Q:6 PNAS PERSPECTIVE

Advancing interdisciplinary science for disrupting wildlife trafficking networks

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Q:5 **Wildlife trafficking, whether local or transnational in scope, undermines sustainable development efforts, degrades cultural resources, endangers species, erodes the local and global economy, and facilitates the spread of zoonotic diseases. Wildlife trafficking networks (WTNs) occupy a unique gray space in supply chains—straddling licit and illicit networks, supporting legitimate and criminal workforces, and often demonstrating high resilience in their sourcing flexibility and adaptability. Authorities in different sectors desire, but frequently lack knowledge about how to allocate resources to disrupt illicit wildlife supply networks and prevent negative collateral impacts. Novel conceptualizations and a deeper scientific understanding of WTN structures are needed to help unravel the dynamics of interaction between disruption and resilience while accommodating socioenvironmental context. We use the case of ploughshare tortoise trafficking to help illustrate the potential of key advancements in interdisciplinary thinking. Insights herein suggest a significant need and opportunity for scientists to generate new science-based recommendations for WTN-related data collection and analysis for supply chain visibility, shifts in illicit supply chain dominance, network resilience, or limits of the supplier base.**

green security games | illegal wildlife trade | illicit networks | operations research | supply chain resilience

Q:7 Thinking About Wildlife Trafficking as an Illicit Supply Chain

Wildlife trafficking is a transnational environmental challenge globally distributed in scope and scale, species targeted, and societal impacts. Wildlife trafficking can simultaneously serve as a vector for zoonotic disease and nonnative species invasion, endanger flora and fauna, undermine returns on sustainable development investment, associate with human rights violations, and support an exploited labor force. Although wildlife trafficking can have a unique, illicit supply network, it is not universally considered by conservation, law enforcement, sustainable development, or other authorities to be a severe problem relative to other challenges. Current thinking about wildlife trafficking networks (WTNs) suggests they overlap with and exploit the processes and mechanisms of licit supply chains (e.g., laundering legally protected and wild-caught European glass eels with a shipment of eels raised via aquaculture) (1). In some instances, wildlife trafficking converges with illicit supply networks for light weapons, narcotics, diamonds, and antiquities (e.g., ref. 2). In transnational spaces, WTNs can signal governance challenges such as insider threats, corruption, and social conflicts such as ethnic strife. For example, Seleka rebels in the Central African Republic, which include armed fighters from Sudan, have been accused of poaching wildlife in Dzanga-Ndoki National Park to support their activities; Resistência Nacional Moçambicana reportedly traded in rhino horn and elephant ivory during Mozambique's civil war. Recently, two officials of the Cambodian Forestry Administration, Ministry of Agriculture, Forestry and Fisheries were indicted in the USA on eight counts of smuggling and conspiracy to violate multiple federal laws for facilitating the capture of wild-caught long-tailed macaques and laundering them through Cambodian entities for export to the U.S. and elsewhere, falsely labeled as captive bread (3). The animals were sent around the USA to biomedical testing facilities and were one of the main species employed to test COVID-19 vaccines (4). Scholars have long noted the social contexts and human dimensions associated with wildlife trafficking that encourage broad engagement by scientific disciplines and professional sectors, including and beyond law enforcement (e.g., ref. 5). Wildlife trafficking is a driver of species declines, and no ecosystem in the world has avoided negative impacts from the activity. Wild species are trafficked for a range of purposes, including food, income, medicine, companionship, novelty, entertainment, and research—contributing to degraded ecosystems and compounding negative impacts of climate change. Because human health and well-being are intricately linked to ecosystem health, degraded ecosystems ultimately result in degraded human health.

Policymakers, donors, and scientists around the world typically define WTNs as occurring across source, transit, and destination geographies (i.e., nodes and pathways or routes between these nodes). WTNs exploit spaces and places operating on the margins of government and the rule of law; they can deepen social fault lines and increase

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facets of risk exposure that may rise to the level of geopolitical consequence. The consequences of their actions are varied; the recent indictment of monkey importers in the USA from Cambodia may disrupt US drug and vaccine research (4). Advanced scientific thinking involving quantitative cross-disciplinary data and cross-sectoral approaches may dramatically improve the data landscape for informing programmatic and policy efforts to address WTN's scope, scale, and success across the variety of social contexts within which they occur (e.g., rural to urban, global south to the global north, savanna to forest, very low to very high income) (Fig. 1). WTNs are dynamic and diverse; similarly diverse is the nature of the harm and range of offenses, organization of the people involved, and the impact on the socioenvironmental systems within which harms accrue. The scientific baseline about WTNs remains nebulous and siloed; network and supply chain characteristics of WTNs remain poorly understood and are primarily case based. Push and pull factors driving consumer preferences for wildlife products are generally recognized as being essential for enduring demand reduction interventions; respect for government authority, cultural shifts to and from conspicuous consumption, trade bans, and economic recessions are known to exert varying influence on demand, yet insight remains cross-sectional (6). Risks to legal supply networks can go undetected and unmitigated (e.g., unusual patterns, counterintuitive correlations, and emergence of obfuscated monopolies). Relevant conservation biology data sources are scattered and maintained with different standards by diverse groups of stakeholders with their own interests.

Integrating knowledge, methods, and expertise from different disciplines (e.g., Fig. 1) can help catalyze scientific discovery and innovation (7). Coupled human and natural systems thinking (e.g., ref. 8), telecoupling (e.g., ref. 9), and convergent science (e.g., ref. 10), for example, are all scientific mechanisms for achieving this goal. However, these approaches need to be complemented by robust operational insight, predictive capabilities, and the ability to work with incomplete, noisy datasets: characteristics that wildlife trafficking embodies. To advance scientific understanding of WTNs, we were inspired by the concept of supply chain resilience, or supply network resilience (SNR)—the ability of supply networks to operate in the face of disturbance and disruption without a substantial decrease in performance. Understanding the operational resilience of illicit supply networks is an almost ubiquitous contemporary need, as illicit trade has emerged as a significant problem for almost every government in the world (11). This ubiquity, combined with broad gaps in knowledge, encouraged us to explore new opportunities to explore advanced analytical methods from licit supply networks to help make more effective and efficient decisions about disrupting WTN operations (12), whether they are disrupted via law enforcement activities, social marketing, or economic incentive programs designed to shift or reduce or minimize harm. We believe there is a great opportunity for an exploratory paper to advance convergent thinking about WTNs among scientists, particularly those from conservation criminology, supply chain management (SCM), operations research, and computational science who can leverage strengths and overcome weaknesses of their single-discipline silos.

Key Features of Licit and Illicit Supply Networks in a Resilience Context

Transnational illicit supply networks exist for products beyond natural resources including drugs, guns, humans, microelectronics, organs, counterfeit medication, and antiquities. Counterfeit and pirated products are known to be purchased by consumers who sometimes know they are

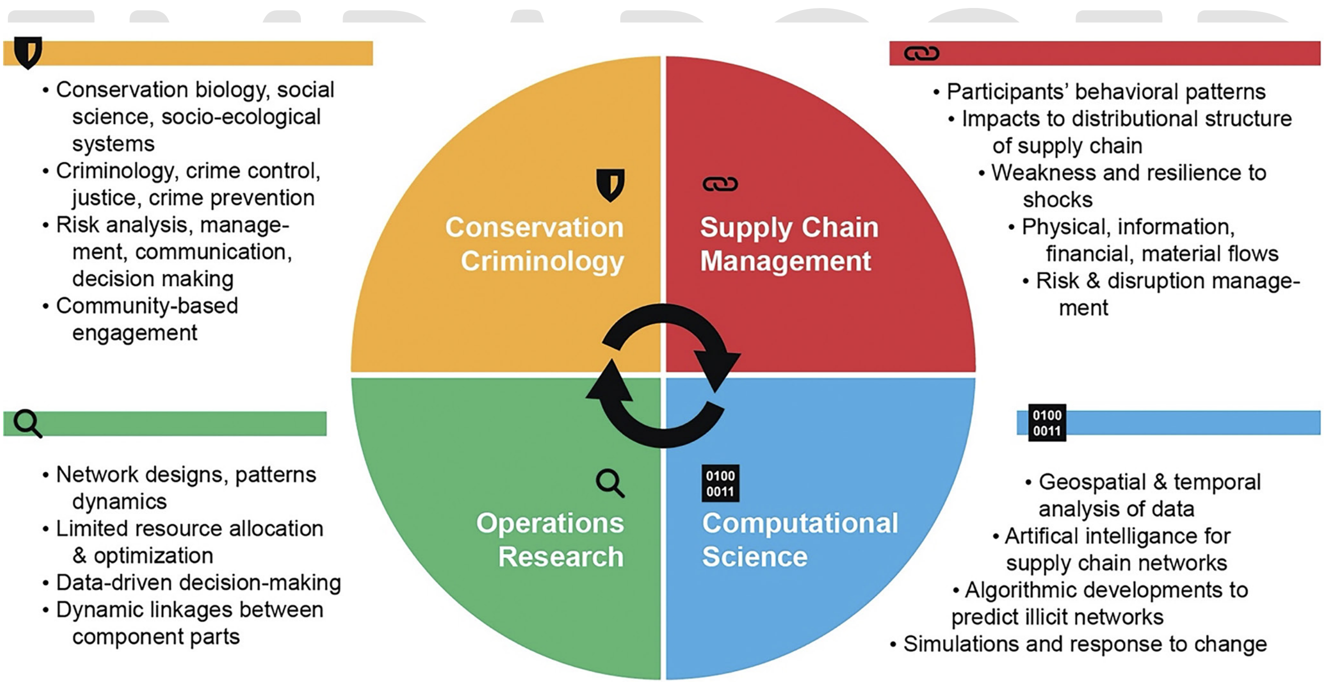

Fig. 1. Interdisciplinary approaches can advance scientific thinking about WTNs to help support efforts to disrupt them and help minimize their negative collateral impacts. The strengths of individual disciplines combine and mutually enhance one another.

buying fake products regardless of their awareness of the impacts of the illicit trade, access to licit alternatives, price, or value system. The comingling of licit and illicit goods through the economy is termed convergence (13). This convergence may occur across space, time, transport method, money laundering, and form of corruption (e.g., ref. 14). Although illicit supply networks have long been known to converge with licit supply networks as a function of logistics (15), much of illicit supply networks' operations function in the shadow of the licit global economy. In this regard, licit and illicit supply networks share many features. Licit SCM incorporates insights about physical, informational, and financial flows of products and services in the direction of the supplier to the consumer. Network characteristics can predict supply chain resilience for these flows moving in multiple directions. Licit supply network analysis characterizes flow shocks and vulnerabilities which adversely affect a legitimate firm's performance operationally, financially, and strategically (16). Just as marketing and supplier development initiatives can increase demand and supply for licit products, they can also serve to increase them for licit products. Operational perturbations and vulnerabilities are often spatially mapped according to network objects characteristics such as manufacturing plants (i.e., nodes) and roads (i.e., edges) (e.g., ref. 17). Disruptions in supply chains arise from discrete vulnerabilities in interconnected flows (18). Double-edged thinking about supply chain resilience offers a window into how licit supply networks can maximize efforts to maintain resilience throughout its component parts (e.g., be resistant to or quickly recover from disruptive events) and emergent processes such as order processing times. The general supply chain resilience concepts do not appear to have ever been applied to WTNs. Opportunities for research are proliferative.

SNR thinking encourages scientists to identify operational perturbations and the relevance of disturbance to supply chain function. One class of quantitative tools, especially analytic models based on operations research and machine learning, offer opportunities to advance scientific knowledge about resilience and vulnerability to operational perturbations such as interventions but are not possible to execute without first understanding the underlying supply network(s). Examples of possible interventions include legal remedies that revoke business licenses or mandate employee training; resource reallocation to reroute traffic patterns; human relations job and social services messaging. We know licit networks enhance their resilience using slack resources (e.g., more reserve inventory), responsive processes (e.g., nearshoring), and increased visibility through information sharing (e.g., track and trace capabilities) (e.g., 19). In an illicit setting, knowledge of the structure and scope of a WTN's structure could help those seeking to limit a WTN's actions. For example, the World WISE database covering 2007 to 2018 reported that India and Thailand (e.g., reserve inventories) were the main source countries of shipments seized in international tiger trade, together representing 82% of the whole tiger equivalents where the origin was known. Trafficking routes that have been identified are the trans-Himalayan route from wild populations in South Asia and multiple Southeast Asian routes (e.g., network diversification) through the Mekong Delta, making use of both wild and captive tigers (i.e., multisourcing) (1).

Although not all WTNs are managed as formally as licit organizations, the same physical, financial, and information flows for resistance and recovery remain necessary to get a product to market. WTNs responding to external and intentional shocks to their network need to make recovery decisions in a sequence involving disruption recognition, diagnosis of the problem, development of alternatives, and implementation, similar to what has been documented for licit supply chains (18). These disruptions can occur not only from law enforcement activities but also from the community and economic programs designed to reduce supply and demand, effectively dismantling the source and sink nodes that link pathways for WTNs. WTN research has failed to produce a single profile that describes all objects and issues in WTNs (20), it is generally known that: a) wildlife trafficking involves formal and informal inventory warehousing (21), which can serve to support development and implementation of alternative routes; b) the proportion of wildlife products subdivided into smaller parcels often increases as inventory flows away from protected areas (i.e., wildlife source) and toward urban areas (i.e., demand centers) (22), helping traffickers identify efforts to disrupt supply chains; and c) wildlife trafficking hotspots can be identified using combinations of proxy measures such as poaching locations for certain species, high-frequency seizure locations, crime commission process points (23), social media reports (e.g., ref. 24), or DNA typing (25). These traits apply across supply chain geography.

While SNR is often the primary objective of private sector managers and government officials, intentional disruption of illicit networks at vulnerable spaces is an important purpose of law enforcement and conservation entities as well as some financial institutions and regulatory bodies. Interdiction is a strategy by which authorities, from a variety of disciplines, can intentionally disrupt a network in a vulnerable space identified using hotspot deployment or focused deterrence (26, 27). In a licit supply network context, interdiction could be an action where one organization intervenes to prevent competitors from acquiring, moving, or converting critical resources, to gain market advantages (28). Examples of wildlife trafficking interdiction actions include technology-assisted interceptions at border crossings; boarding, detaining, or seizing, under lawful authority, of vessels, vehicles, aircraft, people, cargo, information, facilities, and finances. Other actions to reduce resilience could involve economic actions to prevent individual actors from supplying wildlife products (e.g., new regulations about fines) and community initiatives to increase the importance and protection of natural resources (e.g., education, awareness). These interdiction actions can be oriented toward prevention, deterrence, or intervention activities. WTN interdiction could be thought of a one set of possible actions taken to, among other goals, decrease WTN resilience through a focus on vulnerable network characteristics. Intervention is relevant to discrete, in-process, ongoing trafficking activities (e.g., a shipment of refrigerated containers of European glass eels via air freight under cover of, or misdeclared as, other seafood products) to blunt the actions, shipments, or network of specific traffickers, shipments, or their supply chains (e.g., Ireland's Rathkeale Rovers gang and their rhino horn trafficking) (29). The application of disruption activities for different WTN's varies according to their nodes (e.g., actors or locations) and edges (e.g., physical product movement, information flows, pathways).

Quantitative Models Can Advance Understanding about Illicit Network Resilience

Algorithms can help detect signals of WTN resilience and vulnerability characteristics and predict novel operational dynamics of edges, nodes, and flows. Operations research and game theory can provide insight into the most efficient and effective use of limited interdiction resources, by identifying network nodes and arcs that are vulnerable, and how a WTN may respond to interdiction activities. Together, they offer novel and robust opportunities to prescribe changes to WTN interdiction activities, understand WTN resilience, or optimize targeting of limited resources in a dynamic system (Fig. 2). There are decision-making trade-offs for WTN actors particularly with regard to how they will respond to interdiction activities. Because the characteristics of wildlife trafficking (e.g., obfuscation, laundering), and the products involved (e.g., tarantulas, tigers), are varied, it is possible that an interdiction that is effective for a specific wildlife product (e.g., nonperishable jaguar teeth being trafficked via postal service and personal luggage during international flights for consumers purchasing necklaces, keychains) may not work for another product (e.g., perishable tiger meat being trafficked to treat nausea or malaria). These conceptual feedbacks are situated within the local context often captured by conservation criminology and supply chain resilience thinking and be quantified through operations research and computational science (Fig. 2).

There is a risk that an interdiction activity targeting a vulnerable node in a WTN may not always be helpful or valuable in terms of impact. Resilience and vulnerability may also be time-and location-dependent as a WTN evolves over time. Competing goals for decision-makers can exist, such as to maximize the "total benefit" (e.g., maximize the number of nodes disrupted) or to minimize the "cumulative regret" (e.g., minimize the amount of illicit wildlife products flowing through the supply chain). Authorities can sometimes be considered defenders (e.g., law enforcement agencies or wildlife conservationists) in the context of modeling WTNs to maximize disruption of harmful activities, increase the traffickers' cost, reduce their flows, or make them easier to interdict by limiting their options. However, such officials can also be offenders (e.g., smugglers, hunters, and wildlife trade enablers) when corrupted.

Domain-specific challenges to applying computer science and operations research models to WTN are complicated by a lack of interoperable data about conservation biology and conservation crime (1) as well as a lack of common standards (30). Machine learning can help fill in data gaps by using available data to build models for predicting likely linkages and routes that have not been detected yet. Many quantitative methods are available for dealing with limited and difficult to process data, which is helpful in this interdisciplinary context (31). Techniques in reinforcement learning have become popular in the Operations Research literature in recent years and present a powerful opportunity to apply optimization methods to areas that have traditionally suffered from a lack of quality data (32). These methods attempt to balance exploring previously untested decisions to gather information about their potential benefits with exploiting decisions that are known to return benefits. In the context of WTNs, this could mean the trade-off between exploiting known trafficking routes by deploying resources to seize illicit goods and exploring potential new trafficking routes where perpetrators have not previously been detected to expand knowledge of WTN operations. Another example could involve the trade-off between dedicating resources to new programs, with unknown effectiveness, designed to reduce the supply/demand for a product in a certain area and increasing resources to enforcement initiatives.

Quantitative approaches that can advance understanding of the contours of WTN vulnerability from the perspective of both offenders and defenders include bilevel optimization and network design models, among others (33). Operations research models offer insight into more effective resource allocation for tactical and operational actions, sourcing practices to reduce the laundering of illicitly obtained products, and data-based decision-making for interdiction (31). Bilevel optimization models, for example, could help incorporate a range of domain-specific characteristics about WTNs and address both offender and defender objectives instead of single-focused analysis. Bilevel optimization models

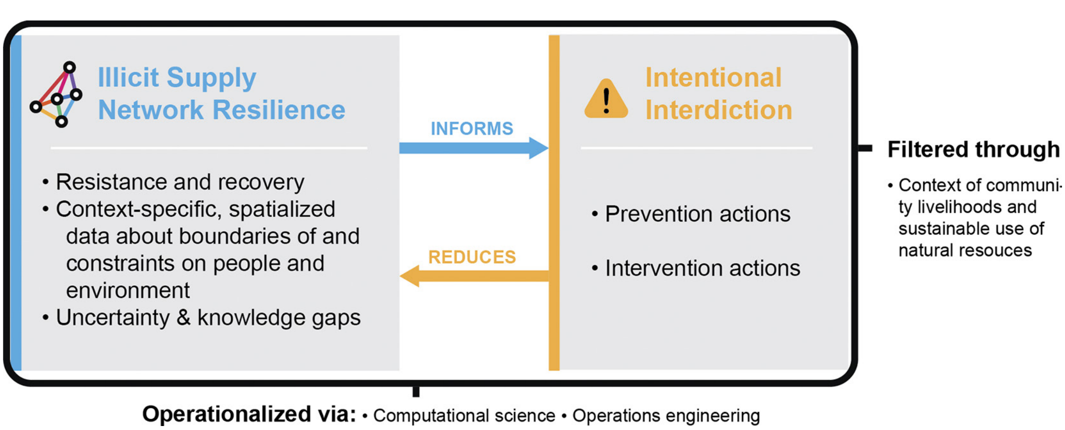

Fig. 2. Scientific thinking about WTNs can be advanced by quantitative computer science and operations engineering models that both inform on-the-ground interventions and consider the impacts of interventions on the resilience of the network. Feedbacks are filtered through the local socioenvironmental context.

determine how to best interdict WTNs by staying one step ahead of traffickers and considering how traffickers will respond to a deployed strategy such as focused deterrence. Models can predict the efficacy of different interdictions for a variety of single or group defender and offender objectives. For example, a trafficker's objectives may include minimizing cost when choosing a path from origin to destination, maximizing their chance of evading detection during trafficking, or minimizing the severity of consequences if caught. Different objectives could be applicable in different contexts and for different products or actors. For example, when trafficking rhino horn, minimizing the chance of detection or minimizing the severity of consequences would likely be appropriate objectives for traffickers, given the international attention placed on rhino horn trafficking in comparison to other wildlife products. Defenders, or other stakeholders working to interdict WTN's, have their own objectives, which may not align with offenders' objectives. Defenders may aim to minimize the probability of escape for the trafficker or maximize the penalty for the trafficker, such as concentrating interdiction in countries where legal systems are best equipped to penalize traffickers. Varying enforcement landscapes are a key characteristic of WTNs. For example, Randriamady et al. (34) noted multiple management authorities could be present in the same region of Madagascar at the same time (e.g., traditional management with no external assistance, community-based forest management with nongovernmental support and externally developed policies, strict eternal management policies), where illegal hunting and trafficking of endangered lemurs occur. We cannot identify any empirical study applying such tools in the scientific literature.

Path prediction models could, for example, advance understanding about transit routes between source and destination geographies based on resilient systems and noisy data: which pathways are used because they enable network diversification, inventory buffers, or nearshoring? Because WTNs are agile and can adapt quickly to changes in enforcement efforts and shifting patterns of supply and demand, data-driven models about transit routes can incorporate important factors and their weights to provide insight into traffickers' objectives and decision dynamics that can be used when making interdiction decisions and predicting trafficking responses. For example, in Madagascar's Baly Bay National Park, ploughshare tortoise poachers and traffickers may choose between boat, bike, or walking trails to transit between source and destination geographies depending on the season (e.g., rainy, dry), tide and moon cycle, size of the group (e.g., single person, multiple people, single animal, multiple animals). Path prediction can be considered as a type of inverse optimization problem, where scientists use historical trafficking path examples to infer how traffickers value different aspects of a route beyond environmental variables, such as transportation cost, local resilience efforts, cultural drivers, and the presence of other illicit activities. Predicting transition probabilities offers an opportunity to consider the source, destination, *and* alternative transit geographies of a WTN alongside multiple features of the system. Computational models could advance consideration on the tactical allocation of defender resources as well as the strategic question of how to deploy resources as networks adapt to change (e.g., tactical and strategic decision-making). Once the network structure and components are understood, the security-related, game-theoretic approaches that currently exist for cyber, cyberphysical, and licit supply networks systems (e.g., ref. 35) could be utilized to inform security investments, such as sensor or checkpoint placement, to detect and interdict specific WTNs or to create a deterrent effect. In practice, law enforcement authorities could use hot spot deployment (i.e., focusing limited resources on specific geographic regions deemed high priority) and/or focused deterrence (i.e., targeting co-offenders with tactics to increase the certainty, severity, and celerity of punishment) strategies based on such analysis (36).

Toward Transforming the Knowledge Landscape About WTNs: The Case of the Ploughshare Tortoise

Knowledge of the process model and systems for licit networks and their resilience is needed from SCM to begin informing insights about illicit network resilience and opportunities for specific interdiction actions. SCM recognizes that interdiction does not have to target a person (e.g., poacher, trafficker), but can rather target the nodes, the mode, or the structure of a network. When promoting resilience into licit supply chains, theory suggests adding visibility and collaboration among partners (37). Conversely, these same capabilities reveal a potential exposure of, and interdiction opportunity against, illicit supply chains trying to operate unimpeded and keep their network from being visible while minimizing additional collaboration among partners to account for growing risk of detection or focused deterrence.

As a case exemplar for the interdisciplinary approach advocated in this paper, we profile ploughshare tortoise (*Astochelys yniphoroa*) trafficking. The tortoise is endemic to Madagascar's Baly Bay National Park and affected by poaching for the international illegal pet trade because of the animals' rarity, beautiful carapace, and charismatic "plough." Prior to 2010 few tortoises were confiscated either in Madagascar or internationally, but global demand for charismatic and unique pets fueled an explosion in trafficking. Field reports suggest that two of the four subpopulations are now extinct; population estimation studies conclude the species has declined rapidly. There is a need for increased action both within Madagascar and along international trade routes if the extinction of the ploughshare tortoise in the wild is to be prevented (38). Ploughshare tortoises are one of the rarest tortoises in the world; they have been protected by Malagasy law since 1960 and are listed on Appendix I of CITES. All known ploughshare habitat is protected as a "core zone" of Baly Bay National Park. Conservationists know the primary destinations for ploughshare tortoises based on confiscation patterns are southeast Asia with animals typically transiting through the Middle East (38).

The potential for interdisciplinary approaches such as those discussed herein is still unrealized and could help transform the knowledge landscape of ploughshare tortoise trafficking and poaching and inform new supply network interventions designed to reduce the illegal trade, particularly if interoperable datasets became more widely available and accessible. Key questions include, given knowledge about ploughshare source and destination geographies, can we predict which path a trafficker will take? Or, what helps explain a trafficker's path and at a given node, what node will be next? Which nodes could be targeted for communication programs designed to decrease the supply of tortoises coming from the park? Which paths are associated with cultural practices and historical drivers of social disadvantage? How could we allocate limited resources to target nodes most efficiently to stem the flow of ploughshare tortoises out of Baly Bay National Park and off the island of Madagascar? Our efforts to operationalize this interdisciplinary framework for disrupting WTNs are in their scientific adolescence but portend exciting possibilities for advancing knowledge.

In 2018, a participatory risk mapping workshop was held in Soalala, Madagascar with approximately 50 stakeholders. A color base map of the region was placed underneath a clear plastic overlay and participants used colored grease pencils and markers to map the physical location of tortoises, trafficking pathways, villages, and other places that participants deemed relevant to the WTN (Fig. 3*A*). Participants mapped their lived experience and expertise about ploughshare tortoise source locations, transit routes on land and sea; they also numerically weighted the risk of each node and edge to trafficking (i.e., vulnerability), distinguishing between bike, foot, and vehicle paths (i.e., feature importance) (Fig. 3*B*). Participants provided data based on their lived experience about paths associated with cultural practices (e.g., avoiding an ancestorial and sacred tree), details about how tides influenced decisions to use boats versus bicycles to move animals, and where poachers staged nearshore while planning their activities. All stages of research adhered to human subject protection protocol requirements.

Data from the plastic overlays were digitized and georeferenced in a geographic information system, triangulating a "mess" of possible pathways and nodes existing in a slack or inefficient supply network. SCR-related insights about ploughshare tortoise trafficking helped identify key feature importance among this "mess" (e.g., where key places such as poacher camps, source of animals, and transit pathways spatially overlapped). The data also illustrated key network resilience characteristics (e.g., ocean-based transit pathways were prolific and preferred but could only be used during specific tide and moon phases) and a suite of variables that could be used in SCR analysis (e.g., clustering of poacher camps along coastlines) to offer a different foundation for modeling the knowledge landscape other than, for example, a conservation-only– or land-only–based study. The WTN reliance on water for logistics (e.g., serving as a resilient pathway for moving tortoises) and worker access (e.g., staging poacher camps on coastline) for example, was deemed important by participants.

The potential effect of network interdiction on ploughshare tortoise trafficking, or other WTNs, cannot be measured without understanding its underlying network resilience. There are multiple entry points for applying process or computational approaches to the problem domain; however, the need for larger datasets and data collection precedes the benefits of existing tools being realized or translating new methodologies that fit WTN requirements. Different knowledge landscapes portray a different definition of the problem, for example, mapping the multiple network routes on land and at sea indicate where the network has the capacity to absorb and thus withstand disruption and also the capacity to adapt, when necessary, to changes arising from interdiction.

Resilience depends on the level of redundancy that is inhabited in the network structure, which has now been mapped and can be computationally analyzed. Beyond the mathematical analysis of the ploughshare trafficking network structure, the approaches suggest considering multiple transit routes (e.g., multiple edges) and spaces outside the national park (e.g., nodes) as part of the resilience characteristics of the WTN. For example, applying path prediction analysis and bilevel optimization to water-related transit data could refocus hotspot deployment about where to target interdiction activities targeting primary node pairs or node-path pairs and suggest new focused deterrence locations on water where partners such as small-scale fishers might be engaged in surveillance, reporting, and monitoring. One could compare different disruption strategies (e.g., hotpot deployment, focused deterrence) aimed at new nodes within the network (i.e., high degree centrality places such as poacher camps instead of the protected area where the tortoises are sourced) or focus on pathways within the network

Fig. 3. Selected (*A*) supply chain network features and locations for ploughshare trafficking, and (*B*) different paths used for trafficking ploughshares, derived using participatory mapping methods in Soalala, Madagascar, 2018. Line color denotes boat, foot, or bike path. Q:8

(i.e., high betweenness-centrality places such as water routes converging around the northeastern peninsula instead of the walking trails surrounding the protected area)?

Although we lack the data to model how the WTN would recover by replacing target actors and relations using ties and connections in the network, such insight would significantly advance our understanding of resilience. SCM process mapping provides initial network understanding, while larger-sized, interoperable, and open-access datasets would help achieve the objective of further interdiction. Empirical research would be hugely beneficial to this knowledge base across spatial scales and amplify the novel contribution of WTNs through machine learning and computational modeling.

A Call for Convergent Science to Disrupt WTNs

Wildlife trafficking can be a financial driver of social conflict, with implications for geopolitics, security, and sustainability. Illicit markets for wildlife and wildlife products have received insufficient interdisciplinary scientific attention. New scientific evidence about how WTNs operate can help inform resource allocation, monitoring and enforcement, promote equity, and communication effectively across efforts to combat wildlife trafficking. Given the changing and shifting patterns of WTNs, more advanced, dynamic, and convergent science techniques will most accurately capture patterns and respond to the changing environment. Convergent science frameworks should be employed to enable new thinking about the characteristics, mechanics, and resiliencies of WTNs comprising complex supply chain network components and decision point(s) made by multiple decision-makers with the goal of interdicting WTNs and helping to maintain the Earth's biodiversity. Insights herein suggest a wide berth to generate new science-based recommendations for WTN-related data collection and analysis for supply chain visibility, shifts in illicit supply chain dominance, or limits of the supplier base. Until then, it will be difficult to systematically identify WTN threats, vulnerabilities, and resilience to disruption efforts. Understanding WTN resilience has major implications for the way we think about control strategies aimed at wildlife trafficking, promoting justice in control actions, and conserving biodiversity. We humbly offer the following opportunities: 1) multidisciplinary teams should be supported and provided the time and resources to succeed; 2) universities could include more socioenvironmental systems thinking in required courses; and 3) scientific journals more widely publish convergent science exploring different problem domains.

Data, Materials, and Software Availability. All study data are included in the main text. Q:9

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