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ORIGINAL ARTICLE

Introducing Bayesian belief updating as a method to counter improvised explosive devices: a qualitative case study on identifying human behaviours associated with explosive chemical precursor diversion

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Abstract

Countering improvised explosive devices (C-IED) is a significant theme of the twenty-first century, particularly in regions with limited governance and a fragile rule of law. Many strands of activity are involved, with human interaction proving difficult to predict. However, Bayesian belief updating (used across several academic fields to provide insight into human behaviours) has never been considered. Given the breadth of C-IED, this research focusses on a state affected by conflict, and where illicit diversion of explosive chemical precursors (ECP) for IED manufacture is supported by the population. It aims to represent (both visually and probabilistically) a methodology by which human relationships could be better understood, thereby promoting belief updating as new evidence becomes available. Such belief updating would refine focus and improve resource mobilisation.

Keywords Explosive chemical precursor (ECP) · Bayesian belief updating · Countering improvised explosive devices (C-IED) · Home-made explosive (HME)

Introduction

The international approach to countering improvised explosive devices (NATO Standardization Office 2018) suggests that *'IED networks'* are responsible for the diversion of commodities for use within improvised explosive devices. The IED network is defined within that approach as interconnected human and/or materiel nodes that may be identified, isolated, or engaged. Commodities range from electronic components, such as relays and switches, to military and commercial explosives (such as plastic explosives, detonators, and detonating cord), and precursor chemicals used to manufacture home-made explosives (HME). By attacking these networks, the intent of C-IED is to minimise component acquisition

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and IED use. However, such networks do not exist in isolation (Radisch 2016), they are a subset of broader criminality, with component acquisition promoted and inhibited by many different pressures and variables (Jackson 2001), such as supply chain availability and the relative advantage to be gained over the opponent by favouring one commodity over another. For example, global illicit trade involves the economic or ideological exchange of prohibited goods and services within interlinked *'dark'* networks, ranging from the trafficking of illegal narcotics and endangered wildlife to the exploitation of migrants, children, and sex workers (UNCTAD 2019). These networks are well-established, lucrative businesses for transnational criminal organisations, and as such there is no need to establish one specifically related to IEDs. Given that they are estimated at U.S. $2.2 trillion per annum, or 3% of the world's global economy, these networks are protected, financed, and extremely difficult to disrupt (Coke-Hamilton and Hardy 2019).

The scope for 'trafficking' IED components across *'dark'* networks is therefore extensive. As such, this paper focusses on the acquisition and use of explosive chemical precursors (ECP) used in the manufacture of HME since there has been a significant increase in their use over the past decade, despite improved regulation or other sensible measures such as substitution being applied. For example, hydrogen peroxide (a heavily regulated ECP) has been used in 43% of all Jihadist explosive devices in Europe over five years (Bertelsmann Stifftung 2022), whilst sodium nitrite (used as an oxidiser within certain HME), cannot be substituted by a less useful precursor since it appears on the World Health Organisation's list of essential medicines as an antidote to poisons (WHO 2021). The dual-use nature of most ECP considered useful in HME manufacturing therefore invokes a supply chain conundrum, which must be addressed at the global level (Collett et al. 2021).

Similar to wildlife crimes, drug smuggling, human trafficking, and terrorism, the illicit diversion of ECP is accompanied by societal need (Duffy and St John 2013) and behavioural prediction (Azjen 1991). Criminal behaviour is based on the social learning theory (Pallone and Hennessy 2018), which considers how environmental and cognitive factors interact to influence human learning and behaviour. As such, the participating society is required to change, and for that to happen, human security must be strengthened, and visibly so. If not, the problem endures, which has been one of the aspects of C-IED failure in Iraq due to the cyclical violence of the lived Iraqi experience at the individual and collective level, owing to repeated failures in reconciliation (Sanbar 2020).

There is ample physical evidence of the illicit diversion of ECP and the widespread adverse effects of HME on economies (CAIN 1996), societies (Chepkenen et al. 2020), and the environment (Hussona 2020), including broader security implications (United Nations Security Council 2017). ECP use in HME manufacture is therefore likely where access is possible. This is because criminal supply chain activity does not conform to any regulation that can be policed effectively when national capacity is fragile (Naylor 2004). Such criminality involves murder, intimidation, corruption, circumvention, concealment, avoidance, and preemption (Williams 2001). In many instances, this criminality embeds itself within

the organisation providing the security function, whether by intelligence-gathering roles (such as reporting when consignments of importance are being delivered/transported), or simply turning a blind eye. Indeed, individuals' sole motivation may be the need to provide for the family (Shinn 2016) (Dieye 2017). Causal factors such as this may therefore influence the human environment surrounding the illicit diversion of commodities and must be considered within any approach if identified.

NATO's C-IED strategy encompasses collective efforts to defeat an IED system by attacking networks, defeating devices, and preparing a force to operate effectively (NATO Standardization Office 2018, pp. 1–5). Within this doctrine, the IED system incorporates the personnel, resources, and activities necessary to resource, plan, execute, and exploit an IED event, with *'attack the network*' (AtN) identifying key nodes (such as a node of supply) for degradation. This degradation can be kinetic or non-kinetic, with such strategies sequenced or combined in some manner to achieve greater effect (Roberts and Everton 2009). Degrading such a network aims to identify critical vulnerabilities against which appropriate countermeasures can be applied. Understanding and intelligence gathering therefore underpins the NATO C-IED approach for identifying critical vulnerabilities (MOD 2013). Such an approach helps to identify and assess the relationships or connections amongst people and organisations involved in crime, helping to understand and visualise the network. Terminology such as *'critical node'* demonstrates that those of high importance or low redundancy levels can be selected to focus law enforcement efforts (Sparrow 1991). However, the approach is often initiated at the request of state or international governments, with few breakthroughs achieved (Nolin 2011). It is shaped by the interests of leaders rather than being guided by a consultative process to assure the security needs of communities (Guiyranan et al. 2021). Such initiatives fuel corruption, repression, and violence, whilst neglecting social capital and social contracts that may govern any node, or a criminal organisation's ability to regain stability after a significant AtN setback (Woods and Hollnagel 2006).

Furthermore, human intelligence (HUMINT) is often overlooked in favour of technical intelligence by policymakers, leaving operations vulnerable to counter-intelligence (Margolis 2013). An example of this is Afghanistan, where technical intelligence focussed on developing equipment solutions to defeat the IED threat posed by the Taleban, as opposed to the Taleban's counter-intelligence cycle that outpaced most solutions delivered (Medina 2011; Rayment 2011). Damage assessment is therefore difficult to verify in the NATO approach when people and their motives form the most vulnerable element of any network. Afghanistan and Iraq present recent historical examples where this long-term NATO strategy has failed through NATO's inability to neutralise transnational terrorist groups (Bauer 2007).

In terms of a humanitarian C-IED approach, the UNIDIR model considers sixteen upstream and downstream capacity development measures, which are either preventative or mitigative. These are described as all the activities a State may undertake to prevent and mitigate the use of IEDs (UNIDIR 2020, p. 11), with ECP mentioned explicitly in *'Upstream Capacity Development Measure 6'*. The upstream measure is entitled *'Control of IED Precursors'*. It attempts to assist states to recognise that some materials may be misused in the manufacture of HME and how restrictions may be applied to protect communities and improve information flow. Under the

assessment criteria proposed within this model, the complexity of the human environment is not considered (Guiyranan et al. 2021), and may also be compromised.

Therefore, common approaches to C-IED do not reveal the causal nature of the problem amongst the people. They lack a mathematical theory of evidence which Shafer (1976) purported to be essential for serious research on problems relating to the rules of combination of evidence in complex systems. Current approaches systematically identify points of failure (FMEA) within an *'IED System'* for interdiction, action or pressure, or where capacity development can be focussed. This reductionist approach underplays the *'wickedness'* associated with criminal networks (Rittel and Webber 1973). Using the illicit poaching of rhino horns as an ecological example (Koen et al. 2017), reductionism proves insufficient to resolve problems involving complexity and human beings. As such, military, humanitarian, and ecological approaches to C-IED provide limited resolution but, with the help of belief updating, based on community observations, may provide insights that facilitate effective countermeasures. It is within that modelling context where Bayesian belief updating is considered useful since it has been used across several academic fields to provide insights into human behaviours that influence decision-making (Goldszmidt and Pearl 1996).

Aim

The aim of this paper is to illustrate how community dialogue can be a useful tool to flesh out strategic options in dealing with an IED threat, and to introduce Bayesian belief updating as a method to improve focus, using the illicit diversion of ECP in a conflict-affected state as an example.

Methodological approach

The methodology used in this research can be considered in seven steps: literature review; the identification of peer-reviewed mathematical modelling pertinent to C-IED; the consideration of ethics and approvals to underpin anonymity; minimising bias and controversy within data collection; identifying and understanding an appropriate ECP; determining the role of human beings in the diversionary process; and selecting the most appropriate modelling method from which to establish areas of focus and predict future success. The research does not distinguish between terrorism and organised crime since the act of illicit diversion of ECP is a criminal activity, whether used for terrorist purposes or otherwise (United Nations Security Council 2019).

Literature review

Step 1 involved a literature review of the institutional approaches to C-IED adopted by states and armed forces concerning human security (Paris 2001), including a

review of the international programmes undertaken to degrade criminal networks. This literature review is incorporated within the introduction.

Peer-reviewed mathematical modelling pertinent to C-IED

Step 2 comprised an examination of peer-reviewed mathematical modelling used to identify instability within regions, and in particular the region pertaining to the state considered within the research. It was found that academia applies mathematical modelling to regional instability through several published indices that analyse the impact of conflict, terrorism, and corruption within a state, and where the status of governance and the rule of law is placed in relation to stability. These indices provided meaningful statistical information to inform understanding of that state, and the most applicable to C-IED are summarised in Table 1, including their relevance to the research:

Ethics

Step 3 involved receiving ethical approval. There are obvious ethical considerations when researching sensitive material relating to C-IED and the human environment. The methodology of this paper was therefore guided by the normative ethical principle of *'do no harm'* (Beauchamp and Childress 2001). Ethics approval was made and accepted by Cranfield University's Ethics Committee in early 2021, and subsequently the United Nations Development Programme (UNDP), which has been pivotal in completing this work. UNDP ethical approval insisted that any information be collected impartially by an implementing partner and safeguarded. It should be presented for this paper in a qualitative and *'stateless'* form; and that non-disclosure of implementing partners and experts be observed (UNDP 2017). Confidentiality was assured through the establishment of community focus groups, not individuals or professions. Focus groups were not remunerated, and attendees at C-IED consultations were advised of their rights to participate, or to be present and simply observe rather than actively engaging in the discussion. Focus groups were aware that the overall intent was to identify areas from which to improve community safety. They were free to discuss various issues within consultation, such as drugs, gender, and sexual violence.

No comment, statement, or answer by a focus group is identifiable. Several academics and historians expressed the desire to be cited directly, but the authors determined to withhold this for security and sensitivity.

Working within communities where non-state armed groups operate is also challenging, and few organisations manage to do it successfully. Ceasefires may stop the violence for a while, but they do not resolve conflict (Clayton et al. 2019). Therefore, this paper does not examine the capability and intent of any terrorist organisation mentioned, or seek to resolve conflict, but considers how ECP use could be diminished by better defining the causal factors on which to focus.

Table 1 Peer-reviewed indices relevant to C-IED

Index	Description	Relevance to research
The Global Terrorism Index (GTI)	A comprehensive study analysing the impact of terrorism, covering 99.7% of the world's population (Institute for Economics & Peace 2022)	Examines human security, and the definition recognises that acts of terrorism have a psychological and physical impact on society for many years. This index positions a country as the most and least affected by terrorism. For this research, the authors are interested in the socio-economic conditions under which terrorism occurs within the state
The Global Peace Index (GPI)	Comprises 23 indicators of the absence of violence or fear of violence within a state (Institute for Economics & Peace 2021). Positions the most and least peaceful countries within a regional context	How the level of societal safety and security, the extent of ongoing domestic conflict, and the attitudes of the local security forces towards the population affects the illicit diversion of ECP
Corruption Perceptions Index (CPI)	The CPI aggregates data from several different sources that provide perceptions amongst business people and country experts of the level of corruption in the public sector (Transparency International 2021)	The impact of corruption on the illicit diversion of ECP. Criminal threats and common distrust in society are linked to corruption (Francis 1986)—the higher the level of corruption, the higher the distrust in society, which reduces interaction with law enforcement. This paper draws data from a country within the 'developing' bracket (limited ability to counter corruption)
The Bertelsmann Stiftung's Transformation Index (BTI). Governance and Rule of Law	Considers transformation processes towards democracy and a market economy in international comparison and identifies successful strategies for steering towards peaceful change (Bertelsmann Stifftung 2022)	Whether or not communities have confidence in the rule of law and if any economic considerations motivate illicit diversion

Minimising controversy and bias

Step 4 involved minimising controversy and bias.

The use of IEDs within, and by communities, has long been a point of controversy, with the IED narrative of the twentieth and twenty-first centuries, linking them to terror organisations and brutal regimes (Revill 2016). Use is driven by hate, support is driven by fear or ideology. Stacey (1988) initially advanced the importance of including sensitive and controversial areas, such as war crimes and ethnic violence, in their association with a group narrative. She argues that institutional behaviour is informed by presumptions of human behaviour, not the actual reasons for behaviour. It is from successes in such an approach that the sensitivity of gathering information on IED use was considered less *'taboo'* when debating issues concerning community safety. To ensure that such a controversial approach was acceptable, clearance was sought from the Prime Minister's Office, the Ministry of Interior, family protection directorates, victim support organisations, and the governors/community leaders of the locations where focus groups would convene. Access to affected communities was unanimously supported.

To ensure no bias from the authors, UNDP selected the implementing partner independently and through fair competition. The implementing partner needed to be of national descent given the mistrust towards international organisations yet divorced of the politics within the communities. Similarly, to prevent bias from the implementing partner, the organisation was provided direction from UNDP governance and rule of law representatives and international humanitarian law experts to introduce and discuss several thematic areas concerning human security and steer debate, and did not provide an opinion.

Locations for the research were identified from humanitarian organisations recording the impact of explosive violence within the country as part of the ongoing conflict. Those areas most heavily affected by IED attacks were chosen, but where safe access could be guaranteed. Focus groups were established only in areas separated by hundreds of miles and facing entirely different IED threats from non-state actors, criminals, and terror groups. Representation comprised men and women from across society, including those working extensively within the supply chain and victims of explosive violence. Given all the above, risk of bias was reduced to as low as reasonably practical.

Choice of precursor and percentage use in IEDs

Following ethical considerations and approval from sponsors, Step 5 involved the identification of a suitable ECP within that state whose use could be determined. Ammonium nitrate was chosen given its significant volume of global trade (Knomea 2021), the overt involvement of international law enforcement towards its regulation (Collett et al. 2021), and increasing evidence of its use in that particular state through United Nations Security Council reporting.

For this research to determine the type and amount of ammonium nitrate used in HME, it was necessary to compare the volume of legitimate trade to that country and liaise with national demining organisations and local law enforcement to assess the volume used in IEDs. This would provide a percentage figure of use over several years where records were available.

Determination of causal factors in ECP use

Step 6 involved the interpretation of information provided by the focus groups so that trends in ECP activity could be identified. The information provided by the implementing partner and focus groups was assessed by an expert panel to determine the most appropriate modelling method to represent and interpret data. Owing to the complexity of the information provided, a panel of defence, security, and humanitarian experts was convened to interrogate the views of focus groups into root causality that could be used within an appropriate model. The expert panel was also provided access to the indices for the country in question (described at Step 2) and associated UN Security Council reporting. The expert panel adopted the following process to submit, review, or reject the available evidence provided by ten (10) focus groups, based on its relevance to ECP diversion (see Table 2).

Choice of modelling method

Following the collation of data and further literature review based on the data obtained (Steps 5 and 6), the authors identified Bayesian belief updating as the potential modelling method (Step 7). Firstly, the methodology supported reasoning under uncertainty (Goldszmidt and Pearl 1996), and has been successfully applied throughout human factors research across several disciplines such as engineering safety (Sii et al. 2001), failure mode analysis (Braglia et al. 2003), security (Yang et al. 2009), poaching (Koen et al. 2017), and most recently genetics (Zhu et al. 2021). Secondly, Bayesian reasoning could conveniently update prior judgments when new evidence becomes available (Korb and Nicholson 2011), making it ideal for changes in circumstance over time (as a state moves towards improved governance and rule of law for example). This would provide longevity to future research. Thirdly, further reading on the diversity and uncertainty of information in complex environments (Chin et al. 2009) led the authors to discount other theories such as FMEA, AHP, and ANP. Bayes' theorem was therefore chosen as a viable method to assess ECP diversion since it provided *'weights of evidence'* to determine the level of risk priority that should be apportioned to effective decision-making, and which has proven successful in unpacking the complexity of poaching (Koen et al. 2017).

However, two fundamental problems have been addressed to build a Bayesian network around ECP. The first was to determine the structure of the network (the

Table 2 Qualitative acceptance criteria

Focus group	Implementing partner		Panel of experts		Authors
1	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
2	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
3	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
4	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
5	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
6	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
7	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
8	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
9	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject
10	Validated	Submit	Validated	Submit	Accept
	Not validated	Review	Not validated	Review	Review
		Reject		Reject	Reject

qualitative part, which is usually called a directed acyclic graph (DAG)), and the second was to determine the conditional probabilities associated with each node (quantitative). In this research, the experts sought to establish the DAG associated with ECP diversion within the state, but stopped at anything further than establishing the most basic conditional probabilities. Based on those areas of potential focus identified, belief updating would need to be applied to determine successful outcomes, and which is funded throughout 2023 and 2024.

Results and discussion

Ammonium nitrate use in HME

Senior law enforcement officials within the state identified that by far the largest explosive constituent of IEDs comprised military ordnance, owing to the limited security of ammunition stockpiles. However, discussion with the national demining authority and UNDP established that the use of ammonium nitrate (energised with aluminium) within improvised mines and IEDs over four years had been significant. Whilst the numbers in circulation are difficult to predict (they are only encountered during clearance operations), the use of AN between 2018 and 2021 could be determined from the Information Management System for Mine Action (IMSMA) as 92,000 kg (see Table 3):

Port Authority data identified that 1,457,610 kg of AN had been delivered as part of legitimate trade over that same period, intimating that 6.3% of total volume imported had potentially been used to manufacture IEDs and improvised mines. This percentage is important since it establishes the start-point from which to determine whether usage would diminish over time by applying belief updating. For example, if the amount of usage is 6.3% in 2022 (based on data over 4 years) what would that percentage be in 2026, once the causal factors had been identified and belief updating implemented?

Vulnerabilities identified through focus groups

Of the ten focus groups established between November 2020 and December 2021, the authors can determine (alphabetically) eleven critical vulnerabilities specific to the illicit diversion of AN: awareness (lack of); bribery and corruption; coercion and intimidation; consultation (inappropriate international focus); domestic availability; employment (limited funded employment); idealism; inspection (limited checks); opportunity (relative advantage moving towards HME); security (lack of); and visibility (of overt criminality). These are described in more detail in Table 4:

It must be pointed out that focus groups remained fully engaged throughout the research and were passionate about the impact of IEDs within their communities. They were keen to express views, which is paradoxical to the opinions and humanitarian imperatives of many international organisations (UNMAS 2018). Just as Stacey has surmised (Stacey 1988), it was a *'taboo'* topic that needed to be aired, so

Table 3 Numbers of mines and IEDs recovered over 4 years containing HME—source IMSMA (Geneva International Centre for Humanitarian Demining 2019)

Year	Improvised mine	IED	Contain HME
2021	1204	1032	448
2020	923	512	287
2019	1536	786	465
2018	1691	918	522
Totals	5354	3248	1722

Table 4 Vulnerabilities identified by focus groups

Vulnerability	Remarks
Awareness	Limited understanding within the supply chain regarding an ECP and its dual-use. As such, little attention was paid to the movement of agricultural or industrial products, less those with a corruptible value chain (food, fuel, water). Ammonium nitrate was seen solely as a fertiliser for agricultural use
Bribery and corruption	A heuristic and anecdotal view that access of criminal entities to some key contributors in the supply chain was known about, but not acted upon. The local security forces, immigration, port, and customs authorities were cited as the most problematic, with significant irregularity in the payment of wages being the principal cause. The *'shadow economy'* available through terrorism and criminality was a method of obtaining income security
Coercison and intimidation	Punishments imposed by terrorist and criminal entities for non-compliance were an ominous undertone within some focus groups, but not all. Impotent justice systems were unable to react to reporting. The legal system was confession instead of evidence-based, leading to minimal prosecution and subsequent retribution for crimes reported. Little, if any, evidential process or the will of security forces to see an investigation to a conclusion
Consultation	Lack of international investment on matters of priority within communities. The community need may not necessarily align with the international view of need, and the impact of IEDs has never been previously discussed. Explosive violence, sexual violence, and drugs were cited as significant issues, leading to identifying many areas where governance and the rule of law levers could be better applied. Local security force response to IEDs was focussed upon specific points of intervention (such as an individual) with no understanding of the long-term effect of that intervention. There had been no reduction in the number of events or civilian casualties due to such interventions. Indeed, IED use had increased by over 20% from the previous year
Domestic availability	Ammonium nitrate was reported to be commonly available for purchase at market, and in quantity. There is no understanding of regulation given that the need for nitrate fertilisers was widely shared across multiple households given food insecurity. IEDs comprising AN were considered easy to manufacture by those with a knowledge of explosives (no requirement for melt casting such as TNT)
Employment	The lack of jobs was seen as a critical driver amongst disaffected youth to support the illicit supply chain. The deteriorating security situation drove the necessity of cash incentives to feed the family. The government was not paying wages across several employment groups, including those with supply chain access. Coordination with endowment offices to intensify awareness was lacking. The shadow economy's attraction severely undermined any advancement towards achieving peace, justice, and strong institutions
Idealism	There was little support for terrorism or criminal acts based on idealism. Of those consulted, very few recognised ideologies as a motive to stymie their communities
Inspection	A lack of resources, or even funds to pay staff, prevented effective security regimes from being put in place

Table 4 (continued)

Vulnerability	Remarks
Opportunity	The opportunity to use military and commercial explosives was diminishing due to improved physical stockpile and security management. The chance to use ECP existed, with access to the internet readily available. However, focus groups alluded that IED use was at an industrial scale, with users proficient in HME manufacture
Security	Lack of investment in security architecture or facilities. Limited training. Multiple security entities with differing allegiance working within ports—some recognised within the peace process, others not. They have limited information technology and surveillance. Some institutions are more corruptible than others. 'Insiders' can flag and identify shipments of vital interest. Little evidence, if any, of criminal entities promoting opportunism but more organised planning. Trusted insiders manipulate access to ECP for use by organisations (Shalini Punithavathani et al. 2015). Tribal contracts override security contracts. Gathering accurate and meaningful metrics for illicit diversion had never been attempted, given limited national law enforcement (Anderson 2007)
Visibility	Mixed views on the visibility of criminal entities. Whilst a common principle in states with a robust rule of law would be to avoid law enforcement (Malik 1990), observations were made that criminal elements did not necessarily hide their presence or involvement in some districts. It added to an individual's *'wasta'*

that improved international focus could be applied to the problem. Indeed, focus groups were so enthusiastic that they applied themselves to the materials provided (such as flip-chart, post-it, or picture), collating thoughts into areas of similarity.

The views of the expert panel, based on available data from focus groups, indices, and reporting

The vulnerabilities identified by the focus groups were consolidated into 12 root causalities by the expert panel, as shown in Table 5. In terms of terrorism, corruption, human security freedoms, and violence, there was a direct correlation to the peer-reviewed indices. For example, the GTI provided index scores relating to the modus operandi and intent of the world's four most deadly terror groups, including reference to their impact on the local population. Whilst the focus groups did not refer to these organisations by any western nomenclature, two of those four terror groups were described as hugely influential within the community, but not for all the reasons western definitions of terrorist organisations may reflect. It was, therefore, quite simple to pull several strands of observation under the heading of 'terrorism', to have confidence that the GTI rating was statistically accurate, to determine the main area of impact which was almost exclusively security related, and to separate out those areas that were not solely attributed to security (such as idealism, intimidation, disaffection, and so on).

Table 5 Definitions of root causality

Root causality	Description
Idealism	The impact of idealism driving a society to be involved in illicit diversion
Terrorism (GTI)	The impact of terrorism on society to facilitate illicit diversion—assessed within the GTI scores for country
Corruption (CPI)	The impact of corruption on human rights as a driver to illicit diversion—assessed within the CPI scores for country
Human security freedoms (BTI)	The status of human security freedoms as a driver behind illicit diversion—assessed within the BTI scores for country
Intimidation	The impact of intimidation, tribal, or otherwise, on a society to be involved in illicit diversion
Disaffection	Societal disaffection, employment, or otherwise, as a principal cause behind illicit diversion
Financial need	The basic need to provide for the family given insurmountable financial hardship
Regulation	The absence of, or poor understanding of, ECP regulation in the workplace
Accessibility	The accessibility of ECP within the supply chain at the point of delivery
Opportunity	Opportunities being presented within society for illicit diversion to take place at the point of delivery and beyond
Volume of trade	The status in the volume of legitimate trade of an ECP to the state in question
Violence (GPI)	The status of negative peace as a driver for illicit diversion—assessed within the GPI for country

Furthermore, the expert panel noted that the country under research did not fall within the scope of international support concerning the policing of ECP due to the levels of violence and corruption present. Ports were integral to the economy, yet the influence of certain terror groups and their affiliations outside these ports was significant.

It was also evident from the focus groups that the illicit diversion of ECP had not been considered within the context of a change of attitudes and behaviours, but rather poorly informed FMEA (Schmitter et al. 2014). For example, C-IED involves multiple functional areas and, therefore, relies upon an integrated and comprehensive approach that is joint, inter-agency, and multinational. The focus groups responded that this was not the case, given limited capacity within the rule of law, and the absence of civil–military interaction. As such the main facilitator (effective cooperation) within the C-IED context was absent. This lack of coordination and cooperation filled law enforcement with the desire to obtain direct and immediate effects, acting on limited information to provide resolution. Such a kinetic approach led to greater discontent, thereby eroding the rule of law further. It did not reduce the IED threat to a manageable level that returned any tangible freedoms to the community. As such, there was limited knowledge and experience evident to support other C-IED pillars, or pursue any meaningful activity without the proactive involvement of the community.

System modelling the human environment

The DAG

The DAG was constructed from the root nodes identified in Table 5, based on successful transition through the qualitative acceptance criteria (Table 2). Once this exercise had been completed, the expert panel agreed that the end state of the research was to determine the *probability that ammonium nitrate would be diverted for use within an IED*, and through belief updating, whether a focus on specific causalities would reduce that probability. Based on the root causalities identified, the expert panel began to consider how these root issues could be depicted visually. It was important to identify common issues to some, to identify cross-over, and if any could be subsequently eliminated. For example, the GTI considered specific issues relating to terrorism, which mainly influenced security concerns within the focus groups, whilst idealism (commonly associated with terrorism) was a motivator of willingness to support illicit diversion because of social and tribal ties. As such, the DAG was consolidated into three generic non-root nodes based on focus group feedback, specifically SECURITY (S), WILLINGNESS (W), and AVAILABILITY (A). Whilst this may seem simplistic, the greatest difficulty was defining what was meant by each non-root node so that data could be manipulated correctly.

The expert panel defined: 1) Security Risk as the *likelihood that current supply chain security protocols cannot inhibit illicit diversion;* 2) Willingness as *the likelihood that those with access to ECP will actively and knowingly support the process of illicit diversion;* and 3) Availability of Supply Risk as *the volume of annual trade in an ECP to a particular country based on legitimate need.*

The inter-relationships are shown in Fig. 1.

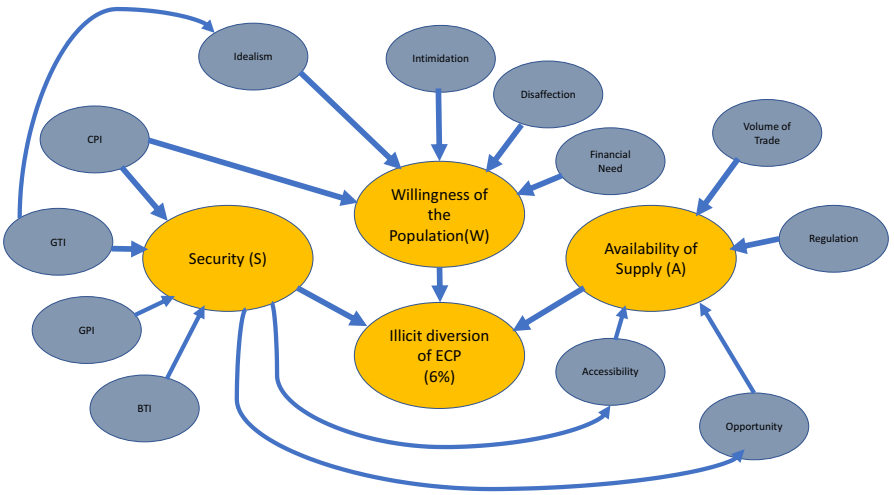

Fig. 1 Suggested DAG for ECP diversion

Table 6 Probabilities associated with DAG

Probability	BTI	CPI	GTI	GPI
High	>0.7	>0.7	>0.7	>0.7
Medium	>0.5	>0.5	>0.5	>0.5
Low	<0.5	<0.5	<0.5	<0.5

It should be noted that the responses surrounding matters of security dove-tailed (for the most part) with the academic research conducted by the CPI, GTI, GPI, and BTI. As such, the expert panel assessed that the statistical information provided within these indices for the state in question chimed with the views of the focus groups. Where there was a degree of cross-over, this was not ignored, with the expert panel linking nodes of common interest within the DAG. As can be seen, the willingness of the population was predominantly driven by human factors, with a degree of cross-over from the CPI and GTI. Again, the expert panel agreed that it was appropriate to capture the cross-over so that the basic model of probabilities could be refined as part of further work.

Establishing root probabilities

A DAG such as this requires the generation of conditional probabilities for several multi-parent nodes, whereby adjustment to S, W, and A influences the degree of diversion. For this research, the initial degree of diversion was set as 6.3% for ammonium nitrate, based on use compared to volume of annual trade over 4 years. Given that this research is introductory, the expert panel set probabilities of diversion associated with the non-root nodes to High, Medium, and Low, using the framework as shown in Table 6. For example, the GTI ranks Afghanistan and the United Kingdom as HIGH and LOW, respectively, since the weighted average on the impact of terrorism in those countries returns scores of 0.91 and 0.477, respectively.

The input from focus groups relating to the root causalities in Table 6 was considered similarly. Based on this hypothesis, a reduction in the figure of 6.3% ammonium nitrate used in IEDs would be expected over time if specific causalities were funded and acted upon. This approach mirrors the methodology associated with supply chain security risk assessment (Curbelo et al. 2020), suggesting that future research synergies may be possible.

Security risk

The methodologies and results of the latest BTI, CPI, GTI, and GPI indices all demonstrate that the case-study country should be set at HIGH for security risk. This is due to the levels of corruption within the security forces, significant economic instability, and the absence of effective governance and the rule of law (see Table 7).

Given the considerable cost of security investment, the expert panel considered that supply chain security investment in conflict-affected states would do little to influence the illicit diversion of ECP. Therefore, it could be excluded from

Table 7 Diversion probabilities associated with indices relating to security

Root node	Impact
Bertelsmann stiftung	HIGH (> 0.7)
Corruption perception index	HIGH (> 0.7)
Global terrorism index	MEDIUM (> 0.5)
Global peace index	MEDIUM (> 0.7)

a DAG until such a time that BTI, GTI, CPI, and GPI index scores realised a return of < 0.7 in terms of 5-year weighted averages. For example, the United States has provided just under one billion dollars of security assistance in recent years (Security Assistance Monitor 2021), and the UN Security Council indicates two hundred million dollars in development assistance to ports and security infrastructure since 2017. There has been very little security improvement in that time, with the state remaining in a similar position on the indices year-on-year. As such, there has been little impact on improvements to governance, the rule of law, or the economy. Therefore, is there any point in throwing more money at security relationships associated with ECP when greater impact may be achieved in other areas? A trade-off is required, but evidence must be gathered to determine how that trade-off should be applied. It is hoped that belief updating will provide that evidence.

Willingness to support

Initial conditional probability is determined from the consultations conducted relating to the root nodes of economics (the need to provide for the family), idealism, intimidation, corruption, and disaffection. Again, each root node is split into HIGH, MEDIUM, and LOW based on the number of focus groups who responded similarly to Table 6. For example, if seven or more focus groups raised the issue of idealism as a problem in terms of illicit diversion, then the impact would be set as HIGH. If less than five focus groups raised the issue, then the impact would be set at LOW. During consultations, the following conditional probabilities were obtained: see Table 8 below.

As can be seen above, it is the provision for family within this research that is by far the most significant contributor to ECP diversion, with > 70% of focus

Table 8 Probabilities associated with willingness

Root node	Impact
Economics (need)	HIGH (> 0.7)
Idealism	LOW (< 0.5)
Intimidation	LOW (< 0.5)
Corruption	MEDIUM (> 0.5)
Disaffection	LOW (< 0.5)

groups citing this. For example, contributors to some focus groups had not received government salaries for over 12 months and had been required to turn to *'dark'* network income streams to support the family. Coercion, intimidation, and targeted violence as incentives to carry out ECP diversion were not as dramatic as the research had anticipated, yet continue to drive the thought processes for international interventions within that state (Paoli 2002).

These findings would suggest that the international focus for C-IED in this state should be weighted towards salary incentivisation as opposed to security. Whilst efforts are made to do this, the majority are short term and target specific community areas such as education (UNICEF 2022), not those within the supply chain.

Availability of supply

Again, community focus groups played a considerable part in determining the causal probabilities in this area, with the following attributes (Table 9):

For supply volume, chemicals were only prioritised if they are on the PGS list (WCO 2013). Prioritisation is based on whether they are readily available (HIGH), moderately available (MEDIUM), or have minimal availability (LOW) within a country. For this paper, probabilities were based on the available annual volume of chemicals within OECD countries as follows: less than 1000 kg (LOW); more than 10,000 kg (MODERATE); and above 500,000 kg (HIGH), see Table 9 below.[1]

Improvements to regulation are dependent upon its presence and an understanding of it. Six focus groups had never heard of a precursor chemical or its intended subversive use, let alone received any training in regulatory practice for those in supply chain employment. It was considered unlikely that many would recognise AN beyond a broad understanding of its agricultural use.

Focus group outcomes demonstrated that accessibility and opportunity are influenced by security. However, focus groups believed that opportunity (specifically insiders) instead of general accessibility drove diversion. Although fertilisers such as ammonium nitrate, urea, and potassium nitrate were openly sold in markets, they were not exposed in quantities sufficient to support such industrial-scale IED manufacture. This was being conducted 'somewhere' following a diversion within the

Table 9 Probabilities associated with availability of supply

Root node	Impact
Volume of supply (kg)	HIGH (> 500,000)
Regulation	MEDIUM (> 0.5)
Accessibility	LOW (< 0.5)
Opportunity	HIGH (> 0.7)

[1] The data within OECD reports can be accessed for public research with permission.

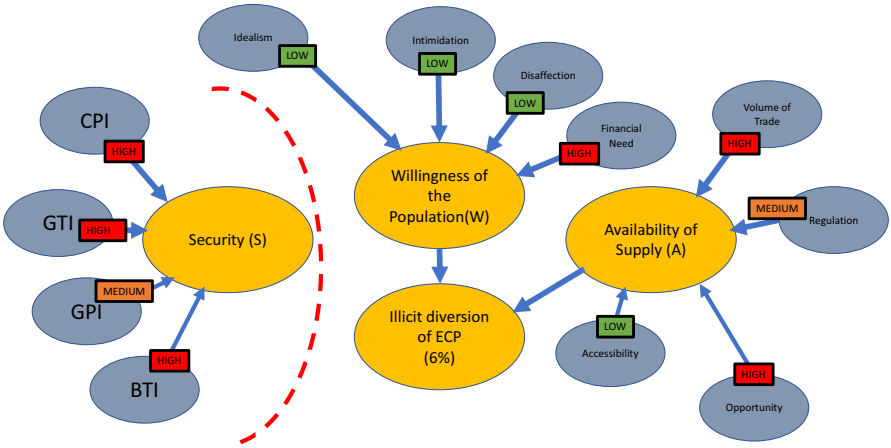

Fig. 2 Revised DAG with associated probabilities

national supply chain. Chemicals did enjoy a degree of security within ports (even if stored out in the open). However, the specific issue was a lack of training of security officials to know what was entering or leaving a facility, understanding who the end-user was, and how policing on route to the end-user, or once in the end-user's hands, could be managed.

Establishing the final Bayesian network

Based on the expert panel deliberations over security, and its short-term irrelevance given the limited return on investment, the final DAG was approved (see Fig. 2), with the associated probabilities highlighted from focus group findings at Tables 7, 8, and 9. Belief updating can now be conducted through Bayesian network analysis as more information becomes available to governance and rule of law programmes.

In this instance, the DAG and its associated probabilities highlight that the impetus for C-IED interventions concerning ECP should rest on reducing the willingness of the population to facilitate diversion through financial incentivisation, or reducing the volume of annual trade in ammonium nitrate. Addressing the financial need of a population is undoubtedly within the gift of donor governments as an economic recovery initiative, most likely centred on those professions with access to the supply chain initially. However, reducing the annual trade volume of fertiliser is difficult in a country experiencing significant food instability. Improvement can be achieved through substitution of ammonium nitrate with lesser potent fertilisers (such as urea), standardisation of nitrogen content from the supplier, increasing awareness of regulation, or reducing the opportunity for acquisition beyond the point of delivery if substitution and standardisation are not acceptable. If urea were a viable alternative for example, then effective risk and risk management would also require similar regulation for nitric acid (Collett et al. 2021), which is vital in the manufacture of urea nitrate explosives (Fedoroff and Sheffield 1962, p. B296).

Conclusion

In conflict-affected states, C-IED approaches are often initiated at the request of state or international governments. They are shaped by the interests of leaders rather than being guided by a consultative process to assure the security needs of communities. Damage assessment is, therefore, challenging to verify within any military and humanitarian C-IED response. This paper has used the concept of Bayesian networks to identify the causal factors behind the illicit diversion of a supply chain commodity (ECP), and offers a start point from which to progress belief updating. The methodology could be applied to any part of the C-IED process, military or humanitarian, thereby refining cost–benefit analysis and resource mobilisation.

Whilst a DAG has been established around ECP diversion within a state, it stops at anything further than establishing the most basic conditional probabilities that could inform more appropriate strategic interventions. The DAG proposes that people and their motives form the most vulnerable element of the network, and that increased investment in security would do very little to improve the situation.

This is not obvious to international C-IED approaches within the state under study, and the application of belief updating in specific areas could return higher rewards.

In this research, the willingness of the population to support the illicit diversion of commodities would seem to be the principal societal turning point, suggesting that resolution to the financial burden imposed on those areas of society with access to the supply chain should be pursued. International regulation on ECP exists within the context of availability but can be challenging to implement during conflict, or where food insecurity is a significant consideration. It suggests that the most appropriate place to apply mitigation is through consistent regulation and standardisation of ECP (or their substitution with less useful chemicals) at the point of manufacture, not at the point of delivery, since this is hugely costly to police when the rule of law is fragile. Such an approach would reduce the burden on overstretched resources attempting to apply mitigation within already compromised supply chains.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Anderson, B. 2007. Securing the supply chain—prevent cargo theft. *Security* 44 (5): 56–58.

Azjen, I. 1991. The theory of planned behavior. *Organizational Behavior and Human Decision Processes* 50 (2): 179–211.

Bauer, S. 2007. Bureaucratic authority and the implementation of international treaties: Evidence from two convention secretariats. In *International organizations and implementation: Enforcers, managers, authorities, Chapter 5*, ed. Jutta Joachim, Bob Reinalda, and Bertjan Verbeek. London: Routledge.

Beauchamp, Tom L., and James F. Childress. 2001. *Principles of biomedical ethics*. Oxford: Oxford University Press.

Bertelsmann Stifftung. 2022. *The transformation index 2022.* 01 May. https://bti-project.org/en/?&cb=00000. Accessed May 2022.

Braglia, M., M. Frosolini, and M. Montanari. 2003. Fuzzy criticality assessment model for failure modes and effects analysis. *International Journal of Quality and Reliability Management* 20 (4): 503–524.

CAIN. 1996. *A chronology of the conflict 1996.* 9 February. https://cain.ulster.ac.uk/othelem/chron/ch96.htm. Accessed May 2022.

Chepkenen, Paul, Duncan Ochieng, and Antony Odek. 2020. Economic effects of IED attacks on the livelihoods of people of Mandera County, Kenya. *International Journal of Science and Research (IJSR)* 9 (7): 1202–1209.

Chin, Kwai-Sang., Da-Wei. Tang, Jian-Bo. Yang, Shiu Yee Wong, and Hongwei Wang. 2009. Assessing new product development project risk by Baysian network with systematic probability generation methodology. *Expert Systems with Applications* 36: 9879–9890.

Clayton, Govinda, Simon J Mason, Valerie Sticher, and Claudia Wiehler. 2019. Ceasefires in intra-state peace processes. *CSS Analyses in Security Policy* (Center for Security Stuides—ETH Zurich) (246): 1–4.

Coke-Hamilton, Pamela, and Jeffrey Hardy. 2019. *Illicit trade endangers the environment, the law and the SDGs. We need a global response.* 18 July. https://www.weforum.org/agenda/2019/07/illicit-trade-sdgs-environment-global-danger/. Accessed August 2021.

Collett, Gareth Paul, Melissa Ladyman, Rachael Hazael, and Tracey Temple. 2021. The use of a predictive threat analysis to propose revisions to existing risk assessments for precursor chemicals used in the manufacture of home-made explosives (HME). *Heliyon* 7 (12): e08343.

Curbelo, A.D., A.M. Municio, and F.M. Delgado. 2020. Tools for risk management in supply chains: A review of literature. *Direction and Organisation (universidad Politecnica de Madrid)* 64: 5–35.

Dieye, Abdoulaye Mar. 2017. *Journey to Extremism.* Regional Bureau for Africa, UNDP, New York: UNDP.

Duffy, Rosaleen, and Freya St John. 2013. *Poverty, poaching and trafficking: What are the links?* London: Evidence on Demand.

Fedoroff, Basil T., and Oliver E. Sheffield. 1962. *Encyclopedia of explosives and related items*, vol. 2. Picatinny Arsenal: U.S. Army Research and Development Coommand.

Francis, T.L. 1986. A dynamic model of corruption deterrence. *Journal of Public Economics* 31: 215–236.

Geneva International Centre for Humanitarian Demining. 2019. *Information Management System for Mine Action (IMSMA).* 6 May. https://www.gichd.org/resources/tools-and-applications/detail/publication/information-management-system-for-mine-action-imsma/. Accessed May 2022.

Goldszmidt, M., and J. Pearl. 1996. Qualitative probabilities for default reasoning, belief revision and causal modeling. *Artificial Intelligence* 84 (1–2): 57–112.

Guiyranan, Olivier, Lucia Montanaro, and Tuuli Raty. 2021. *European security assistance. The search for stability in the Sahel*. London: Saferworld.

Hussona, Jake. 2020. *The reverberating effects of explosive violence on agriculture in Yemen.* 10 July. https://aoav.org.uk/2020/the-reverberating-effects-of-explosive-violence-on-agriculture-in-yemen/. Accessed April 2022.

Institute for Economics & Peace. 2021. *Global Peace Index 2021: Measuring peace in a complex world.* 01 June. http://visionofhumanity.org/reports. Accessed September 2021.

Institute for Economics & Peace. 2022. *Global Terrorism Index 2022: Measuring the impact of terrorism.* 11 March. http://visionofhumanity.org/reports. Accessed May 2022.

Jackson, Brian A. 2001. Technology acquisition by terrorist groups. *Studies in Conflict & Terrorism* 24: 183–213.

Knomea. 2021. *Global ammonium nitrate (AN) production (tonnes).* 25 January. https://knoema.com/atlas/topics/Agriculture/Fertilizers-Production-Quantity-in-Nutrients/Ammonium-nitrate-production. Accessed May 2022.

Koen, Hildergarde, Henk Roodt, and J.P. de Villiers. 2017. System-level causal modelling of widespread resource plundering: Acting on the rhino poaching catastrophe. *Futures* 93: 102–114.

Korb, Kevin B., and Ann E. Nicholson. 2011. *Bayesian artificial intelligence*, 2nd ed. Boca Raton: CRC Press.

Malik, A.S. 1990. Avoidance, screening and optimum enforcement. *RAND Journal of Economics* 21 (3): 341–353.

Margolis, Gabriel. 2013. The Lack of HUMINT: A recurring intelligence problem. *Global Security Studies* 4 (2): 43–60.

Medina, Evan W. 2011. Roads of War: Paved Highways and the Rise of IED Attacks in Afghanistan. *CUREJ: College Undergraduate Research Electronic Journal, University of Pennsylvania* (Penn Libraries, University of Pennsylvania) 22.

MOD. 2013. *Joint Doctrine Puplication 2.00—Understanding and intelligence support to joint operations*. Shrivenham: DCDC.

NATO Standardization Office. 2018. *AJP 3.15—Allied joint doctrine for countering improvised explosive devices.* Vol. Edition C Version 1. Brussels: NATO.

Naylor, R.T. 2004. *Wages of crime: Black markets, illegal finance, and the underworld economy*. Ithaca: Cornell University Press.

Nolin, Pierre Claude. 2011. *Countering the Afghan Insurgency: Low-Tech Threats, High-Tech Solutions.* Special Report, Science and Technology, NATO Parliamentary Assembly, Romania: NATO International Secretariat.

Pallone, Nathaniel J., and James J. Hennessy. 2018. *Criminal behavior: A process psychology analysis*. Abingdon on Thames: Taylor and Francis.

Paoli, Letizia. 2002. The paradoxes of organised crime. *Crime Law and Social Change* 37 (1): 51–97.

Paris, Roland. 2001. Human security: A paradigm shift, or hot air? *International Security* 26 (2): 87–102.

Radisch, Jack. 2016. *"Illicit trade: Convergence of criminal networks", in Illicit Trade: Converging Criminal Networks*. Paris: OECD Publishing.

Rayment, Sean. 2011. *Bomb hunters: In Afghanistan with Britain's elite bomb disposal unit*. London: Harper Collins.

Revill, James. 2016. *Improvised explosive devices: The paradigmatic weapon of new wars*. Switzerland: Palgrave MacMillan.

Rittel, H.W., and M.M. Webber. 1973. Dilemmas in a general theory of planning. *Policy Sciences* 4: 155–169.

Roberts, Nancy Charlotte, and Sean Everton. 2009. Strategied for combatting dark networks. *Journal of Social Structure* 12 (2): 1–32.

Sanbar, Sarah. 2020. *Barriers to reconciliation in Iraq*. Kuwait: Sciences Po.

Schmitter, Christopher, Thomas Gruber, Peter Puschner, and Erwin Schoitsch. 2014. Security applications of Failure Mode and Effect Analysis (FMEA). In *Computer safety, reliability, and security*, 310-325.

Security Assistance Monitor. 2021. *Security Sector Assistance.* https://securityassistance.org/security-sector-assistance/. Accessed 24 Feb 2022.

Shafer, G. 1976. *Mathematical theory of evidence*. Princeton: Princeton University Press.

Shalini Punithavathani, D., K. Sujatha, and J. MarkJain. 2015. Surveillance of anomaly and misuse in critical networks to counter insider threats using computational intelligence. *Cluster Computing* 18: 435–451.

Shinn, David. 2016. Poverty and terrorism: The debate continues. *Georgetown Journal of International Affairs* 17 (2): 16–22.

Sii, H.S., J. Wang, and T. Ruxton. 2001. Novel risk assessment techniques for maritime safety management system. *International Journal of Quality and Reliability Management* 18 (9): 982–999.

Sparrow, Malcolm K. 1991. Network vulnerabilities and strategic intelligence in law enforcement. *International Journal of Intelligence and CounterIntelligence* 5 (3): 255–274.

Stacey, Judith. 1988. Can there be a feminist ethnography? *Women's Studies International Forum* 11 (1): 21–27.

Transparency International. 2021. *Corruption Perceptions Index 2021.* 31 December. Accessed April 2022. https://www.transparency.org/en/cpi/2021.
UNCTAD. 2019. *Mapping the impact of illicit trade on the sustainable development goals.* 18 July. https://unctad.org/system/files/non-official-document/DITC2019_TRACIT_IllicitTradeandSDGs_fullreport_en.pdf. Accessed October 2021.
UNDP. 2017. *UNDP code of ethics—operating with unwavering integrity*. New York: UNDP Ethics Department.
UNMAS. 2018. *International Mine Action Standards (IMAS)*, 2 ed., vol. 01.1. New York: GICHD.
UNICEF. 2022. *EU, UNICEF to support Primary School Teachers in Hard-to-Reach areas with incentives for 2 years.* 1 February. https://www.eeas.europa.eu/delegations/south-sudan/eu-unicef-support-primary-school-teachers-hard-reach-areas-incentives-2_en?s=121. Accessed 14 April 2022.
UNIDIR. 2020. *Counter-IED capability maturity model and self assessment tool*. New York: UNIDIR.
United Nations Security Council. 2017. *Security Council Resolution 2370(2017)*. New York: UNSC.
United Nations Security Council. 2019. *United Nations Security Council Resolution 2482 (2019).* Resolution, United Nations Security Council, New York: UNSC, 3/7.
WCO. 2013. *Programme Global Shield (PGS).* August. http://www.wcoomd.org/-/media/wco/public/global/pdf/topics/enforcement-and-compliance/activities-and-programmes/security-programme/pgs/programme-global-shield-en.pdf?la=en.
WHO. 2021. *Model List of Essential Medicines.* 01 February. https://www.who.int/groups/expert-committee-on-selection-and-use-of-essential-medicines/essential-medicines-lists. Accessed May 2022.
Williams, Phil. 2001. *Networks and netwars: Future of terror, crime and militancy.* Vols. Chapter 3, Transnational Crime Networks. Rand Corporation.
Woods, D.D., and E. Hollnagel. 2006. *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton: Taylor & Francis.
Yang, Z.L., J. Wang, S. Bonsall, and Q.G. Fang. 2009. Use of fuzzy evidential reasoning in maritime security assessment. *Risk Analysis* 29 (1): 95–120.
Zhu, X., Z. Duren, and W.H. Wong. 2021. Modeling regulatory network topology improves genome-wide analyses of complex human traits. *Nature Communications* 14: 1–15.

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