Towards spatially disaggregated cocaine supply chain modeling

Abstract

Despite the global reach and economic scale of cocaine trafficking, our best geographic understanding of the global trade remains coarse. A more spatially disaggregated understanding of how the cocaine supply chain embeds across multiple locations is necessary for informing security policies and anticipating the spread and intensity of social and environmental harms associated with the cocaine trade. In this research, modeling methods used for legal supply chains are adapted to spatially disaggregate illicit supply chain flows. Profit and supply maximization model versions were compared to elucidate key decision parameters cocaine traffickers might be facing. Cocaine flows to EU+3 (Norway, Turkey, and United Kingdom) markets were estimated based on the smuggling capacity of major Central American ports and bilateral trade volumes of selected commodities most often seized with cocaine shipments. The resulting estimates of cocaine volumes diverted to EU+3 countries from Central America ranged between 938 and 1526 metric tons (MT). Generally, easier concealment and storage in Central America led to less volume supplied to the United States (US) and increased shipments to EU+3 markets. Importantly, the value of this modeling approach is not in the quantitative estimates produced, but in the methodological approach that provides the ability to rigorously ground *any* quantitative estimates of clandestine phenomenon in the best available data.

Keywords: illicit supply networks, globalization, drug policy, container shipping

1. Introduction

The transnational cocaine trade has transformed over the last decade to become increasingly global in geographic and economic scope. The estimated retail value of illicit drug markets has increased from US$322 billion in 2003 (United Nations Office on Drugs and Crime (UNODC), 2005) to US$426 to $652 billion in 2017 (Yansura and Kumar, 2020). Additionally, while the value of the US cocaine market is estimated at US$37 billion per year, other markets are growing, with the transatlantic cocaine market nearly reaching parity at an estimated US$23.7 to US$33.6 billion in 2017 (United Nations Office on Drugs and Crime (UNODC), 2011; McDermott et al., 2021). Despite the global reach and economic scale of cocaine trafficking, our best geographic understanding of the global trade remains coarse, often limited to national statistics (European Monitoring Centre for Drugs and Addiction, 2019) and stylized depictions of smuggling routes (Boekhout van Solinge, 2022; UNODC, 2020; McDermott et al., 2021). A more spatially disaggregated understanding of how the cocaine supply chain embeds across multiple locations is necessary for informing security policies and anticipating the spread and intensity of social and environmental harms associated with the cocaine trade (Dávila et al., 2021; Devine et al., 2021; Tellman et al., 2021; Anzoom et al., 2024). This article addresses this research gap with a new approach for spatially disaggregated modeling of illicit supply chain flows through the adaptation of operations research methods for modeling and analyzing legal supply chains.

Current approaches to mapping illicit supply networks lack the spatial and temporal resolution needed to provide actionable insights (Magliocca et al., 2021). Social micro- or individual-level network approaches to analyzing drug trafficking networks leverage qualitative information that identifies influential actors and their links to other actors in criminal networks (e.g., (Bright and Delaney, 2013; Ferrara et al., 2014; Alzaabi, Taha and Martin, 2015; Bright, Rose and Urban, 2016; Calderoni et al., 2017; Bright et al., 2019). The strength of this perspective is its focus on the actors directly executing illicit supply chain logistics, as the spatiality of illicit supply chain operations can be inferred from the geographies of the actors and their relations (Anzoom et al., 2021). However, the origins of connections between actors may be highly idiosyncratic (i.e., familial connections), which are difficult to generalize and scale up to the transnational scope of many illicit supply networks. Conversely, macro-level network approaches utilize fragmented but widely available law enforcement information (i.e., seizures), media and investigative journalism reports, or non-governmental information sources (e.g., Boekhout van Solinge, 2022; McDermott et al., 2021). The strength of this approach is that network analyses are based on high-confidence observations of illicit activity and often with temporal and geographic (albeit typically coarse) specificity. Despite the well-known biases of drug seizure data, which better reflect law enforcement rather than illicit activities (Barratt and Aldridge, 2016; Enghoff and Aldridge, 2019; Magliocca et al., 2022), the broad availability of drug seizure data makes it appropriate for use with network analysis tools at a transnational scale. However, these analyses are typically limited to country-level seizure and consumption data and assume that illicit supply operations are homogeneous within countries. This is demonstrably not the case, as illicit supply network actors rely on targeting locations of weak governance, officials that can be easily corrupted, and/or geographies that otherwise reduce transaction costs (e.g., labor supply, access to transportation infrastructure, lax security) (Basu, 2014; Magliocca et al., 2022). Due to these limitations, illicit supply network maps are typically more like stylized diagrams with large, vaguely placed arrows symbolizing flows, rather than a truly grounded depiction of the spaces through which illicit goods move. Consequently, the actionability of insights from aggregate analyses of supply networks is significantly reduced (Godar et al., 2015).

More importantly, aggregate analyses of illicit supply networks cannot address a core question facing US and international drug policy: given a transit space with uneven attractiveness, how do transnational drug traffickers adaptively respond to law enforcement pressure? History has shown that drug traffickers respond to disruptions from counterdrug interdiction by spatially reconfiguring and diversifying their trafficking routes and methods of concealment (Caulkins, Crawford and Reuter, 1993; Bright et al., 2019; Magliocca et al., 2019; Kosmas et al., 2023). Understanding the mechanisms driving these adaptive dynamics requires a holistic and disaggregated view of the cocaine supply chain. In addition to the arguments for disaggregation made above, there is a clear need to understand the spatial contingencies and specific geographic characteristics that render certain locations more attractive for drug trafficking activities than others (Basu, 2014; McSweeney et al., 2017; Tellman et al., 2021; Magliocca et al., 2022). A holistic view is also essential to understand how different parts of the supply chain influence and are influenced by one another. The effects of market diversification on the entire supply chain, particularly on new spaces for smuggling routes and innovation in smuggling methods, are not fully understood. For example, recent growth in European and Asian markets has certainly redistributed cocaine shipments to more diverse end destinations. This may also create incentives or pressures for restructuring the upstream transshipment phases of the supply chain (i.e., within Central America), which were previously oriented toward the North American consumer markets. New spaces of logistical importance may be created, and existing transshipment locations may change or diminish in importance.

To answer these questions, an approach is needed that links the *modus operandi* of illicit supply network operations with spatially disaggregated and embedded factors influencing supply network performance. The next section describes a convergence between conceptual advances in illicit supply network research and operations research-based supply chain modeling techniques to advance illicit supply network modeling. Next, we provide an empirical example application to modeling the northbound cocaine supply chain and the growing transatlantic trade. In section 4, we present the cocaine supply chain model formulation as a network flow problem. In section 5, we present numerical results and insights for the Supply Maximization and Profit Maximization models. In section 6, we present a sensitivity analysis on the model parameters and discuss their impact on the results. Finally, Section 7 concludes with a summary of our findings and insights.

2. Conceptualizing disaggregated illicit supply network modeling

Diverse approaches exist to modeling illicit supply networks from a supply chain perspective (see reviews by Smith and Song (2020), Anzoom *et al.* (2021), and Keskin et al. (2022)). Approaches that focus on supply chain dynamics and performance are best suited to spatially disaggregated modeling due to their (often implicit) consideration of spatial relationships among supply chain nodes. We use the categorization synthesized by Anzoom et al. (2021) for describing illicit supply chain performance, which draws on traditional supply chain performance factors (Chopra and Meindl, 2019) and additional features specific to illicit supply chains (Anzoom et al., 2021, 2024; Basu, 2014). Of the ten categories described by Anzoom et al. (2021), we focus specifically on the five (facilities, inventory, transportation, concealment, and corruption) that are most relevant for disaggregating and spatializing the smuggling phase, which is functionally equivalent to logistics in legal supply chains (Anzoom et al., 2021) and constitutes a core competency of illicit supply chains (Basu, 2014). Conceptually mapping these supply chain features onto the realities of illicit supply networks provides a framework for implementing existing supply chain modeling techniques in a novel context.

Facilities are defined broadly in legal supply chains as any entities and their locations that mediate supplier-buyer interactions, including the provisioning of raw inputs, value-added processing, storage, or other services (Stevens, 1989). In the context of the smuggling phase of the cocaine supply chain, facilities take the form of transshipment 'nodes' in which cocaine shipments and payments exchange hands *en route* to the retail market (Dávila et al., 2021; Magliocca et al., 2021). Consistent with legal supply chains, geographic factors influence facility location decisions based on cost considerations and disruption risks. The location of illicit supply network nodes additionally depends on favorable trade-offs between security and efficiency (Morselli et al., 2007; Basu, 2014). For example, Zhao (2019) found that manufacturing facilities involved in the supply chain within China for precursor chemicals for narcotics were geographically concentrated in border provinces and rural settings. Similarly, Magliocca et al. (2022) found that spaces of contested land governance, particularly protected areas and Indigenous territories, were targeted by cocaine traffickers in Central America after law enforcement pressure.

Similar to legal supply chains, mismatches between supply and demand must be managed through efficient allocation and storage of goods or *inventory*. For example, illegally mined sand controlled by one or more of India's 'Sand Mafias' can be stored to better manage supply and adapt to seasonal variations in construction demand (Rege 2016). Additionally, illicit goods may need to be stored to allow time for 'cooling off' to avoid detection by law enforcement (Johns and Hayes, 2003). Similarly, five tons of cocaine awaiting shipment to the Netherlands were seized at Costa Rica's port of Limón (Bargent, 2020). Such large volume shipments must likely be aggregated over time, which requires innovative inventory management by traffickers (McSweeney, 2020).

Facilities, as both transaction and storage locations, are closely tied to access to *transportation* infrastructure. The modes and routes chosen for transporting illicit products depend on the balance of profit and risk, which together constitute the main transaction costs in illicit supply networks (Anzoom et al., 2021; Basu, 2014; Magliocca et al., 2019). Additionally, the location and number of transshipment points influence the profitability and risk of detection. In the case of transatlantic cocaine smuggling in shipping containers, infiltration of the formal export system enables the global export of illicit goods, provides legitimate business fronts to conceal smuggling activities, and reduces transaction costs associated with the transportation of drugs (McDermott et al., 2021). For example, Costa Rican authorities raided two pineapple exporting companies in 2018 that acted as fronts to hide cocaine in apparently legitimate shipments of pineapple, cassava, and other products (Ministry of Public Safety Office of Public Relations and Press, 2018; Bargent, 2020). Numerous other examples of organized crime's infiltration of formal transportation and export infrastructure exist, including oil palm plantations and cattle ranching in Guatemala and Honduras (Devine et al., 2020, 2021; Tellman et al., 2021; InSight Crime, 2022) and Colombia (Ballvé, 2019). Transportation is thus central to smuggling and transportation choices will depend heavily on the other four factors' effects on transportation costs.

In addition to strategically locating smuggling routes, *concealment* strategies drive the performance of illicit supply networks. Risk of detection and its influence on transaction costs drives the concealment ingenuity of smugglers (Caulkins and Reuter, 2010; McDermott et al., 2021). The transaction cost, however, greatly depends on concealment ingenuity (Reuter 2002). There are multiple risks involved in deciding the type of transport to use. When formal transportation infrastructure is used, sophisticated concealment is required to minimize detection risk, resulting in higher transaction costs. For example, illicit products are often intermingled with or hidden in licit goods, such as shipping containers, cars, livestock, or people. However, transshipment via trafficker's private resources (e.g., go-fast boats or semi-submersibles) require less attention to concealment (Basu, 2013). Nevertheless, the concealment method of choice depends on the relative costs of implementation relative to the costs incurred by law enforcement for detection (Basu, 2013); detection risk decreases and profitability increases when the latter exceeds the former (Anzoom et al., 2021). For example, concealing drugs in car engine parts and panels, filling hollow candles with marijuana, or using human mules for body packing methods can be time-consuming and expensive for smugglers, but the difficulties and costs of detection by law enforcement make such methods highly successful for international drug traffickers (Grillo 2012; Traub et al. 2003).

When strategic transportation and concealment methods are not sufficient, *corruption* of law enforcement and governing entities creates a competitive advantage for operating in a particular space since "it allows [smugglers] to use cost-efficient transportation routes, enjoy lenient or no inspection, and protect territorial integrity (Michael, 2012)" (Anzoom et al., 2021: 17). Moreover, corruption is one of the major factors in escalating interdiction incompetence, especially among US partner nations with poor law enforcement authorities (Reuter and O'Regan, 2017; United States General Accounting Office, 2017; Yansura and Kumar, 2020). Smugglers develop links with actors connected to boating, fisheries, customs, transport, and logistics departments to bribe and facilitate the concealment of illegal goods with legal commodities. For example, in the 1980s, almost 10% of Miami's police force was suspected to be under the influence of drug corruption and was fired (Basu, 2013). Corruption is critical for the prolonged operation of illicit supply networks in any given jurisdiction. Bribery, while presenting a short-term cost, is key to ultimately lowering long-term transaction costs by reducing security risks (Basu, 2014; Shelley, 2018; Magliocca *et al.*, 2021).

3. Example application: Transatlantic cocaine smuggling

Modeling motivations and objectives

Applying the conceptualization articulated above, this research adapts the standard approach of network flow modeling used to model transnational trade for various legal commodities in the operations management literature (Chopra and Meindl, 2007) to describe and quantify the transatlantic cocaine supply network. This approach can determine a possible allocation of commodity flows among alternative routes in a supply network. However, insights from the study of illicit supply networks, criminology, and economic geography were used to modify the standard modeling assumptions to deal with the clandestine nature (and associated data gaps) associated with the transnational cocaine trade.

The focus here is modeling northbound cocaine flows through 'transit zone' countries to international consumption markets. Transit zone (TZ) countries included Belize, Costa Rica, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, and Panama. The models do not begin the supply chain model from production countries (i.e., Colombia, Bolivia, Peru), as is typical in legal supply chain modeling, because the conversion between hectares of coca cultivated, volume of coca paste produced, and volume of final product (cocaine hydrochloride (HCL), the most common form of cocaine) produced is highly uncertain (UNODC, 2020). These specific countries were chosen based on the best available cocaine (HCL) flow estimates from the Consolidated Counterdrug Database (CCDB) (McSweeney, 2020) and in-depth analysis of seizure reports from official and new media reports. Consumption markets of interest included the United States (US) and the European Union+3 (EU+3) countries (Belgium, France, Germany, Greece, Italy, Netherlands, Norway, Portugal, Spain, Turkey, and the United Kingdom) that have been reported to receive direct transatlantic cocaine shipments (McDermott et al., 2021). Starting with the estimated volumes of cocaine in each TZ country that arrived from South American producing countries (i.e., *primary shipments*), these models describe subsequent transshipments among TZ countries and the US and transatlantic shipments to the EU+3.

Since cocaine is an illicit substance with a high addiction rate, two possible objectives of the cocaine supply network were considered: maximizing supply to target markets (e.g., growing demand in the EU+3 markets) or maximizing profits. These objectives allowed for alternative versions of the flow model, named Supply Maximization and Profit Maximization. These alternative models fundamentally differed in the flow allocation criteria. The Profit Maximization model considered geographically varying wholesale prices, monetary transaction and transport costs, and volume losses from seizures, while the Supply Maximization model ignored monetary costs or profits. Instead, in the Supply Maximization model, the volume of the cocaine that arrived in target markets was maximized through minimum friction routes that minimized seizures at each stage of transport. The outcomes of these alternative model versions were then compared to provide insights into the possible structure and functioning of the transatlantic cocaine supply network.

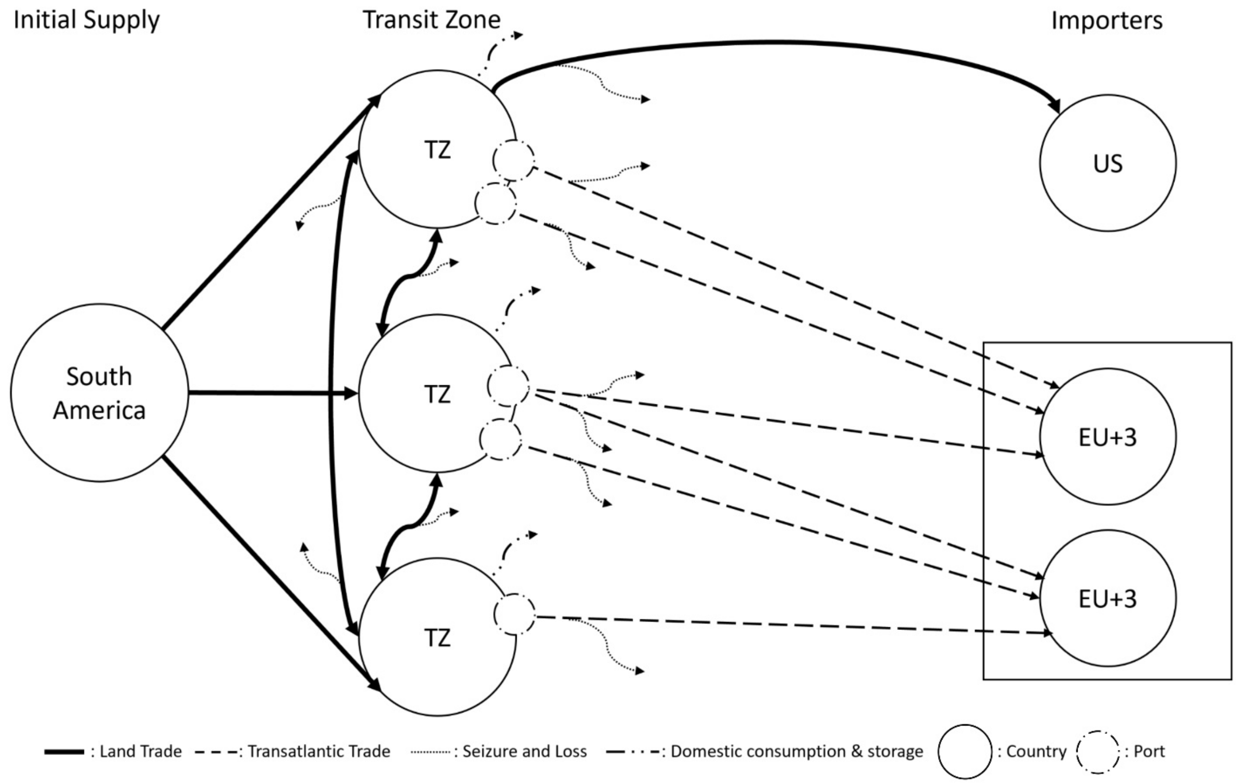


Figure 1. Conceptual model of cocaine supply chain structure linking primary shipments from South America , secondary shipments among 'transit zone' (TZ) countries, and consumption markets in the United States (US) and European Union plus the United Kingdom, Norway, and Turkey (EU+3). Seizures and losses (S&L) of cocaine shipments occur at ports or through over-land reallocation within TZ countries. Storage occurs only in TZ countries.

A conceptual overview of the model is provided in Figure 1. The initial cocaine supply coming from South America (i.e., *primary shipments*) is distributed among TZ countries based on estimated port security characteristics, cocaine trade capacities, transactions costs, and minimum cocaine demands in targeted markets. *Primary shipments* were then divided into transatlantic shipments to EU+3 destinations and shipments reallocated among TZ countries (i.e., *secondary shipments*). *Secondary shipments* are either moved to other TZ countries to utilize additional trade capacity to EU+3 countries, sent to the US via Mexico, or stored in the destination TZ country for later shipment to EU+3 countries. The total amount received by an EU+3 country was between the minimum estimated consumption for each EU+3 country and the maximum total import capacity of that country. While there is no upper limit for US consumption, a lower limit was set to a conservative estimate of US consumption (Table 1). Storage within TZ countries was determined by comparing the storage loss rate (SLR) of the shipment for later export against its current value sent to either EU+3 or US markets net of transaction costs. A TZ country cannot store more than its total cocaine trade capacity. Seizures were approximated using annual probabilities related to security parameters and transportation costs among TZ countries.

The following subsections provide more detailed descriptions of the assumptions necessary to adapt the conventional supply network flow modeling framework and fill data and understanding gaps for the cocaine trade. The model is formulated as a linear programming (LP) model, implemented in Python, and solved using Gurobi 9.1.2.

Port security parameters

Port security was an important influence on supply chain performance. Individual port characteristics, such as location, harbor depth, controlling channel depth, anchorage depth, maximum vessel size, and the presence of US civilian/military representative, were obtained from the World Port Index (WPI; NGA, 2019). Information for ports that were not included in the WPI but could accommodate Panamax vessels was collected through targeted searches for each port in transportation professional news sites Transport Topics (2019) or the MarineTraffic (2019) ports database. The probability, P_i, of a cocaine shipment being detected and seized at port i was estimated as:

$$P_i = 0.02\ SI + \frac{P_{global}}{\left(1+P_{global}F_i\right)^{0.1}} \quad (1).$$

The port security indicator, SI, was a binary value representing the presence of a US representative, provided in the WPI dataset, or whether the port was enrolled in the Container Security Initiative (CSI; USCBP, 2019a). The maximum average percentage of containers searched, P_{global}, was assumed to be 10%, which was then adjusted downward based on the average annual twenty-foot equivalent unit (TEU) throughput, F_i, of port i. Ten percent was considered a conservative estimate as reported scanning rates are considerably lower (e.g., about 4% of all containers in the US (American Journal of Transportation, 2021)). However, shipping containers sent to Europe from TZ countries can be flagged by authorities to undergo additional security screening (EMCDDA, 2016), which could bias the scanning of these containers upward. Each port's probability of seizure was normalized to a range of 0.03 and 0.07 (i.e., a port with SI = 1 would have a minimum probability of 0.03) to ensure comparability with the minimum probability of seizure at the US border. This range was chosen abductively based on our understanding of container smuggling strategies and data-driven values for each port. Given the expanse of the US-Mexico border, the number of cocaine shipments, and the relatively low interdiction rate at the border (1.2 MT reported in FY2018 compared to 145 MT consumed in the US in 2016; (USCBP, 2019b)), cocaine trafficking northward across the US border has been persistent and prevalent for many decades and can be considered low risk relative to newer transatlantic routes. The probability of seizure was implemented as a percent loss of shipment volume at each port representing the port-specific risk of seizures.

Estimating trade capacities

Agricultural commodities are a frequent choice for concealing cocaine in shipping containers because they typically clear customs faster due to perishability and are major exports of the transit zone countries (EMCDDA, 2016). Based on a series of assumptions about the trade volumes of selected agricultural commodities and a survey of shipping container cocaine seizures (Figure 2), we estimated the cocaine trade capacities for specific ports within each TZ country that trade with EU+3 importer countries. First, bilateral commodity trade flows between TZ countries and EU+3 importers were obtained from the Observatory of Economic Complexity (OEC) (2021) for the Dominican Republic and Haiti and Food and Agriculture Organization (FAO) of the United Nations (2021) for all other TZ countries. Bilateral trade flows for banana, pineapple, other fresh produce, and coffee were specifically extracted and aggregated for each TZ country to calculate their proportion of all country exports to EU+3 trade partners. These specific commodities were targeted because they were economically important exports for most TZ countries to EU+3 countries, and thus commodity-level trade data was available for these commodities for all TZ countries.

Additionally, we collected and analyzed 219 news media reports of transatlantic cocaine shipments that were seized but destined for EU+3 countries. These reports provided information about the contents of shipping containers in which seized cocaine was smuggled. See Supplemental Information 1 for a description of methods used to identify relevant articles. As a result, we estimated the volume of targeted agricultural commodities as a proportion of total trade flows, which was converted to the estimated number of TEU shipping containers by dividing by the approximate shipping tonnage of an 8.5-ft TEU container (32 MT).

Next, annual data for bilateral TEU shipping container flows between specific exporter-importer ports (MarineTraffic, 2019; NGA, 2019; Transport Topics, 2019) were summed for each country. An estimate of country-level, bilateral TEU flows for targeted commodities was then calculated as the product of the proportion of each country's targeted commodities relative to total trade flows (i.e., all traded goods shipped in containers) and bilateral TEU flows between TZ exporter and EU+3 importer countries. Each TZ country's cocaine trade capacity was then estimated as the sum of country-level TEU flows of targeted commodities and an average smuggled volume of cocaine per TEU of 0.018 MT. This volume was estimated by dividing the average volume of transatlantic cocaine seizures from shipment containers as reported in our news media database (see Supplementary Material 1) by the total number of TEUs between all trade partners considered. The resulting figure was then increased by 100% as a conservative estimate to account for known underestimation biases in seizure data (Magliocca et al., 2021) and the smuggling of cocaine in shipments of commodities other than those most frequently reported (e.g., raw materials).

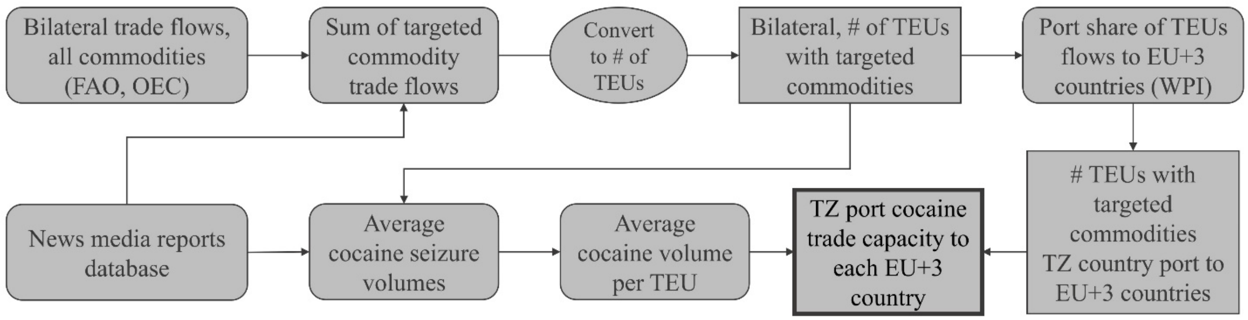


Figure 2. Workflow and data conversions used to estimate shipping container volumes with target commodities and overall cocaine trade capacities (i.e., square boxes) between transit zone (TZ) countries and EU+3 markets.

Transaction and transport costs

In addition to losses incurred at TZ country ports, additional losses were possible due to port transaction costs, storage losses, transportation costs among TZ countries, and seizures between TZ countries. Port transaction costs represented the costs of bribing port personnel, administrators, or government officials (Basu, 2014; McDermott et al., 2021). Corruption is essential to ensure the smooth operation of loading, concealing, and retrieving containers used to smuggle cocaine. To approximate the transaction costs associated with bribery, a normalized value between 0 and 1, termed the *corruption coefficient*, was assigned to all ports in a given country based on that country's Corruption Perceptions Index (TI, 2019) value. This value was then used to adjust the per MT port corruption payment (Table 1) to estimate a monetary transaction cost for each port. Losses were also incurred when cocaine shipments were stored in TZ countries. Storing shipments increases the risk of detection, but it may also be necessary to aggregate sufficient volumes of cocaine to fulfill buyers' demand and make container smuggling worth the risk (McDermott et al. 2021). To account for those losses, the SLR parameter was assigned such that it reflected physical losses that might occur during storage either from detection or additional domestic consumption. The SLR was experimentally varied to test its effect on transatlantic flows.

Redistribution of cocaine shipments among TZ countries – for example when trade capacity was reached in a given country and additional capacity was available in another country – incurred losses related to the shipment volume and distance of transport. A cost of $4.46 per kg/km (Magliocca et al., 2019; Pearson et al., 2022) was assigned to transnational redistributions using the minimum, straight-line length of each TZ country as the transportation distance. Transport costs only applied to the profit maximization model. Seizures of cocaine shipments moving between TZ and/or to the US were implemented using the same normalized range as the security parameters (0.03 – 0.07) so that the highest risk was associated with transport from Panama to the US, and movement to adjacent neighbors was associated with the lowest risk. Shipment volumes were then reduced due to seizures by the corresponding percentage.

Cocaine supply and demand

The total supply to TZ countries was equal to primary shipment (i.e., bulk shipments from South America source countries to TZ countries) volumes reported in the CCDB (McSweeney, 2020). Domestic consumption was parameterized based on high-end estimates for Central American countries and US consumption based on prevalence of cocaine use data from ONDCP (2018) and Bernal et al. (2020). Domestic consumption values served as minimum supply constraints for each respective country. Only regional estimates were available for TZ countries, and we assumed 5% of the total supply to each country goes to domestic consumption. The minimum supply (e.g., domestic consumption and seizures) to North America was assumed to be 311.35 MT (US = 258.93 MT; Canada = 17.3 MT). A 5-year average (2015-2019) for the prevalence of cocaine consumption among target EU+3 countries was calculated based on estimates derived from wastewater analyses (EMCDDA, 2019). Minimum cocaine demands were then assigned to each EU+3 country based on the relative prevalence of cocaine use per country as a proportion of the total estimate in EU+3 countries in 2017 of 190.34 MT (EMCDDA, 2021).

A summary of parameter values used to implement the supply chain model is provided in Table 1. It is worth noting that multiple (and sometimes quite disparate) estimates may exist for these parameter values, particularly for consumption estimates, and observed values change over time. Only single values are implemented here since the goal of this modeling exercise was to formalize northbound and transatlantic cocaine flows through and out of the TZ to develop plausible scenarios, and to more broadly document the methodology of implementing licit supply chain modeling techniques to illicit goods.

Table 1. Single value parameters used to estimate supply chain flows and costs.

Parameter	Value	Description	Source
Average retail cocaine purity	0.56	Average estimated retail cocaine purity in 2017.	DEA (2017)
U.S Consumption	258.93 MT	Minimum estimated volume of cocaine at 56% purity consumed in the U.S. in 2016.	ONDCP (2018)
Canada Consumption	17.3 MT	Minimum estimated volume of cocaine at 56% purity consumed in Canada in 2016.	ONDCP (2018)
EU Consumption	190.34 MT	Minimum estimated volume of cocaine at 56% purity consumed in the EU in 2017.	EMCDDA and Europol (2016)
Transit zone countries domestic consumption rate	0.05	Estimated prevalence of cocaine consumption in transit zone countries; assumed proportion of cocaine flows that were consumed in-country.	Bernal et al. (2020)

U.S. Border Seizures	1.232 MT	Reported volume of cocaine seizures at the U.S. border in fiscal year 2018.	USCBP (2016)
U.S. Security Parameter	0.03	Conservative estimate of probability of seizure entering the U.S. based on minimum consumption volume and U.S. border seizures.	Calculated
P_{global}	0.10	Maximum proportion of containers searched globally; adjusted downward for specific ports based on TEU throughput per port.	American Journal of Transportation (2021)
Port Corruption Payment	$10,000	Maximum per MT payment to bribe port personnel; adjusted downward with higher corruption index values.	Navarrete Forero (2019)
Average smuggled cocaine volume per container	0.018 MT	Calculated as the average volume of transatlantic cocaine seizures divided by the total number of TEUs between all trade partners considered, and then doubles to account for underreporting and alternative commodities involved in smuggling that were not considered.	Calculated
Transnational redistribution costs	$4.46 kg/km	Per kilo and kilometer transport cost for redistributing cocaine shipment among transit zone countries.	Magliocca et al. (2019); Pearson et al. (2022)

4. Cocaine Supply Chain Model Formulation

A cocaine supply chain model was formulated to represent flows from TZ countries to the US and EU+3 based on empirical data from 2017. An abstract network representation of the model is provided in Fig. 1. Due to the challenges of equating areas of coca production to volumes of cocaine (UNODC, 2020), our supply chain formulation begins with the initial volume delivered to TZ countries based on flows reported in the CCDB (Table 2). Cocaine wholesale prices in target countries (US, EU+3) were used to estimate relative profit levels among possible destinations (Table 3).

Table 2: Supply and Trade Data of Transit Zone Countries (metric tons).

Country	Supply from S. America (*MT*)*	Total Trade Capacity (*MT*)
Guatemala	920.92	115.67
El Salvador	6.95	5.60
Belize	1.48	39.97
Honduras	129.81	145.25
Nicaragua	21.59	45.21

Costa Rica	450.57	1219.72
Panama	445.41	128.91
Mexico	620.61	57.62
Jamaica	7.13	0.04
Haiti	6.23	0.79
Dominican Republic	107.34	21.04

* Source: CCDB

Table 3: Importer Country Consumption and Price Data

Country	Wholesale Price *($/kg)**	Trade Capacity *(MT)*	Min Consumption *(MT)*
Portugal	27,643	53.61	12.40
Spain	39,747	168.22	26.81
France	38,293	19.47	14.29
UK	35,990	293.03	43.95
Germany	44,893	183.84	9.24
Greece	46,832	23.77	1.99
Italy	43,527	258.20	18.82
Netherlands	41,877	417.97	29.77
Belgium	32,155	276.51	21.94
Norway	46,678	27.14	9.94
Turkey	40,388	58.04	1.20
US	28,000	N/A	311.35

* Source: EMCDDA (2019)

Two supply chain models, based on the network representation in Fig. 1, were formulated using the notation presented in Table 4. These two models only differ in the objective function consideration (Profit Maximization and Supply Maximization) and units of analysis (i.e., monetary value and shipment volume, respectively). All constraints are shared between the two models. The profit maximization objective function (2) calculated the total revenue from importing countries, plus the value of stored cocaine subject to SLR, minus the cost of operations via land and port trade in TZ countries. The supply maximization objective function is presented in (3), which maximized the total cocaine volume sent to importer countries (EU+3 and US) taking into account stored cocaine in TZ, exporting countries subject to the SLR. Under this objective, cocaine traffickers attempted to supply as much cocaine as possible to importer countries. When trade capacities were met, cocaine was moved into storage, incurring volume losses based on the SLR and thereby encouraging delivery over storage. The two objectives are not combined into a single multi-objective problem because these objectives are complementary measures of operational effectiveness (with differing units of measure), rather than conflicting objectives that require trade-offs of one over the other.

Table 4: Notation used throughout the paper.

Sets & Indices	
i, I	The index and set of exporter countries, $I = I^{CA} \cup I^{CB}$.
j, J	The index and set of importer countries, including the US.

p, P	The index and set of all exporter ports.
P_i	The set of ports in country i, $P = \cup_{i \in I} P_i$.
I^{CA}	The set of Central American Countries.
I^{CB}	The set of Caribbean Countries.

Parameters & Functions

ϕ_j	Wholesale price of cocaine in country j.
ϕ_i^0	Weighted average wholesale price of cocaine at trade partners of exporter i.
ν	Storage Loss Rate multiplier of stored cocaine.
ω_i	Cocaine received by country i from SA.
$\gamma_{i,\tilde{\imath}}^L$	Land transport cost per metric ton between exporters i and $\tilde{\imath}$.
γ_p	Port trade cost per metric ton at port p.
σ_p	Port security parameter at port p.
σ_{US}	US security parameters for imports to the US from Mexico and Caribbean.
$\theta_{i,j}$	Trade capacity between export-import pair (i, j).
$\tilde{\theta}_p$	Total trade capacity of port p.
μ_j	Lower bound for country j's import.
$\lambda_{i,\tilde{\imath}}$	Land trade seizure risk between $(i, \tilde{\imath})$.

Decision Variables

$X_{p,j}$	The cocaine flow between port p and importer j before land reallocation.
$\hat{X}_{p,j}$	The cocaine flow between port p and importer j after land reallocation.
$X_{i,\tilde{\imath}}^L$	The land reallocation from TZ countries i to $\tilde{\imath}$.
X_i^{US}	The cocaine flow from Caribbean country i to the US.
X_{MX}^{US}	The cocaine flow from Mexico to the US.
X_i^r	The remaining amount of cocaine in exporter i after the pre-reallocation shipment.
X_i^S	The cocaine allocated to be stored in exporter i.
Y_j	The cocaine consumed in importer country j.
Y_{US}	The cocaine consumed in the US.

subject to

$$\sum_{p \in P_i} \sum_{j \in J/\{US\}} X_{p,j} + X_i^r = \omega_i, \qquad \forall i \in I \quad (4)$$

$$\sum_{\tilde{\imath} \in I^x} X_{i,\tilde{\imath}}^L / (1 - \lambda_{i,\tilde{\imath}}) = X_i^r, \qquad \forall i \in I^x \forall x \in \{CA, CB\} \quad (5)$$

$$\sum_{p \in P_i} \sum_{j \in J/\{US\}} \hat{X}_{p,j} + X_i^S = \sum_{\tilde{\imath} \in I^{CA}} X_{\tilde{\imath},i}^L, \qquad \forall i \in I^{CA} \backslash \{MX\} \quad (6)$$

$$\sum_{p \in P_i} \sum_{j \in J/\{US\}} \hat{X}_{p,j} + X_i^S + X_i^{US} = \sum_{\tilde{\imath} \in I^x} X_{\tilde{\imath},i}^L, \qquad \forall i \in I^x \forall x \in \{MX, CB\} \quad (7)$$

$$\sum_{p \in P_i} (X_{p,j} + \hat{X}_{p,j}) \leq \theta_{i,j}, \qquad \forall i \in I, \forall j \in J/\{US\} \quad (8)$$

$$\sum_{j \in J \setminus \{US\}} (X_{p,j} + \hat{X}_{p,j}) \leq \tilde{\theta}_p, \qquad \forall p \in P_i, \forall i \in I \quad (9)$$

$$Y_j \geq \mu^j, \qquad \forall j \in J \quad (10)$$

$$\sum_{i \in I} \sum_{p \in P_i} (X_{p,j} + \hat{X}_{p,j})(1 - \sigma_p) = Y_j, \qquad \forall j \in J/\{US\} \quad (11)$$

$$\left(X_{MX}^{US} + \sum_{i \in I^{CB}} X_i^{US} \right)(1 - \sigma_{US}) = Y_{US}, \qquad (12)$$

$$X_{p,j}, \hat{X}_{p,j}, X_i^r, X_i^S, X_i^{US}, Y_j, Y_{US} \geq 0, \qquad \forall p \in P_i, \forall i \in I, \forall j \in J \quad (13)$$

To present our model, we introduce the sets of countries and ports. $I = I^{CA} \cup I^{CB}$ is the set of TZ countries (exporter set) where I^{CA} stands for Central American countries and I^{CB} is the set of Caribbean countries. We separated them due to the reallocation being possible within each subset but prohibited between Central American and Caribbean countries. $P = \cup_{i \in I} P_i$ is the set of exporter ports where P_i is the set of ports for the exporter country $i \in I$. Finally, J is the set of importer countries, consist of EU+3 and US.

The decisions in the model are regarding the movement of cocaine: trade to exporters ($X_{p,j}$,$\hat{X}_{p,j}$, X_i^{US}), land reallocation ($X_{i,\tilde{\imath}}^L$), to storage (X_i^S), remaining cocaine after reallocation (X_i^r), and the consumption (Y_j). Transatlantic trade is represented by two variables $X_{p,j}$ and $\hat{X}_{p,j}$ where the latter stands for the trade after land reallocation and denoted between a port and an importer country pair (p, j). US trade (X_i^{US}) is treated separately since it does not utilize the cargo vessels and not subject to the same constraints as transatlantic shipments, such as trade capacity. X_i^r and $X_{i,\tilde{\imath}}^L$ are intermediary variables where the former is the cocaine present in exporter i after the initial transatlantic shipment, and the latter is the amount received by country $\tilde{\imath}$ from country i, including the cocaine left in the country ($X_{i,i}^L$ can be non-zero). Note that the land reallocation between Central American and Caribbean countries is not allowed. X_i^S is the amount set to be stored, and Y_j is the amount consumed in exporter countries.

The profit maximization objective function (2) calculates the total revenue from importing countries ($\sum_{j \in J} Y_j \phi_j$), plus the value of stored cocaine subject to SLR ($\sum_{i \in I} X_i^S \phi_i^0 \nu$), minus the cost of operations via land ($\sum_{i \in I} \sum_{\tilde{\imath} \in I} X_{i,\tilde{\imath}}^L \gamma_{i,\tilde{\imath}}^L$) and port trade ($\sum_{i \in I} \sum_{p \in P_i} \gamma_p \sum_{j \in J/\{US\}} X_{p,j} + \hat{X}_{p,j}$) in TZ countries.

Profit Maximization Objective:

$Z_{PM} = \sum_{j \in J} Y_j \, \phi_j + \sum_{i \in I} X_i^S \phi_i^0 \nu - \sum_{i \in I} \sum_{\tilde{\imath} \in I} X_{i,\tilde{\imath}}^L \gamma_{i,\tilde{\imath}}^L - \sum_{p \in P} \sum_{j \in J/\{US\}} (X_{p,j} + \hat{X}_{p,j}) \gamma_p$, (2).

The supply maximization objective function is presented in (3), which maximized the total cocaine volume sent to importer countries (EU+3 and US) ($\sum_{j \in J} Y_j$) taking into account stored cocaine in TZ, exporting countries subject to the SLR ($\sum_{i \in I} X_i^S \nu$). As explained earlier, under this objective, cocaine traffickers attempted to supply as much cocaine as possible to importer countries. When trade capacities were met, cocaine was moved into storage incurring volume losses based on the SLR and thereby encouraging delivery over storage.

Supply Maximization Objective:

$Z_{SM} = \sum_{j \in J} Y_j + \sum_{i \in I} X_i^S \nu,$ (3).

All of the constraints were shared with these two objectives. The first set of constraints ((4)-(9)) dealt with flow balance, i.e., the supply of cocaine received by each TZ country from South America (SA) and reallocation among TZ countries, transatlantic shipments, and storage. Shipments were modeled in three phases: pre-reallocation, reallocation, and post-reallocation. Reallocation entailed the redistribution of the primary shipments supplied from SA, typically via land or short maritime routes as secondary shipments, by a given TZ country to other TZ countries due to relative differences in international trade capacity to target countries (EU+3 and US) and relative profitability/risk of in-country storage.
Constraint (4) ensured that the amounts exported from each country $i \in I$ through its ports plus the amount retained in that country equaled the initial supply of cocaine from SA to that country in its *pre-reallocation shipment*. Constraint (5) ensured that the seizure-loss adjusted amounts reallocated from each exporting country to another exporting country equaled the amount retained, for TZ countries in Central America and the Caribbean, respectively. Constraints (6) and (7) then ensured that the total cocaine received by each TZ country via that reallocation was then distributed into *post-reallocation shipments* to importer countries and/or storage within the TZ country. The two constraints were distinguished by trade to the US , where was not considered by the former. Shipments to the US from TZ countries were assumed to pass through Mexico over land or through each Caribbean country directly via maritime routes.

The next set of constraints ((8)-(10)) set the upper and lower bounds of cocaine flows for exporter and importer countries. The upper limit for outbound cocaine from each TZ port was regulated by constraints (8) and (9). In (8), the sum of pre-reallocation and post-reallocation transatlantic shipments between each export-import pair was limited by the trade capacity of that pair. This ensured that each country pair adhered to the trade capacity set by the present agricultural trade capacity. The capacity of each port limited the total amount leaving a port in transatlantic shipments via (9). Port capacities were calculated by the proportional trade present in each port within each country. The lower bounds received by each importer country were presented in (10). These lower bounds were based on estimates from European Monitoring Centre for Drugs and Addiction (EMCDDA) (2019) and US Office of National Drug Control Policy (ONCDP) (2018). Constraints in (11) and (12) calculated the total amount received by EU+3 countries and US, respectively, accounting for total amounts sent to those countries and security parameters. These amounts were used in objective functions (2) and (3). Finally, non-negativity constraints were defined in (13) for decision variables.

5. Results

Applying this modeling approach to the transatlantic cocaine trade produced estimates of the volume leaving the TZ for the EU+3 markets between 938 to 1526 MT (Table 5). This range was produced by various configurations of model versions and assumptions about transatlantic cocaine trafficking operations within the TZ. The Supply Maximization model most resembled the conventional view of the US as the dominant consumption market and destination for northbound cocaine (Fig. 3). Conversely, the Profit Maximization model favored the EU+3 markets with their higher wholesale prices relative to the US (Fig. 4). For example, comparing the Supply Maximization and Profit Maximization models with the same assumed SLR of 0.3 and no reallocation allowed within the TZ, supply to the US dropped from 1934 to 1140 MT, with most of the difference allocated to storage within TZ countries for later export. Allowing for the reallocation of *primary shipments* among TZ countries as *secondary shipments* amplified this trend.

Table 5. Comparison of cocaine volumes (MT) supplied, stored, and seized among alternative model objectives (i.e., supply vs. profit) maximization and storage loss rate (SLR) assumptions.

Model Version	SLR	Reallocation?	EU+3	US	Stored	Seized*
Supply Max.	0.3	0	938.70	1934.518	0	83.83
Supply Max.	0.1	0	938.70	1819.147	128.9065	70.30
Supply Max.	0.3	1	1402.23	1497.341	0	57.48
Supply Max.	0.1	1	1407.50	1492.066	0	57.48
Profit Max.	0.3	0	1000.42	1140.321	769.6988	46.61
Profit Max.	0.1	0	965.84	311.35	1592.38	87.48
Profit Max.	0.3	1	1526.10	904.2919	474.8763	51.78
Profit Max.	0.1	1	1281.42	311.35	1278.786	85.49

* Total reported seizures volumes from the transit zone in 2017 was 103.56 MT (CCDB).

Comparing the Profit Maximization model without and with reallocation, with the same SLR of 0.3, supply to the US decreased from 1140 to 904 MT and increased to the EU+3 from 1000 to 1526 MT, respectively. Allowing reallocation of supply between TZ countries with relatively small (e.g., Nicaragua) to large (e.g., Costa Rica) cocaine trade capacities maximized profit via supply to the EU+3 markets.

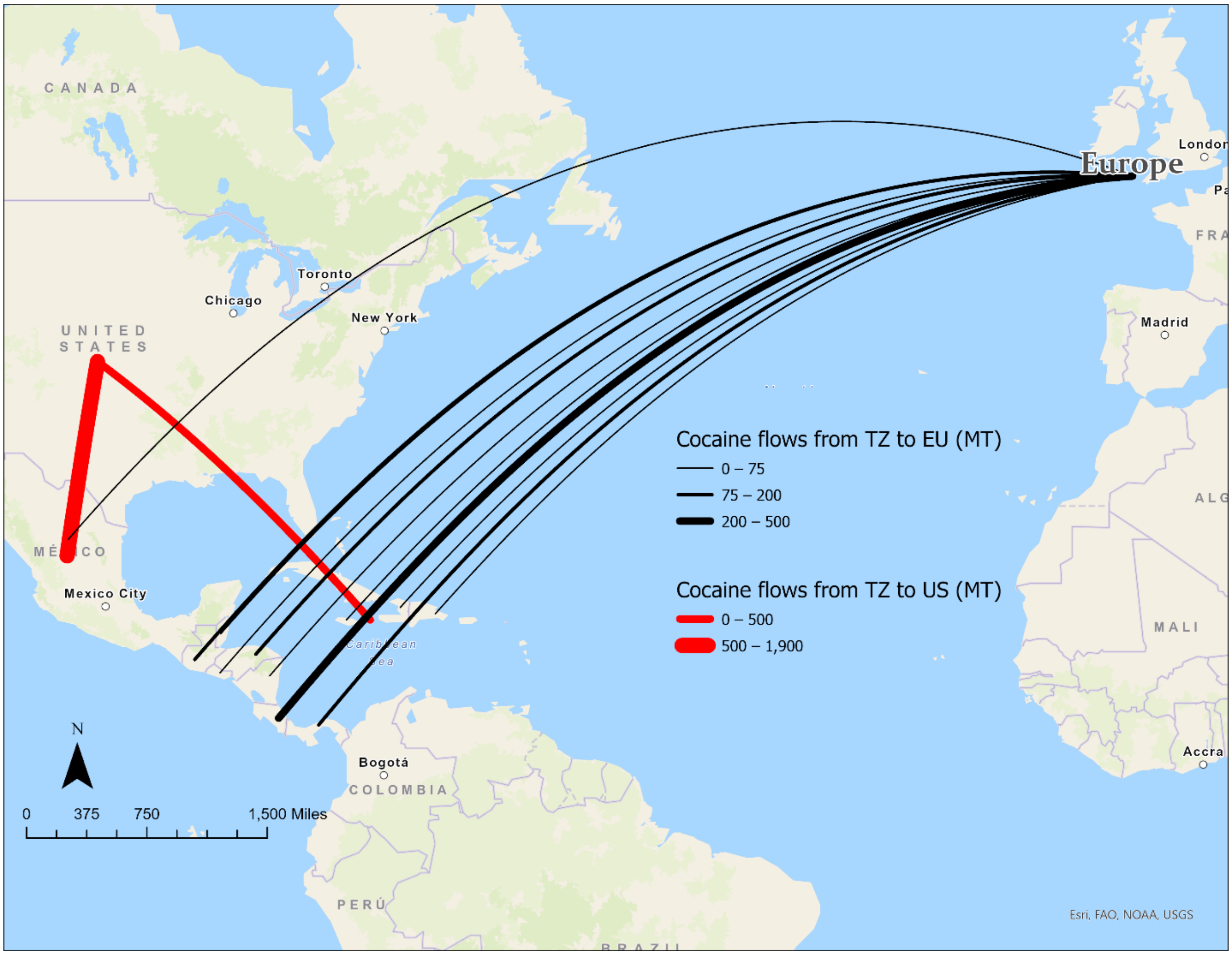


Figure 3. Cocaine flows to the US (red) and EU+3 (black) estimated with the Supply Maximization model, 0.3 SLR, and no reallocation.

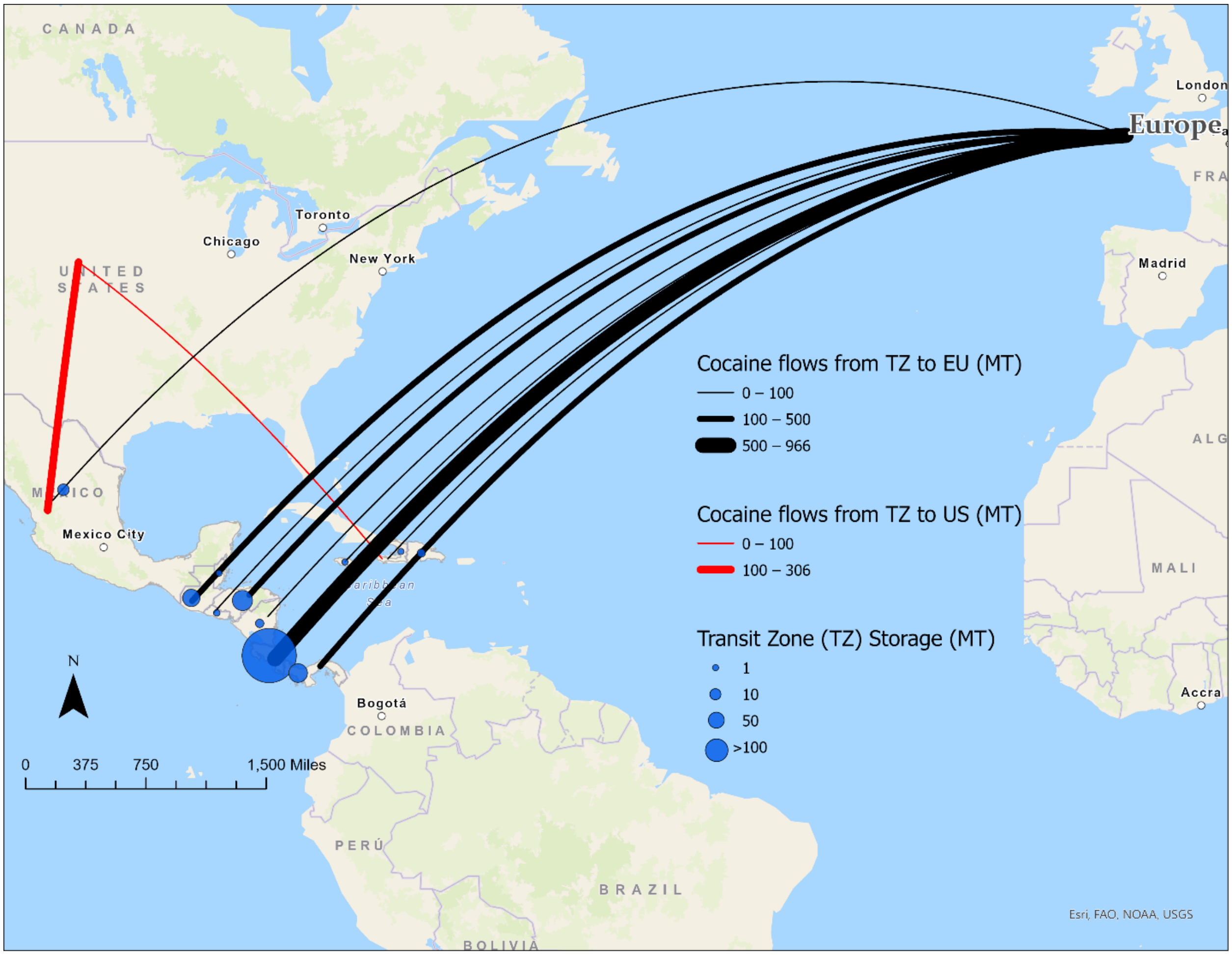


Figure 4: Cocaine flows to the US (red), EU (black), and storage in transit zone (TZ) countries (hot colors) estimated with the Profit Maximization model, 0.1 SLR, and reallocation within the TZ.

Model outcomes also demonstrated sensitivity to opportunity costs of storage (e.g., lost value with changes in SLR; seizures) relative to average of EU+3 wholesale prices. A higher SLR represented lower opportunity costs of storage and greater potential value stored in the TZ for later export to the EU+3 than it would have received if it moved northward to the US incurring losses from transport costs and seizures along the way. With the exception of the Supply Max model with reallocation, all other models produced increased storage in TZ countries when SLR was increased. For example, decreasing the SLR from 0.3 to 0.1 for the Profit Max model with reallocation in the TZ reduced US supply from 904 to 311 MT and increased total TZ storage from 475 to 1279 MT. Although this increased overall seizures by nearly 34 MT, those losses were negligible compared to the total supply to the EU+3 (2.6%).

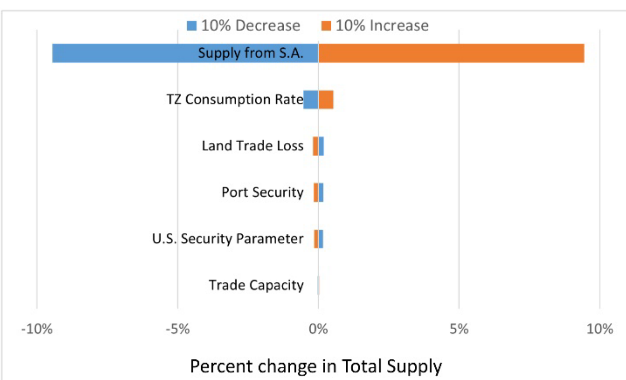
6. Sensitivity Analyses

We used a tornado analysis technique (Borgonovo & Pilschke, 2016) to alter model parameters by increasing and decreasing each parameter by 10% and then ranked the relative importance and their effects on our objectives – specifically total supply, total profit, and transatlantic (to EU+3) profit. Neither total nor transatlantic profits were assessed for the Supply Maximization model since profit was not part of its formulation. The next three subsections present the detailed results on each objective.

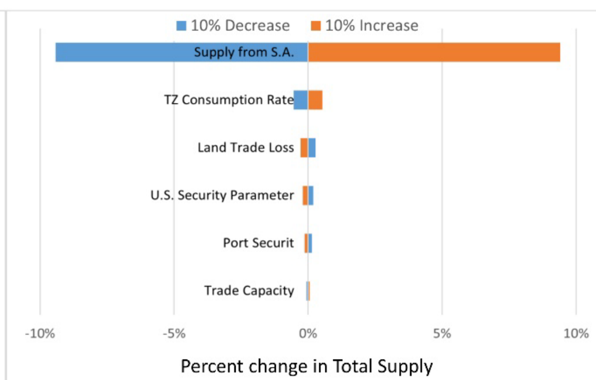
6.1. Total supply

Sensitivity of total supply in the Supply Maximization model (Figure 5) showed that the initial supply from SA had a direct effect on the total supply to the parameter change, as expected. A ten percent increase (decrease) in supply from SA resulted in almost a similar increase (decrease) in supply maximization. Since the majority of the initial supply went to the target countries as consumption, any change in the initial supply was largely observed in the total supply. The second most influential parameter was Consumption Rate in TZ countries. Since the supplies in TZ countries were accounted with almost no loss or seizure, TZ Consumption Rate had a less but still considerable effect on total supply.

Security and loss parameters had the opposite effect on supply and consumption parameters, since any increase in security decreased the supply. These effects were however negligible in the big picture, since these losses already accounted for less than 10% of supply in all cases and any 10% change in any of them resulted in less than 1% change in the total supply. Trade capacity on the other hand did not have any meaningful effect, since most ports were not exporting at full capacity, instead a higher percentage went to the US, as opposed to profit maximization scenario.



(a) With secondary shipments



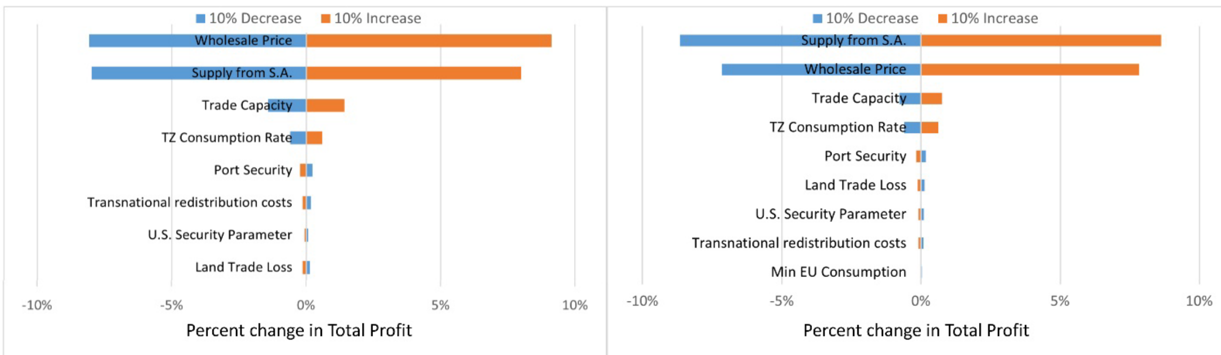
(b) No secondary shipments

Figure 5: Percent change in total supply with 10% decrease/increase in the given parameter values for the Supply Maximization.

The effect of having secondary shipments decreased the effect of land trade loss, due to three reasons: ports with lower security parameters were utilized with reallocation, total consumption increased in secondary shipment scenario, and a decrease in US supply indicated a lower land trade throughout the TZ. A similar effect was observed with trade capacities, since ports with higher capacities were utilized more with secondary shipments allowed.

6.2. Total profit

Sensitivity analysis of the Profit Maximization model produced some interesting results (Figure 6). In this case, compared to supply maximization, the effect of trade capacities were more pronounced and cost-based parameters came into the play.

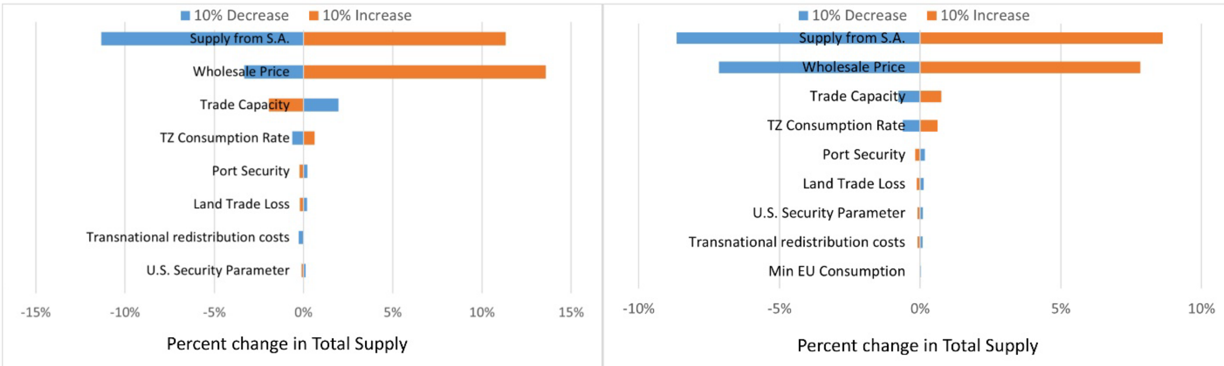


(a) With secondary shipments (b) No secondary shipments

Figure 6: Percent change in total profit with 10% decrease/increase in the given parameter values for the Profit maximization Model.

Secondary shipments significantly influenced total profit. When secondary shipments were allowed, they were sensitive to wholesale prices and substantially affected the overall EU+3 supply. We observed that, the trade capacity and loss/security parameters were also more influential with than without secondary shipments, since the EU+3 trade and the total profit significantly increased with the existence of the secondary shipments.

In terms of the total supply with the Profit Maximization model, nonlinear changes were observed (Fig. 7). A 10% change in initial supply resulted in more than 10% in total supply since the maximizing profits redirected the previously stored cocaine to consumption. Also, a 10% decrease in wholesale price resulted in around 3-4% loss in total supply while a 10% increase causes around 10% or more gain. This was due to redirecting the shipments to minimize costs via losses, which resulted in a greater decrease in profits compared to supply. Finally, an increase in trade capacity resulted in an increase in transatlantic trade, which was more profitable. However, that also meant higher losses due to both port security and land reallocation, which would have been lower if the cocaine was sent to US instead.

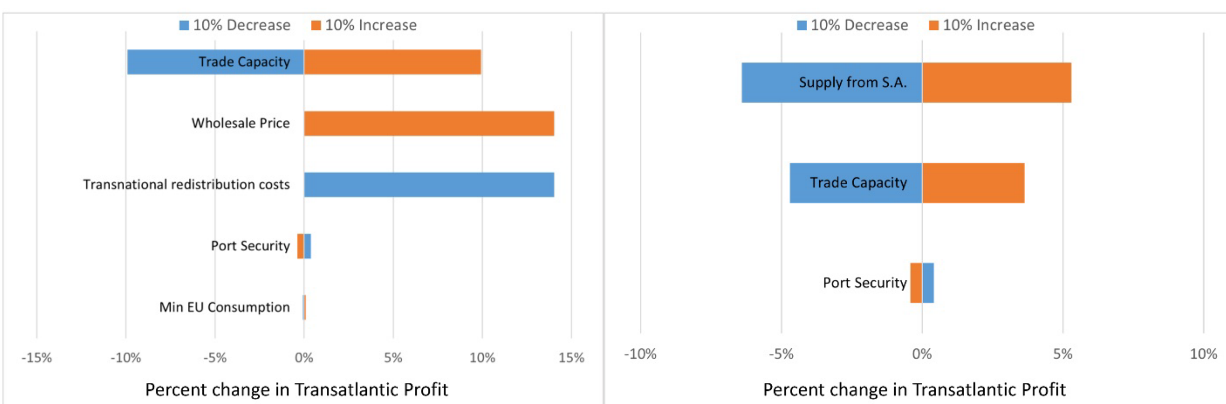


(a) With secondary shipments (b) No secondary shipments

Figure 7. Percent change in total supply with 10% decrease/increase in the given parameter values for the Profit Maximization model.

6.3. Transatlantic profit

In Figure 8, we analyzed sensitivities of profits specifically within the EU+3 countries with Profit Maximization model. With EU+3 market being more profitable, an increase in trade capacity directly affected EU+3 imports. On the other hand, increase in supply from SA resulted in increased US trade and storage since those were more profitable than some EU+3 countries. An increase in wholesale prices or a decrease in redistribution costs allowed the transatlantic trade with less profitable EU+3 countries a preferable option. In model version with no secondary shipments, EU+3 trade was far below capacity and any supply from SA or increase in trade capacity on the profitable ports increased the EU+3 trade. However, since reallocation was not allowed, this had a limited effect due to trade capacity limitations.



(a) With secondary shipments (b) No secondary shipments

Figure 8. Percent change in transatlantic profit with 10% decrease/increase in the given parameter values for the Profit Maximization model.

7. Discussion and Conclusions

Our model estimates that more than 900 MT of cocaine could potentially be leaving the northbound cocaine supply chain to meet growing demand in EU+3 markets. To our knowledge, this is the first quantitative estimate of transatlantic cocaine flows based on empirically grounded and plausible constraints of the agricultural export supply chain. Moreover, our modeling exercise suggested potential mechanisms for the operation of the northbound transatlantic cocaine supply chain. Specifically, our results suggested that secondary movements, i.e., over-land transport of primary shipments delivered to remote locations or to other locations/countries with well-developed export infrastructure, may play a critical role in transatlantic cocaine trafficking operations when trade capacity constraints are present. Also, a key trade-off facing traffickers emerged from our model experiments: the greater the profit potential of EU+3 markets and both need for, and safety of, shipment aggregation and storage, the more cocaine is removed from the US supply and redirected to EU+3 markets.

Several important caveats about the model formulation and evaluating its realism are needed. First, our supply chain model was initialized with cocaine supplies present in TZ countries, rather than the countries of production, which would be consistent with the conventional approach for legal supply chain analysis. This choice was made because of the substantial uncertainty involved with translating production estimates (e.g., hectares of coca planted, harvested) to volumes of cocaine entering the supply chain. There are numerous processing steps between coca leaves and the final product of cocaine HCL, and the resulting volume varies based on the efficiency of those steps and the final purity (McSweeney, 2020; UNODC, 2005, 2020). Instead, we drew upon the CCDB as the most reliable source of estimated cocaine flows entering the TZ.

Second, only minimum demand volumes were parameterized, because estimates of cocaine consumption are highly unreliable. Prevalence of drug use is often used to measure consumption rates among a population and can be based on positive drug tests from arrests (Kilmer et al., 2014), survey responses, or wastewater chemical analysis (EMCDDA, 2021). Regardless of the source of the estimate, prevalence does not equate to the volume consumed, and the two measures can move in opposite directions because consumption is driven by a small number of heavy users (Kilmer and Midgette, 2017; Kilmer et al., 2014). Moreover, the purity of the drug consumed is not known, and estimates of average purity rely on imprecise street surveys and can vary widely by geography and over time (Kilmer et al., 2014; ONDCP, 2018). Because of these data quality issues, comparison of modeled volumes to consumption estimates would not be meaningful, and consumption estimates were better used as minimum supply constraints in our modeling framework.

Finally, cocaine seizure estimates were similarly problematic. Transnational cocaine seizures are subject to multiple data reliability issues, such as inconsistent reporting across jurisdictions, reliance on voluntary reporting methods (e.g., UNODC), and/or political motivation to under- or over-report seizures, all of which render seizures as better indications of law enforcement effort rather than drug trafficking activities (Bichler and Jimenez, 2023; Bright et al., 2021). Moreover, available aggregate estimates of seizures of transnational cocaine shipments are compiled by separate organizations (e.g., Joint Inter-Agency Task Force-South for CCDB vs. UNODC), which are typically independent (i.e., North America vs. EU+3) but may overlap and introduce double-counting. For example, a shipment smuggled in containers might originate from Ecuador, be seized in Costa Rica, but was destined for the port of Antwerp, Belgium. It is possible that the seized volume could be counted in both CCDB and UNODC databases, but the lack of transparent data collection information makes this situation impossible to resolve. Thus, seizure data should be used with caution. We relied instead on TZ flow estimates from CCDB to parameterize potential flow volumes, which are based on intelligence and stringent quality criteria (McSweeney, 2020). Model estimates of seizures should also be only qualitatively compared to observed seizure volumes for model evaluation due to the above uncertainties.

These limitations, however, strengthen the argument in favor of this modeling approach. The value of this modeling approach is not in the specific quantitative estimates produced from any single parameterized scenario, but in the ability to ground *any* quantitative estimates of clandestine phenomenon in the best available data with systematic, formalized assumptions adapted from established supply chain modeling methodologies that can be experimentally manipulated. Indeed, the relative differences between estimated cocaine flows among the experimental model versions provided greater insight into plausible trafficking network operations than the absolute numbers, which were produced using multiple assumptions and compounding uncertainties necessary to fill data gaps. Our modeling approach is also used to experimentally to identify and isolate the effects of sensitive parameters, which improves the understanding of the functioning of the trafficking network and indicate priority areas for improving data availability and quality. The key sensitivities that impact the results include supply from SA, security and loss parameters at ports and between TZ countries, wholesale price, and trade capacity.

Using established techniques for modeling flows of legal commodities through supply networks, the proposed modeling approach is an important first step toward deepening understanding of the workings of trafficking networks. Our current understanding is dominated by qualitative accounts or quantitative, national-level estimates developed using the much more visible – but woefully fragmented and incomplete – picture of transnational illicit supply networks gleaned from seizure data. Notably, the proposed modeling approach provides the subnational disaggregation critical to enabling scenario-based analysis of the effects of law enforcement interventions at specific ports and the likely unintended displacement of cocaine trafficking as a response.

Future work will be in two directions. The model is currently designed to be executed iteratively to investigate supply dynamics but is only implemented for a single year currently.

Given the apparent importance of storage in these findings, an iterative implementation is warranted to analyze the role of storage in US and EU supply over time. Additionally, future analyses will explore scenarios implementing changes in the security parameters of individual TZ country ports, related to improved scanning technology or specific law enforcement operations, to explore the redistribution of cocaine trafficking pressure within the TZ.

Funding

References

Alzaabi, M., Taha, K. and Martin, T.A. (2015) "CISRI: A Crime Investigation System Using the Relative Importance of Information Spreaders in Networks Depicting Criminals Communications," *IEEE Transactions on Information Forensics and Security*, 10(10), pp. 2196–2211. Available at: https://doi.org/10.1109/TIFS.2015.2451073.

Anzoom, R., Nagi, R. and Vogiatzis, C. (2021) "A Review of Research in Illicit Supply-Chain Networks and New Directions to Thwart them," *IISE Transactions*, pp. 1–59. Available at: https://doi.org/10.1080/24725854.2021.1939466.

Anzoom, R., Nagi, R., & Vogiatzis, C. (2024). Uncovering illicit supply networks and their interfaces to licit counterparts through graph-theoretic algorithms. *IISE Transactions*, 56(3), 224-240.

Ballvé, T. (2019) "Narco-frontiers: A spatial framework for drug-fuelled accumulation," *Journal of Agrarian Change*, 19(2), pp. 211–224. Available at: https://doi.org/10.1111/joac.12300.

Bargent, J. (2020) "Why a Measly Five Tons of Cocaine Has Costa Rica Deeply Worried," *InSight Crime*, 17 March.

Barratt, M.J. and Aldridge, J. (2016) "Everything you always wanted to know about drug cryptomarkets*(* but were afraid to ask)," *International Journal of Drug Policy* [Preprint].

Basu, G. (2013) "The role of transnational smuggling operations in illicit supply chains," *Journal of Transportation Security*, 6(4), pp. 315–328. Available at: https://doi.org/10.1007/s12198-013-0118-y.

Basu, G. (2014) "Concealment, corruption, and evasion: A transaction cost and case analysis of illicit supply chain activity," *Journal of Transportation Security*, 7(3), pp. 209–226. Available at: https://doi.org/10.1007/s12198-014-0140-8.

Bernal, J. L., Garzón, J. C., & Gómez, C. R. (2020). Cultivos ilícitos y áreas protegidas del Sistema de Parques Nacionales Naturales Por qué ha sido difícil avanzar y cuáles son las opciones. http://ideaspaz.org/media/website/FIP_NE_PNNCultivosilicitos_web_Corregido_Final.pdf.

Bichler, G., & Jimenez, I. (2023). "Drug Smuggling Seizures: The Effects of Reporting Consistency and Quality on the Observed Transnational Structure". *Journal of Drug Issues*, *53*(1), 159–179.

Boekhout van Solinge, T. (2022). Global Cocaine Flows, Geographical Displacement, and Crime Convergence. In *The Evolution of Illicit Flows* (pp. 57-81). Springer, Cham.

Borgonovo, E., & Plischke, E. (2016). Sensitivity analysis: A review of recent advances. *European Journal of Operational Research*, 248(3), 869-887. Available at: https://doi.org/10.1016/j.ejor.2015.06.032.

Bright, D., Brewer, R., & Morselli, C. (2021). "Using social network analysis to study crime: Navigating the challenges of criminal justice records". *Social Networks*, *66*, 50–64. https://doi.org/10.1016/j.socnet.2021.01.006

Bright, D., Koskinen, J. and Malm, A. (2019) "Illicit Network Dynamics: The Formation and Evolution of a Drug Trafficking Network," *Journal of Quantitative Criminology*, 35(2), pp. 237–258. Available at: https://doi.org/10.1007/s10940-018-9379-8.

Bright, D.A. and Delaney, J.J. (2013) "Evolution of a drug trafficking network: Mapping changes in network structure and function across time," *Global Crime*, 14(2–3), pp. 238–260. Available at: https://doi.org/10.1080/17440572.2013.787927.

Bright, E.A., Rose, A.N. and Urban, M.L. (2016) "LandScan 2015." Oak Ridge, TN: Oak Ridge National Laboratory SE - July 1, 2016 (LandScan).

Calderoni, F., Dugato, M., Aglietti, V., Aziani, A., & Rotondi, M. (2017). Price and Non-price Determinants of the Illicit Cigarette Trade: Analysis at the Subnational Level in the EU. In E. U. Savona, M. A. R. Kleiman, & F. Calderoni (Eds.), *Dual Markets: Comparative Approaches to Regulation* (pp. 267–286). Springer International Publishing. https://doi.org/10.1007/978-3-319-65361-7_17

Caulkins, J.P., Crawford, G. and Reuter, P. (1993) "Simulation of adaptive response: A model of drug interdiction," *Mathematical and Computer Modelling*, 17(2), pp. 37–52. Available at: https://doi.org/10.1016/0895-7177(93)90238-T.

Caulkins, J.P. and Reuter, P. (2010) "How drug enforcement affects drug prices," *Crime and Justice*, 39, pp. 213–271. Available at: https://doi.org/10.1086/652386/ASSET/IMAGES/LARGE/FG6.JPEG.

Chopra, S. and Meindl, P. (2007) "Supply Chain Management. Strategy, Planning & Operation," *Das Summa Summarum des Management*, pp. 265–275. Available at: https://doi.org/10.1007/978-3-8349-9320-5_22.

Dávila, A., Magliocca, N., McSweeney, K., & Rueda, X. (2021). Spatialising illicit commodity chains: Comparing coffee and cocaine. *Area*, *53*(3), 501–510. https://doi.org/10.1111/area.12724

Devine, J. A., Wrathall, D., Aguilar-González, B., Benessaiah, K., Tellman, B., Ghaffari, Z., & Ponstingel, D. (2021). Narco-degradation: Cocaine trafficking's environmental impacts in Central America's protected areas. *World Development*, *144*, 105474. https://doi.org/10.1016/j.worlddev.2021.105474

Devine, J. A., Currit, N., Reygadas, Y., Liller, L. I., & Allen, G. (2020). Drug trafficking, cattle ranching and Land use and Land cover change in Guatemala's Maya Biosphere Reserve. *Land Use Policy*, *95*, 104578. https://doi.org/10.1016/j.landusepol.2020.104578

Drug Enforcement Agency (DEA) (2017). 2017 National Drug Threat Assessment. United States Department of Justice, DEA. Available at: https://www.dea.gov/sites/default/files/2018-07/DIR-040-17_2017-NDTA.pdf.

Enghoff, O. and Aldridge, J. (2019) "The value of unsolicited online data in drug policy research," *International Journal of Drug Policy*, 73, pp. 210–218. Available at: https://doi.org/10.1016/J.DRUGPO.2019.01.023.

European Monitoring Centre for Drugs and Addiction (EMCDDA) (2019) *EU Drug Markets Report 2019*, *2019*. Lisbon, Portugal. Available at: https://doi.org/10.2810/561192.

European Monitoring Centre for Drugs and Addiction (EMCDDA) (2021). "European Drug Report 2021: Trends and Developments." Available at: https://www.emcdda.europa.eu/publications/edr/trends-developments/2021_en (Accessed: 1 July 2022).

European Monitoring Centre for Drugs and Drug Addition (EMCDDA) and Europol (2016). "EU Drug Markets Report: In-Depth Analysis". Lisbon, Portugal. Available at: https://www.emcdda.europa.eu/publications/joint-publications/eu-drug-markets-2016-in-depth-analysis_en.

Ferrara, E., De Meo, P., Catanese, S., & Fiumara, G. (2014). Detecting criminal organizations in mobile phone networks. *Expert Systems with Applications*, *41*(13), 5733–5750. https://doi.org/10.1016/j.eswa.2014.03.024

Food and Agriculture Organization (FAO) of the United Nations (2021). Trade of agricultural commodities 2000-2020. Available at: https://www.fao.org/food-agriculture-statistics/data-release/data-release-detail/en/c/1507740/. Last accessed August 1, 2021.

InSight Crime (2022) *Cash Cows - The Inner Workings of Cattle Trafficking from Central America to Mexico*.

Keskin, B. B., Griffin, E. C., Prell, J. O., Dilkina, B., Ferber, A., MacDonald, J., Hilend, R., Griffis, S., & Gore, M. L. (2023). Quantitative Investigation of Wildlife Trafficking Supply Chains: A Review. *Omega*, *115*(C).

Kilmer, B. and Midgette, G. (2017). "Mixed Messages: Is Cocaine Consumption in the U.S. Going Up or Down?" The RAND Blog, RAND Corporation. Available at: https://www.rand.org/blog/2017/04/mixed-messages-is-cocaine-consumption-in-the-us-going.html.

Kilmer, B., Everingham, S., Caulkins, J., Midgette, G., Pacula, R., Reuter, P., Burns, R., Han, B., Lundberg, R. (2014). "What America's Users Spend on Illegal Drugs: 2000-2010." RAND Corporation. Available at: https://obamawhitehouse.archives.gov/sites/default/files/ondcp/policy-and-research/wausid_results_report.pdf.

Kosmas, D., Sharkey, T. C., Mitchell, J. E., Maass, K. L., & Martin, L. (2023). Interdicting restructuring networks with applications in illicit trafficking. *European Journal of Operational Research*, 308(2), 832-851.

Magliocca, N., Torres, A., Margulies, J., McSweeney, K., Arroyo-Quiroz, I., Carter, N., Curtin, K., Easter, T., Gore, M., Hübschle, A., Masse, F., Rege, A., & Tellman, E. (2021). Comparative Analysis of Illicit Supply Network Structure and Operations: Cocaine, Wildlife, and Sand. *Journal of Illicit Economies and Development*, *3*(1), Article 1.

Magliocca, N. R., McSweeney, K., Sesnie, S. E., Tellman, E., Devine, J. A., Nielsen, E. A., Pearson, Z., & Wrathall, D. J. (2019). Modeling cocaine traffickers and counterdrug interdiction forces as a complex adaptive system. *Proceedings of the National Academy of Sciences*, *116*(16), 7784–7792. https://doi.org/10.1073/pnas.1812459116

Magliocca, N. R., Summers, D. S., Curtin, K. M., McSweeney, K., & Price, A. N. (2022). Shifting landscape suitability for cocaine trafficking through Central America in response to counterdrug interdiction. *Landscape and Urban Planning*, *221*, e104359. https://doi.org/10.1016/j.landurbplan.2022.104359

MarineTraffic (2019). Ports Database. Available at: https://www.marinetraffic.com/en/data/?asset_type=ports&columns=flag,portname,unlocode,photo,vessels_in_port,vessels_departures,vessels_arrivals,vessels_expected_arrivals,local_time,anchorage,geographical_area_one,geographical_area_two,coverage.

McDermott, J. & Bargent, J. (2021) *The Cocaine Pipeline to Europe*. Available at: https://globalinitiative.net/analysis/cocaine-to-europe/.

McSweeney, K., Richani, N., Pearson, Z., Devine, J., & Wrathall, D. J. (2017) "Why Do Narcos Invest in Rural Land?," *Journal of Latin American Geography*, 16(2), pp. 3–29. Available at: https://doi.org/10.1353/lag.2017.0019.

McSweeney, K. (2020) "Reliable drug war data: The Consolidated Counterdrug Database and cocaine interdiction in the 'Transit Zone,'" *International Journal of Drug Policy*, 80, p. 102719. Available at: https://doi.org/10.1016/j.drugpo.2020.102719.

Ministry of Public Safety Office of Public Relations and Press (2018) "PCD raids pineapple exporting companies allegedly linked to the transfer of cocaine," *Press Release No. CP-0737-2018*, 7 September.

Morselli, C., Giguère, C. and Petit, K. (2007) "The efficiency/security trade-off in criminal networks," *Social Networks*, 29(1), pp. 143–153. Available at: https://doi.org/10.1016/j.socnet.2006.05.001.

National Geospatial Intelligence Agency (NGA) (2019). "World Port Index". The United States Government, Publication 150. Springfield, Virginia. Available at: https://msi.nga.mil/Publications/WPI.

Navarrete Forero, A. M. (2019, April). *Drug Gangs Corrupt Panama's Shipping Industry*. Insight Crime. https://www.insightcrime.org/news/brief/drug-gangs-corrupt-panama-shipping-industry/

Observatory of Economic Complexity (OEC) (2021). "Historical Data". Available at: https://oec.world/en/profile/country. Last accessed August 1, 2021.

Office of National Drug Control Policy (ONDCP) (2018). "Cocaine". Available at: https://www.whitehouse.gov/ondcp/key-issues/cocaine/ (Accessed: 20 February 2018).

Pearson, Z, Skiba, A, McSweeney, K, Nielsen, E and Piccorelli, J. (2022). "Acknowledging Cocaine Capital in Central American Development," *Journal of Illicit Economies and Development*, 3(3): pp. 1–17. DOI: https://doi. org/10.31389/jied.110.

Rege, A. (2016). Not biting the dust: using a tripartite model of organized crime to examine India's Sand Mafia. *International Journal of Comparative and Applied Criminal Justice*, 40(2), 101-121.

Reuter, P. and O'Regan, D. (2017) "Smuggling wildlife in the americas: Scale, methods, and links to other organised crimes," *Global Crime*, 18(2), pp. 77–99. Available at: https://doi.org/10.1080/17440572.2016.1179633.

Shelley, L.I. (2018) *Dark Commerce: How a New Illicit Economy is Threatening Our Future*. Princeton University Press.

Smith, J.C., Song, Y. (2020). "A survey of network interdiction models and algorithms," *European Journal of Operational Research* 283, 797–811.

Stevens, G.C. (1989) "Integrating the supply chain," *International Journal of Physical Distribution & Materials Management*, 19(8), pp. 3-8. Available at: https://doi.org/10.1108/EUM0000000000329.

Tellman, B., McSweeney, K., Manak, L., Devine, J. A., Sesnie, S., Nielsen, E., & Dávila, A. (2021) "Narcotrafficking and Land Control in Guatemala and Honduras," *Journal of Illicit Economies and Development*, 3(1), p. 132. Available at: https://doi.org/10.31389/JIED.83.

Transparency International (TI). Corruption Perceptions Index. Last accessed July 1, 2019. Available at: https://www.transparency.org/en/cpi/2020/index/hnd.

Transport Topics (2019). "2019 Essential Revenue and Operating Information for the 50 Largest Global Freight Carriers: Central America." Available at: https://www.ttnews.com/top50/port-data-central-america/2019?page=16.

United Nations Office on Drugs and Crime (UNODC) (2005) *World Drug Report 2005*.

United Nations Office on Drugs and Crime (UNODC) (2011) *The Transatlantic cocaine market*.

United Nations Office on Drugs and Crime (UNODC) (2020) *World Drug Report 2020*.

United States Customs and Border Patrol (USCBP) (2019a). "CSI: Container Security Initiative". Available at: https://www.cbp.gov/border-security/ports-entry/cargo-security/csi/csi-brief.

United States Customs and Border Protection (USCBP) (2019b). U.S. Border Patrol Nationwide Checkpoint Drug Seizures in Pounds. Available at: https://www.cbp.gov/newsroom/stats/cbp-enforcement-statistics/usbp-drug-seizures-sector.

United States General Accounting Office, (GAO) (2017) *Counternarcotics: Overview of U.S. Efforts in the Western Hemisphere*. Washington, D.C.

Yansura, J. and Kumar, L. (2020) "Narcotics Proceeds in the Western Hemisphere: Analysis of Narcotics Related Illicit Financial Flows between the United States, Mexico, and Colombia."

Zhao, M. (2019) "The illicit distribution of precursor chemicals in China: A qualitative and quantitative analysis," *Inter*