existing trafficking routes – known as the 'balloon and cockroach effects', respectively (Bagley 2013; Magliocca et al. 2019; Mejia & Restrepo 2016) – into new and more numerous locations. As a result, the Western Hemisphere transit zone for cocaine trafficking has grown from 2 to 7 million square miles between 1996 and 2017 (GAO 1996, 2017), which has enrolled larger numbers of actors and produced social and environmental harms across a broad geographic extent (McSweeney et al. 2014; Tellman et al. 2020a; Wrathall et al. 2020).

Similar innovation and spatial dynamics in response to law enforcement disruptions have been observed in IWT and illegal sand mining ISNs (**Figure 3b, d**). A general shift of elephant and rhino poaching operations into southern Africa has been linked to law enforcement efforts and anti-poaching militarization elsewhere (Hübschle 2016). Spatial displacement of poaching has also been observed at a finer scale where rhino densities are highest, particularly in South Africa's Kruger National Park (KNP). Around 2013–2014, 70% of rhino poachers were believed to enter KNP from Mozambique, but the majority of poaching expeditions shifted to the western boundary of the park in South Africa by 2016 – KNP officials reported increased law enforcement activities close to the Mozambican border as the likely cause (Hübschle 2017b). In the U.S., fish and wildlife agencies believe that the closure of some states to commercial trading of amphibians and reptiles has led to higher exploitation of those species in states where it is still legal or unregulated (Mali et al. 2014). In the case of ISNs for sand, several tactics are used to avoid and/or adapt to law enforcement disruptions. In response to raids/patrols, operations may be shifted temporally (e.g., operating at night, or

weeks after a ban is imposed) and by location (Duan et al. 2019; Masalu 2002), and/or sand may be disguised as other products not subjected to inspections at checkpoints or adulterated to meet demand (Rege 2016). India's sand mafias have invested in cultivating political protection, and thus law enforcement agencies are prevented by both capacity constraints and lack of political support for prosecuting criminal acts. For instance, in return for a kickback, policemen sometimes issue identification markers to transport vehicles to ensure they are not interdicted by their colleagues at checkpoints. Even disruptions to artisanal miners might be orchestrated to concentrate profits in well-connected companies (Mahadevan 2019). Across all three ISNs, disruption by law enforcement tends to induce innovations and/or geographic displacement as an adaptive response.

6. Synthesis

While this synthesis is preliminary and the breadth of ISNs compared necessarily limited, the proposed conceptual framework supported systematic description and explanation of diverse ISNs. Using GCC analysis, many of the apparent differences among these ISNs were traced to differences in the illicit commodities and their implications for network structure, value captured, and spatiality of operations at each stage. Specific commodities have characteristics that impose constraints on ISN structure (e.g., bulk of illegally mined sand; live wildlife), which will always create some divergence among ISNs. However, many commonalities in ISN structure and explanations for *modus operandi* were noted. One such commonality was the role of legality versus illicitness of the commodities moved by these ISNs. For instance, the more illicit the commodity is considered, the higher value per kilogram, potential for parcelization, recruitment of actors, and consequent law enforcement pressures. This suggests a common thread across ISNs: prohibition can be associated with a cycle of increasing illicit commodity value and enrollment of ISN actors and the communities in which they are embedded.

In addition, CAS theory offered a generalizable, causal explanation for differences among ISNs: adaptive behaviors arise through selective pressures in changing environments. In the context of ISNs, law enforcement is the primary selective pressure in the form of interdiction. Relatively nascent and/or low salience ISNs are not typically subjected to frequent or intense law enforcement pressures. More established, organized, and/or high salience ISNs tend to have a history of co-evolution with law enforcement efforts. For example, the current spatial extent and *modus operandi* of the cocaine ISN has been explained through the application of CAS theory as the result of adaptations to recurrent law enforcement disruptions (Magliocca et al. 2019). Across all three ISNs, the more intense and/or impactful the regulation and law enforcement disruption, the greater potential for illicit profits and subsequent geographic dispersion of associated social and environmental harms. Similarly, the lower the law enforcement pressure, the closer ISN structure resembles licit counterparts, and divergence increases with adaptations to law enforcement disruptions. Since spatial and temporal relocation and displacement of illicit activities are primary adaptive behaviors to and unintended consequences of law enforcement, respectively, an ISN's geographic diversity and spatial extent are proxies for ISN maturity or history of interdiction and resilience of the network. Leveraging these comparative insights across ISNs, possible changes in the structure and function of currently nascent and/or low salience ISNs may be *anticipated* if conditions or law enforcement pressure change.

7. Conclusions and Future Research Directions

The policy implications of these insights seem clear: despite the diversity of commodities and ISN attributes compared, social and environmental harms inflicted by the illicit activity often become more widespread with increasing law enforcement disruption (Greenfield & Paoli 2012; Keefer & Loayza 2010). All of the ISNs examined were associated with both social and/or environmental harms, deemed criminal or socially unacceptable, and have resulted in their socially regulated, illegal, or illicit status. However, wildlife and sand ISNs generally concentrated harms in the source stage, particularly environmental harms, whereas harms were uniquely widespread for the cocaine ISN. Prolonged and intense law enforcement pressure on cocaine trafficking networks is a major difference among the ISNs compared. This suggests the need for alternative approaches to ISN disruption. In source/production locations, approaches that support livelihood diversification as an alternative development strategy to illicit economies show promise (Gillies et al. 2019; Wennmann et al. 2021). Other strategies might include those that focus on dynamics external to the spaces through which the illicit commodities themselves pass. Law enforcement might focus more on the organizational superstructure that sustains the movement of these illicit goods, such as illicit financial flows, criminals' wealth holdings, and corruption of public officials (GCDP 2020; UNODC 2019; Walker

2020). Many of these operate ex-situ to the spaces of commodity flow and may be less likely to have spatially embedding effects. Besides law enforcement, in situ interventions, such as community-led initiatives, have been used to tackle illegal wildlife trade in different ways (IIED & IUCN-SULI 2019; Reid et al. 2019; Roe et al. 2020). Successful initiatives have commonalities like shared management rights and fair and equitable benefit-sharing (UNODC 2020).

Further application and testing of this comparative framework is needed and presents the opportunity to consolidate knowledge across diverse ISNs. In particular, we highlight three potential future research directions:

1. *Convergence of ISNs with licit supply networks and among multiple ISNs.* ISNs are a relatively recent focal area for funders, and there are stated beliefs that: a) the supply of multiple illicit commodities can converge in the same ISN; and b) ISNs operate in ways similar to licit supply networks (National Science Foundation 2020). Comparative analysis can confirm or contradict these beliefs for specific ISNs, and if the latter, suggest why significant differences exist. Following the common attributes and structural characteristics presented here, the structure and function of licit supply networks can serve as a null hypothesis against which differences in ISNs can be systematically compared.
2. *Conditions for ISN emergence.* A consistent similarity among the ISNs compared is the pervasive and substantial inequality that exists in source locations. In all cases, the relative deprivation in socioeconomic standards and livelihood alternatives creates vulnerable populations that are easily exploited by ISN actors. This observation is consistent with theories of criminogenic asymmetries in which economic, cultural, and regulatory inequalities arising from globalization are generators of illegal flows (e.g., Albanese 2020; Passas 1999). Synthesizing these research threads with our proposed comparative framework can add spatial specificity to analyses of criminogenic asymmetries as conditions necessary for ISN emergence and link those conditions to ISN structure and *modus operandi*, characteristics of the commodity, and spatial dynamics throughout all phases of the supply network. For example, within a supplying country or region with strong criminogenic asymmetries with locations of market demand (e.g., Arroyo-Quiroz & Wyatt 2019a), specific supply network characteristics (e.g., value capture per actor) and law enforcement pressures may predict in what spaces ISNs may emerge to evade detection and whether local community members are enrolled or successfully resist. With increased spatial specificity, such predictions may also anticipate or be validated against the occurrence of observable environmental and social harms. Also, as ISNs emerge and adapt to changing conditions, such a perspective could investigate whether there are common trajectories as they mature? Comparing ISNs at different stages of maturity seems a productive approach to answer this question.
3. *The value of knowledge consolidation across ISNs.* The three-stage structure of the comparative ISN framework is a useful guide for collecting, consolidating, and sharing data and communicating knowledge about diverse ISNs. Currently, ISN data including prices, seizures, and law enforcement activities are fragmented and rarely integrated (Tellman et al. 2020b). Consolidating and structuring data within a common framework can open opportunities for database interoperability and synthesis and can guide identification and prioritization of data collection efforts. In particular, there is generally a paucity of ISN data relating to the transit stage, yet such data is critical for connecting existing knowledge of ISN operations from source through demand stages.

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Competing Interests

The authors have no competing interests to declare.

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