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Criminal organizations exhibit hysteresis, resilience, and robustness by balancing security and efficiency

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The interplay between (criminal) organizations and (law enforcement) disruption strategies is critical in criminology and social network analysis. Like legitimate businesses, criminal enterprises thrive by fulfilling specific demands and navigating their unique challenges, including balancing operational visibility and security. This study aims at comprehending criminal networks' internal dynamics, resilience to law enforcement interventions, and robustness to changes in external conditions. Using a model based on evolutionary game theory, we analyze these networks as collaborative assemblies of roles, considering expected costs, potential benefits, and the certainty of expected outcomes. Here, we show that criminal organizations exhibit strong hysteresis effects, with increased resilience and robustness once established, challenging the effectiveness of traditional law enforcement strategies focused on deterrence through increased punishment. The hysteresis effect defines optimal thresholds for the formation or dissolution of criminal organisation. Our findings indicate that interventions of similar magnitude can lead to vastly different outcomes depending on the existing state of criminality. This result suggests that the relationship between stricter punishment and its deterrent effect on organized crime is complex and sometimes non-linear. Furthermore, we demonstrate that network structure, specifically interconnectedness (link density) and assortativity of specialized skills, significantly influences the formation and stability of criminal organizations, underscoring the importance of considering social connections and the accessibility of roles in combating organized crime. These insights contribute to a deeper understanding of the systemic nature of criminal behavior from an evolutionary perspective and highlight the need for adaptive, strategic approaches in policy-making and law enforcement to disrupt criminal networks effectively.

Crime pays. The United Nations Office on Drugs and Crime estimates that transnational criminal organizations generate an astonishing annual revenue of approximately \$1.6 trillion[1], equivalent to Canada's Gross Domestic Product. This staggering financial success places criminal organizations among the wealthiest and most influential entities globally, underscoring the substantial challenges law enforcement agencies and governmental bodies face in combating crime.

Beyond its financial prowess and undue influence, crime exerts other profound social, health, and environmental impacts. The illicit drug trade contributed to escalated drug use and disorders, reflecting broader societal issues. The decade ending in 2021 saw a 23% increase to over 296 million people using drugs and a 45% increase in drug use disorders to 39.5 million individuals[2]. These trends reflect the direct consequences of the drug trade but also highlight the resulting social and economic inequalities, with significant healthcare disparities in treatment access. The impact is acute among the youth, especially in Africa[2]. Furthermore, the drug economy fuels additional criminal activities such as illegal logging and mining, particularly in the Amazon Basin, leading to environmental degradation and human rights violations. Indigenous communities and other minority groups are disproportionately affected by these illegal activities. Finally, drug trade funds non-state armed and insurgency groups, contributing to regional instability and potentially escalation to global crises[2].

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The success and far-reaching damaging impact of criminal organizations highlight the need to understand the conditions under which criminal organizations thrive or falter[3,4]. Criminal organizations exhibit intriguing similarities to legitimate businesses. Like successful licit enterprises that cater to societal needs, criminal organizations function by fulfilling a specific demand[5]. Criminal organizations bring illegal products to market through international supply chains, such as cocaine, through a network of coca farmers, smugglers, runners, and dealers[6]. Running an illicit operation requires goal-orientated and management skills not uncommonly found in successful businesses[5,7].

Legitimate organizations thrive on market visibility to attract customers and collaborators, whereas criminal organizations must balance visibility with the risk of exposure to law enforcement. This challenge, known as the security-efficiency trade-off in criminal literature, requires criminal entities to navigate between operational effectiveness and security[8,9]. To achieve this, criminals rely on "dark" social networks to facilitate covert cooperation, essential for their operation[10,11]. The structure of these networks is pivotal; networks with denser connections and a smaller average maximum distance between any two nodes are more efficient in communication, aiding in the growth and functionality of the organization. Conversely, secure networks maintain higher social distance between members, reducing the risk of complete exposure when a member is compromised[12–16]. The security-efficiency trade-off is, thus, a spectrum that characterizes networks based on their connectivity structure. The operational conditions and types of social networks employed by these organizations significantly influence their likelihood of success and ability to sustain operations under various conditions[16,17].

The increasing emphasis on structural analysis based on criminal reports has led to the idea of finding a structural fingerprint to improve interventions by law enforcement[16,17]. Social networks of criminals, commonly constructed from biased data sources such as arrest records, telephone records, or informant data, illuminate divergent facets, engendering distinct network structures[18]. This inherent bias can distort evaluation of when a network is considered secure or efficient. Criminal networks often exhibit patterns where not all nodes are connected, resulting in structures characterized by dense connections within communities, and sparser connections across different communities[13,19,20]. For example, the 'Ndrangheta network[21] displays a nested and hierarchical structure, with bosses and affiliates forming coherent sub-groups within local units. This structure suggests a sophisticated organization and division of roles within criminal networks, which are crucial for understanding the operational dynamics of criminal networks.

In response to these challenges, law enforcement strategies can broadly be categorized into prevention and disruption[22]. Prevention focuses on deterring crime before it occurs through measures such as community policing, public awareness campaigns, and economic support programs. Disruption, on the other hand, aims to destabilize criminal organizations by targeting their structure, leadership, and operations. Real-world evidence indicates that disruption methods can be highly effective in the short term by immediately hindering criminal activities and reducing the influence of key figures within criminal networks[23,24]. However, prevention strategies are often more sustainable in the long term[25–27], as they address the root causes of criminal behavior and reduce the overall crime rate over time. It is unclear, however, how to balance these approaches due to the varying contexts of crimes and the adaptability of criminal organizations. Our study focuses on prevention as we consider interventions in terms of changes in the global environment of individuals, in terms of global costs of crime and error rates.

While complex network analysis has gained traction in studying crime data, its application in predicting static and dynamic properties of criminal networks is still a relatively unexplored area. Evidence suggests that the evolution of criminal organizations exhibits a complex, non-trivial relationship with the environment where agents are embedded[24,28,29]. Additionally, machine learning methods aim to effectively predict future criminal associations based on the current and past systems[30], but they fall short of elucidating the mechanisms that lead to the formation and collapse of criminal organizations in various and potential novel environments. Previous research on the mechanisms behind crime formation has primarily focused on the interactions between criminals, law enforcement, and non-criminal actors[24,28,29,31,32], but there has been little focus on the criminal organization as a multi-role coordination of criminal actors. Our research aims to fill this gap by examining dynamic multi-role coordination decisions in criminal organizations and their social networks. This complex adaptive perspective offers an emergent view of how criminal organizations can prosper based on environmental richness, accessibility to criminal organizations, and the emergence of complex behavior from simple interactions.

In contrast, machine learning methods can effectively predict future criminal associations based on the current system[30], but they fall short of elucidating the mechanisms that lead to the formation and collapse of criminal organizations in various environments. Our research aims to fill this gap by examining dynamic multi-role coordination decisions in criminal organization and their social networks, an area that has received insufficient attention.

At the core of criminal organizations are individuals who evaluate the anticipated cost and benefit of a criminal act, guided by a certainty of the expected payout[3,5,7,16,24,29,33]. Successful execution of a criminal activity often hinges on collaboration among a specific set of distinct roles.

This study explores the underlying mechanisms that govern criminal network formation, expansion, and potential dissolution. Using a model based on concepts from evolutionary game theory, we analyze these networks as collaborative assemblies of roles, considering expected costs, potential benefits, and the certainty of expected outcomes. Our experiments investigate how the interplay of dynamics on social networks and changes to environmental conditions impact the robustness of criminal organizations against law enforcement efforts. The approach complements the extensive literature on multi-actor coordination games by applying them to a criminal context[34–43].

Our results demonstrate an important effect of hysteresis (path dependency) in which the best intervention (e.g., increased punishment) and its effect depends on whether a community already has high levels of criminality or not. We explore the ability of the criminal organization to withstand shocks (sudden loss criminals)—which we call resilience—and its ability to withstand changes in external conditions—which we call robustness. We identify a critical cost-to-benefit ratio where the formation or dissolution of a criminal organization is the most susceptible to both external perturbations, e.g. law enforcement disruption, and internal perturbations, e.g. availability of criminals. Importantly, network effects play a pivotal role in enhancing the robustness and resilience of criminal organizations. Criminal organizations reach peak robustness and resilience, when access to specialized roles necessary to form the organization maximizes, thereby cultivating an environment conducive to exploiting criminal opportunities.

Modeling criminal organizations

An organization, whether licit or illicit, succeeds when all required roles coordinate in the same strategy: criminal or non-criminal. If an agent decides to engage in a criminal act, they receive a payout only if the other members of the organization also choose to perform a criminal act, which results in receiving a benefit; they also incur a cost, embodying the chance of getting detected by law enforcement, or other environmental costs such as loss of shipment or influence of rivaling gangs (see for more background E).

The agents attempt to form a complete organization, a full set of roles, using their social network. Across different networks, reflecting the spectrum of efficiency-secrecy trade-off, we study the emergence of criminal-dominated states and their stability to shocks in criminal numbers—resilience—and to changes in external conditions—robustness.

We consider a population of size Z. Each agent, $a_i = \{r_i, s_i\}, i \in \{1, \ldots, Z\}$, is characterized by having one of R fixed roles, $r_i \in \{1, \ldots, R\}$, and dynamic state, $s_i \in \{0, 1\}$. The fraction of each role is denoted as $z_r = Z_r/Z$, satisfying the constraint $\sum_{r=1}^{R} z_r = 1$. For instance, with $R = 3$, a (criminal) organization consists of three roles: e.g., distribution, production, and management. A state $s_i = 0$ represents a non-criminal state and $s_i = 1$ a criminal state of agent i.

Strategy update

Agents consider the alternative states by exploring their neighborhood and considering forming an organization with neighbors of complementary roles n times. An agent a_i is connected with an agent a_j when $g_{ij} = 1$; otherwise, $g_{ij} = 0$. $G = [g_{ij}]$ forms an undirected, unweighted adjacency matrix, representing the graph of potential interaction partners.

Forming an organization entails finding other agents with all the complementary roles and coordinating to engage in criminal or non-criminal activity. Formally, agent a_i samples $R - 1$ agents, one from each set $\{a_k : r_k = r \text{ and } a_{ik} = 1\}$, where $r \in \{1, \ldots, R\} \setminus r_i$, creating a random set M_i of $R - 1$ complementary-role agents in the neighborhood of a_i to interact with.

In each game, the agent interacts with the set M_i and receives a benefit b when all R individuals are criminals. Criminal activity, however, entails a cost c. The payout for each of these interactions of agent i in state $s \in \{0, 1\}$ is given as

$$\pi_s^{(i)} = s\left(b \prod_{s_j \in M_i} s_j - c\right). \tag{1}$$

The agent aims to maximize their payoff by considering the expected payoff of each strategy by averaging the payoff of the interactions with n random M_i groups, $\langle \pi_s^{(i)} \rangle$.

In each time step, a random agent, i, is selected to consider changing their strategy. The probability of changing one's state from criminal, $s = 1$, to non-criminal, $s = 0$, and vice versa is computed based on the expected payout difference of each strategy. The probability of switching from strategy s to a new strategy s' is given by

$$p_{s \to s'} = \frac{1}{1 + e^{-\frac{1}{\epsilon}\left(\langle \pi_{s'}^{(i)} \rangle - \langle \pi_s^{(i)} \rangle\right)}}, \tag{2}$$

where ϵ represents the decision error controlling the agent's uncertainty when changing strategy. Notice that the transition or conditional probability of changing to a given strategy is independent of the base state, mapping directly to a multinomial logit model that reflects a law of relative effect[44] and, for a single role, maps to the classic Glauber dynamics for the kinetic Ising models[45].

In the extreme case where $\epsilon \to \infty$, using Eq. (2), an agent will choose their next state independently of the information it receives from their neighbors with uniform probability. Conversely, as $\epsilon \to 0$, any minimum expected payoff difference will lead to a change of strategy.

Results

Dynamics of efficient criminal organizations

Efficient communication in a system implies that each agent in the system can, in principle, communicate with all other agents in the system, i.e., $g_{ij} = 1$ for all i and j. For large populations, the dynamics of the collective can be determined by considering the fraction of criminals in a particular role, denoted $x_r = \frac{1}{z_r Z} \sum_{i:r_i=r} s_i$. In the limit of $n \to \infty$, i.e., perfect estimation of the average payoff with the current neighborhood, the system dynamics will follow (see B for details)

$$\lim_{n\to\infty} \frac{d}{dt}x_r = \frac{1}{1+e^{-\frac{1}{\epsilon}b(\prod_{q=0,q\neq r}^{R} x_q - \frac{c}{b})}} - x_r, \tag{3}$$

which distinctly shows how the emergent instantaneous change for the collective of individuals with a given role is controlled (Fig. 1).

The parameters b, c, and ϵ control different aspects of how socially viable the criminal strategy is for the efficiently communicating community. The equation highlights three dependencies: the cost-to-benefit ratio, c/b, the error-to-benefit, ϵ/b, and the number of roles, R.

For the upcoming simulations, we will set $R = 3$, where each role's occurrence is equal, i.e., $z_1 = z_2 = z_3$, unless otherwise specified. Additionally, the cost- and error-to-benefit ratios, c/b and ϵ/b, will be manipulated by maintaining $b = 1$ and adjusting c and ϵ. This choice stems from the dual impact of b on both the curvature of the decision curve as well and the cost-to-benefit ratio (see Eq. (3)). The effect of R on the dynamics are qualitatively similar for $R \geq 2$ and additional results for different R can be found in Appendix C.

Figure 1 shows the fixed points of the dynamics of efficient criminal organizations, which characterize where the system is attracted to (stable fixed points) or repelled from (unstable fixed points). In the case of high decision error, high ϵ, the system exhibits a single stable fixed point, which attracts the dynamics to an intermediate fraction of criminals. In this regime with a single equilibrium, increasing the cost-to-benefit ratio consistently and reversibly decreases the fraction of criminals. When the decision increases further, all dynamics resort to a random choice regardless of the cost of the criminal act, e.g., compare $\epsilon = \infty$ to $\epsilon = 5$. This reflects the conditions in which the lines between criminal and non-criminal acts are blurred. An example could be the formation of a "second" government such as the prevalence of the Mafia in southern Italy[46]. However, reducing the decision error can either decrease the fraction of criminals if the cost-to-benefit ratio is high enough or increase it for a low cost-to-benefit ratio. The number of roles, R, reflecting the complexity of the task, controls the critical cost-to-benefit ratio that determines the direction of the effect (precisely, $(c/b)^{\mathrm{crit}} = 1/2^{R-1}$). For low decision error, low ϵ, the dynamics may exhibit three fixed points: two stable attractors, one with a high fraction of criminals (e.g., the points between A and B) and one with low (e.g., the points between C and D), and an unstable state at an intermediate fraction of criminals. For a high cost-to-benefit ratio, above $(c/b)^{\mathrm{H}}$, only the attractor with a low fraction of criminals is present; for low cost-to-benefit ratio, below $(c/b)^{\mathrm{L}}$, only the attractor with a high fraction of criminals is present; and for intermediate values, between $(c/b)^{\mathrm{L}}$ and $(c/b)^{\mathrm{R}}$, the three are present and the dynamics can be attracted to two different stable states. When the system is in a stable state with a high fraction of criminals (A), changes to the cost-to-benefit ratio are largely ineffective in changing the fraction of criminals ($A \to B$) unless they surpass $(c/b)^{\mathrm{R}}$ ($B \to C$). Similarly, when the system is in a stable state with a low fraction of criminals (C), a reduction of the cost-to-benefit will not lead to an increase ($C \to D$) unless the reduction is beyond $(c/b)^{\mathrm{L}}$ ($D \to C$). In the regime where the three states are present, with intermediate values of cost-to-benefit ratio, the initial number of criminals determines where the system is attracted. The unstable fixed point determines the critical mass of criminals below which criminal activity collapses to the low criminal state and above which it grows to the high criminal state. As the cost-to-benefit ratio increases, this critical mass also increases.

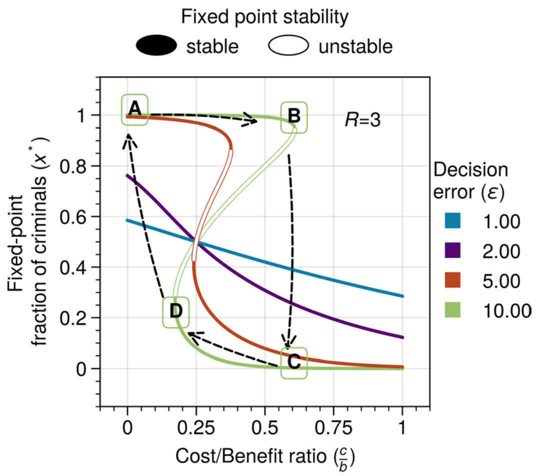

Figure 1. Modulating the decision error induces hysteresis in the system's behavior. In scenarios of low cost-to-benefit and elevated decision error, a single stable attractor prevails. However, as the decision error diminishes, an unstable attractor surfaces, acting as a threshold representing the minimum required fraction of criminals needed to saturate the market. The criminal strategy materializes only under conditions of low cost-to-benefit and recedes with increasing costs. Importantly, in responds to an intervention, the system shows increased robustness and resilience when formed under these conditions. For a comprehensive exploration of bifurcation patterns based on the number of roles, refer to C.

State-dependent fortitude: hysteresis in criminal organizations

The ability to rebound from interventions is crucial for the persistence of criminal organizations. These interventions can be categorized into two dimensions.

Firstly, we consider fluctuations in the fraction of criminals, focusing again on Fig. 1. Over time, the number of criminals may change due to various factors, such as deaths, rivalries, and other dynamics. The ability to resist fluctuations in the population will be denoted as *resilience*[14,47].

Secondly, the viability of a criminal market is influenced by the relative market value of the product being sold and different risks. Fluctuations in supply and demand and law enforcement surveillance impact the sustainability of criminal organizations. The ability to resist fluctuations due to external pressure is denoted as *robustness*[14,47]. For this, we will use Fig. 2.

As described above, at high decision error, there is a single attractor and, thus, the system is fully resilient and robust. Perturbations to the number of criminals, including recruitment actions, will lead to temporary changes in the number of criminals but the same end result. This is seen by the single stable point in Fig. 1 and, in Fig. 2,

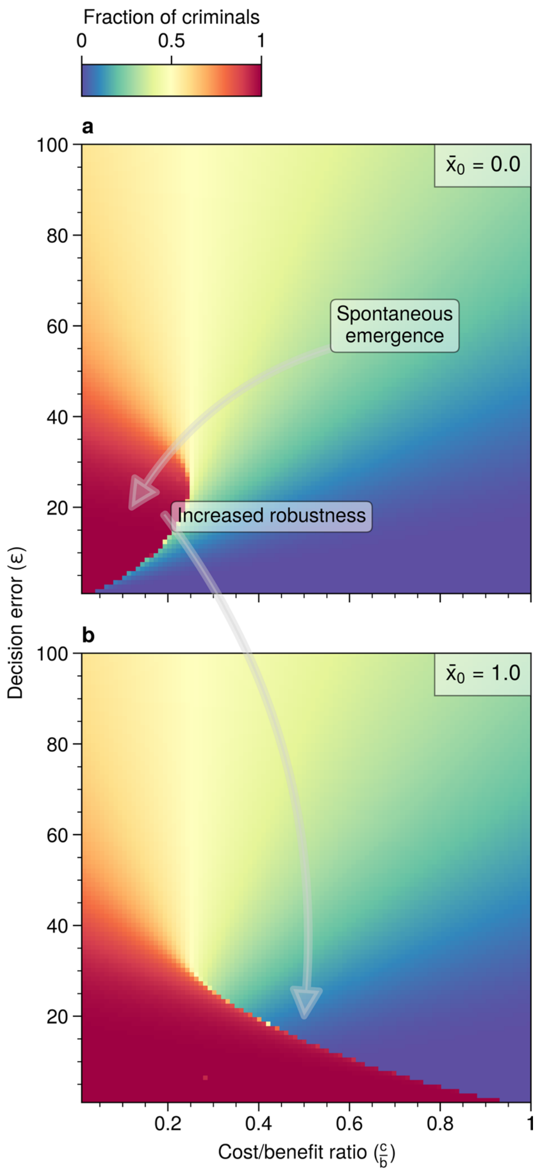

Figure 2. The emergence of criminal organizations depends on the decision error, the cost-to-benefit ratio, and the initial fraction of criminals. (**a**) For low levels of crime in society, criminal organizations spontaneously emerge when the benefit outweighs the cost, and the decision error (ϵ) is moderately high. (**b**) The stability region for criminal organizations becomes large for higher initial fraction of crime, indicating that criminal organizations are more robust to decision error. Once a criminal organization is formed, its *resilience* increases; consider the initial conditions with a lack of criminals in society (**a**), once the criminal organization forms, the criminal *resilience* is higher. That is, stronger interventions are needed to disrupt the criminal organization.

by realizing the identical sections of the two panels, where both extreme initial conditions lead to the same final fraction of criminals across that whole range of parameters (in the figure this includes the whole $\epsilon \gtrsim 40$ region).

A critical regime can be identified at low decision error with the emergence of the two stable states described above with high and low numbers of criminals. The state with many criminals (top solid lines in Fig. 1 and bottom panel in Fig. 2) is resilient to interventions in criminal activity that do not bring the numbers below the unstable state in Fig. 1. Besides, that criminal state is robust to changes in the cost-to-benefit ratio and decision error (the red region in Fig. 2). At the border of the red region, however, the highly criminal state loses its resilience and robustness.

For instance, consider the dynamics of a criminal organization with a decision error $\epsilon = 5$ in Fig. 1, corresponding to the red area in Fig. 2b. When the criminal organization is already established (A), the cost-to-benefit ratio must increase until $\frac{c}{b} \simeq 0.56$, at which point the criminal organization becomes highly sensitive to perturbations in both the number of criminals and the cost-to-benefit ratio. The criminal organization cannot recover from the perturbations then, heading to the non-criminal state ($B \rightarrow C$ transition). Once the criminal organization is dissolved, B (also the corresponding blue area in Fig. 2a), reducing the cost-to-benefit ratio or slightly increasing the fraction of criminals does not reverse the effect. Instead, the system remains non-criminal even as costs to criminal activities are reduced or benefits increase ($C \rightarrow D$). At low enough costs, the criminal organization emergences ($D \rightarrow A$ transition and red area in Fig. 2a).

Spontaneous emergence of criminal organizations

The stability of the non-criminal and criminal strategy intricately varies depending on the initial fraction of criminals in the system (Fig. 2). Criminal organizations can spontaneously form in the absence of criminals in the system (Fig. 2a), particularly as perceived costs of criminal action reduce beyond a critical point (or perceived benefits increase), corresponding to a movement from the blue to the red area in Fig. 2a. Once they emerge, the initial levels of criminals are higher (Fig. 2b), which entail higher *resilience* and higher *robustness*. That is, perturbations in both the fraction of criminals and the cost-to-benefit ratio have little effect on the ability to form and maintain a criminal organization. Further, as the organization is formed, uncertainty in estimating cost and benefits, measured by ϵ, is naturally reduced, so the system moves into an even more robust region.

The potential for criminal organizations to spontaneously emerge carries profound implications for the efficacy of interventions. A plausible scenario arises when there is an extreme relaxation of prolonged periods of stringent punishment for criminal activities (resulting in a perceived cost-to-benefit ratio below the critical value), which triggers a spontaneous upsurge in criminal organizations. Reverting to the original perceived cost-to-benefit ration, may not suffice, requiring much stricter interventions. Additionally, intervening in the decision error may be a more impactful strategy than merely augmenting the cost of punishment for a crime.

Link density and disassortatvity facilitate robustness and recruitment

The robustness of a criminal organization is contingent on its social connections and the accessibility to the roles necessary for the organization to function. We evaluate these based on the effect of link density of the social network and the role assortativity on the dynamics. Importantly, we define criminal robustness for fixed $\epsilon = 10$ as the maximum cost-to-benefit ratio (c^*) such that the system dynamics sustains a highly criminal state (see A.3 for further elaboration on the methods). Graphs ($N = 100$) are initially generated such that $Z = 150$ agents are connected in a ring with minimum role assortativity. Link density was increased by adding edges between agents having differing roles (ensuring minimum role assortativity). For each link density, the role assortativity was increased by swapping the roles of a pair of agents (Fig. A.1).

Increasing link density is associated with an increase in the maximum criminal robustness Fig. 3. For a given role assortativity, c^* is higher when the link density is higher. Increased link density provides more opportunities for criminal organizations to form since it increases the likelihood of connecting to the expertise needed to form a criminal organization Fig. 3. Agents can connect with more individuals possessing the necessary roles, creating social opportunities for criminal organization formation or influencing citizens to join a criminal organization. For example, in D, the effect of link density is studied on the likelihood of recruiting a licit community into a criminal organization. As the link density between a criminal and non-criminal group increases, so does the likelihood of recruiting the group of non-criminals into the criminal organization (Fig. D.1).

Enhancing role assortativity has a pronounced impact on diminishing the overall robustness of criminal networks. This outcome is anticipated, as a deficiency in the requisite roles prevents establishing cohesive criminal organizations. Nonetheless, the rate at which robustness decreases is noteworthy. Specifically, the increase of role assortativity within the social network restricts the formation of criminal organizations in a linear fashion until a critical point is reached, approximately at $c^* \simeq 0.25$, where a sudden shift in maximum criminal robustness is evident. This shift aligns with a seemingly minimal threshold of criminal connections required.

Illustrated in Fig. 4b is the computation of criminal opportunities at the conclusion of the simulation. Criminal opportunities denote the total number of potential criminal organizations an individual could form with their immediate neighbors, given their roles. The immediate drop of criminal robustness (Fig. 4a) can be explained by the lack of available criminal neighbors (Fig. 4b). Increasing the cost c puts a higher requirement on the number of criminal contacts for an individual. It becomes increasingly less likely for a criminal organization to succeed with increasing cost, creating an abrupt dissolution of criminal activity for a given decision error—in Fig. 4 empirically seen as around 10 criminal neighbors.

Increasing criminal awareness: a catalyst for the formation of robust criminal organizations

A successful criminal actor thrives by collaborating with other criminal agents, necessitating awareness of others within the system who hold the right roles. Understanding this collaboration is crucial because, in reality, agents

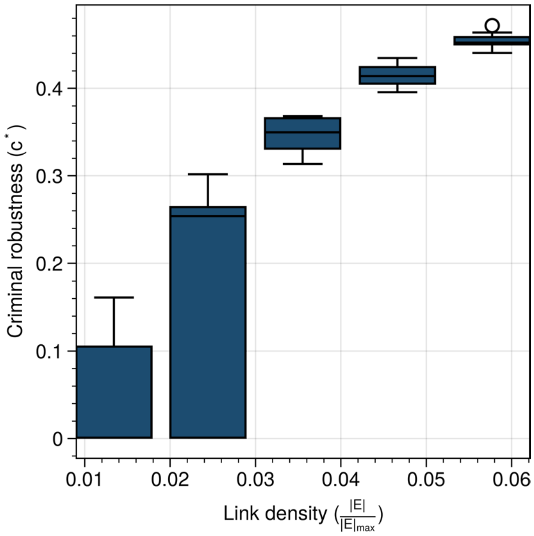

Figure 3. Link density promotes the *resilience* of criminal organizations. The interquantile range is visualized for graphs with role assortativity $<= -0.5$ and $\epsilon = 10$. Outliers are represented by un-filled scatters when they exceed 1.5 the interquantile range.

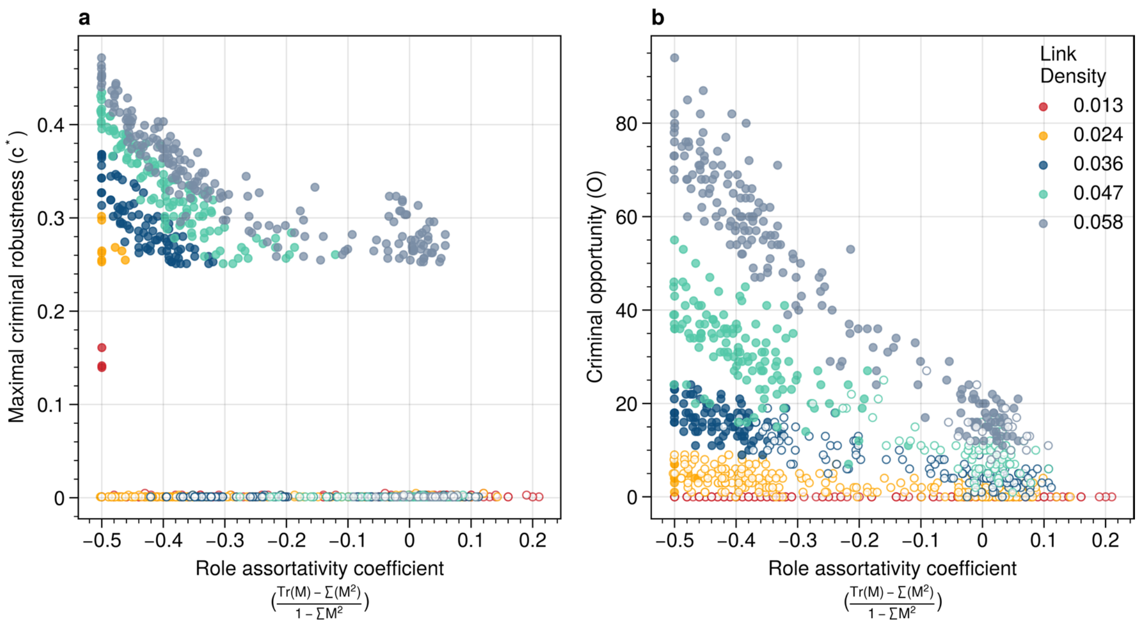

Figure 4. The robustness of criminal organizations is promoted by networks characterized by elevated density and dissortativity. In panel (**a**), an inverse relationship is observed, wherein increasing assortativity leads to a decline in criminal robustness. Notably, the network dynamics reveal a nuanced dependence on link density, as evident in the comparison of the lower link density (red) with other densities. A critical robustness threshold around $c^* \approx 0.2$, demarcates a regime where the stability of the criminal organization undergoes a discernible collapse. The open circles in (**a**,**b**) indicate the systems for which the c^* is close to zero caused by a lack of criminal opportunity (**b**). In (**b**), the criminal opportunity decreases with role assortativity indicating specialized skills need to be available for criminal organizations to form. Criminal opportunity is defined as the number of criminal organization existing at the end ($t = 300$) of each Monte-Carlo run. The results presented herein pertain to a fixed parameter $\epsilon = 10$, utilizing a network structure with $Z = 150$ agents arranged in a ring; further details on the experimental configuration can be found in A.

may seek to identify missing roles by broadcasting within their network. The number of interactions agents have to estimate the current state of the system is vital, as it reflects the limitations imposed by social networks. These networks naturally reduce the visibility of other criminal actors, limiting the formation of criminal organizations. The success of these organizations depends on the immediate connections of an actor and the strategies of agents at further distances, who make decisions based on their local information. We examine the sampling process a focal agent uses to estimate their payoff based on their connections. The number of samples considered in each payoff estimation measures the agent's awareness of others' behavior.

In Fig. 5, we turn again to a population where individuals may potentially identify the state of all others but are restricted by this sampling process. We represent the expected change in the fraction of criminals in the population for any specific value of that fraction, showcasing the expected dynamical behavior of the system for different numbers of samples and roles. The results show that as the organization includes more roles, a higher fraction of criminals is required to form the organization. Further, a higher number of samples accelerates the dynamics since the depth of the basin of attraction increases, effectively making it more likely for criminal organizations to form if the minimum fraction of criminals is reached, acting as a catalyst to robust criminal organizations. Additionally, the number of samples can have a dual effect on the resilience of organizations: a limited number of samples means that criminals have a poorer estimation of the payoff, which either causes the required minimal fraction of criminals to be higher or lower depending on whether the minimum fraction of required criminals is high or low, respectively. Finally, the overall dynamics have a strong non-linear response to an increasing number of samples. The largest qualitative and quantitative differences occur for an increase in sample numbers from 1 to 10, whereas an increase from 100 to infinite (see Eq. (3)) produces identical results.

Discussion and conclusions

Network analysis provides an intuitive approach to decompose the structure of a criminal organization in terms of security and efficiency. However, the results of this article highlight the need to move beyond mere structural analysis and consider the intricate relationship between the organizational structure and the emergence, as well as the stability of criminal organizations amidst external conditions and interventions. Exploring the interplay between cost-benefit analysis and decision-making errors provides insights into how criminal organizations maintain resilience and robustness amidst external perturbations. These findings complement existing empirical research in criminology by providing underlying mechanisms driving the proliferation of illicit enterprises and informing strategic approaches for combating organized crime[7–9,16,17,48,49].

Our results highlight a strong hysteresis effect in the formation and perpetuation of criminal organizations, indicating that higher resilience and robustness are achieved once a criminal organization has formed. In the criminal context, increased costs can be viewed from the standpoint of stricter punishment, either through legislative measures or intensified law enforcement efforts, or from the perspective of the financial gains a criminal organization may derive from illicit activities.

The relationship between stricter punishment and its impact on organized crime is complex and subject to debate among experts[49–52]. While deterrence theory suggests that stricter punishment can reduce criminal behavior[53], its effectiveness in deterring organized crime is not always clear-cut due to the sophisticated strategies

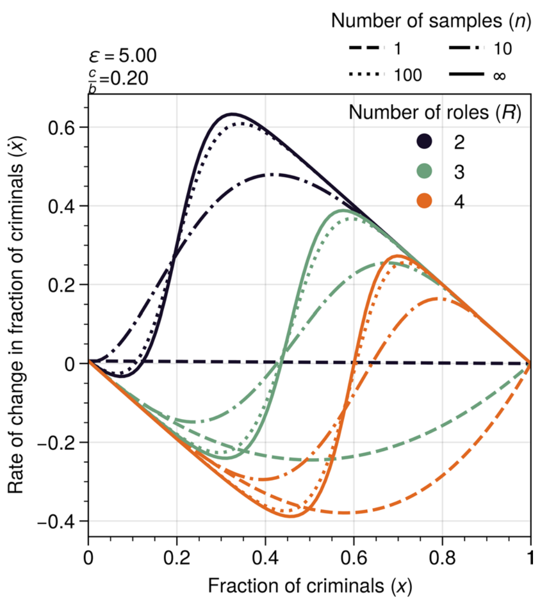

Figure 5. The stability of the system is affected by the exploration rates of the agents and the number of required roles. As the number of samples increases beyond one, the emergence of a criminal organization is possible: There is a critical mass of criminals (the point where the lines cross 0) above which the criminal organizations are formed and below which they disappear, corresponding to an unstable point of the system. Two main effects can be observed. First, for a given number of roles, criminal organizations can emerge faster as the agent samples its environment more when there is a critical mass of criminals. Conversely, they also disappear faster below that critical mass. Second, as the number of roles increases, the critical mass corresponding to the unstable point shifts to the right, highlighting that a higher number of required roles implies a harder-to-form organization.

employed by criminal organizations, such as bribery, corruption, and intimidation[54]. Moreover, the lack of effectiveness of increased punishment on organized crime may be attributed to the creation of in-group versus out-group dynamics that occur within criminal organizations. In such circumstances criminal co-offence reduces the impact of external perturbations and increases their resilience and robustness[10,55].

Increased punishment is not the sole determinant of the effectiveness of a criminal organization[56]. Depending on the diversity of the portfolio of the criminal organization, the benefits derived from engaging in criminal activities are contingent upon the forces of supply and demand[5]. These forces may compel criminal organizations to alter their criminal portfolio, either by moving into different financial markets or by changing their methods of operation[57,58].

The insights gained from this study have important implications for policymakers and law enforcement agencies. They can be used to inform the development of targeted intervention strategies that address network resilience, awareness dynamics, and societal factors driving illicit behavior. The results reveal how interventions of similar scale may lead to the downfall of a criminal organization under certain conditions, while delivering marginal effects under others. This implies that increasing criminal punishment may not have the desired effects on reducing organized crime, while having a profound effect on the personal freedoms novel policies may entail[24,28,29,59,60]. Understanding the cost-benefit analysis and decision-making processes within criminal organizations is imperative for formulating effective policy frameworks aimed at preventing and disrupting organized crime[61,62].

Furthermore, this perspective reframes law enforcement policies not merely as reactive measures to criminal actions but as integral components of a dynamic system. Within this system, policymakers, law enforcement agencies, and criminal organizations form a collective wherein each party can influence the other. This systemic approach underscores the interplay between enforcement strategies and criminal behavior, emphasizing the need for proactive, adaptive policy measures that anticipate and counteract criminal activities effectively[16,17,63,64].

Looking ahead, there remain several unanswered questions and areas for future research. Further exploration of temporal dynamics, environmental adaptability, and the nuanced dynamics of social ties within criminal networks is warranted. The literature underscores the social embeddedness of criminal organizations, and introducing heterogeneous agents to include a chain-of-command could enhance the realism of the criminal process. Additionally, specifying different sources of cost or benefit could provide insights into how the effects of law enforcement and the supply and demand of illicit goods interact and affect the effectiveness of criminal organizations. Moreover, integrating trust between agents or dynamics between roles may lead to a more detailed understanding of real-world criminal organizations.

Finally, the integration of real-world data to validate and extend model findings, coupled with an examination of intervention strategies targeting structural dependencies, will contribute to a more comprehensive understanding of effective crime prevention measures. In sum, this study offers valuable insights into the dynamics of criminal organizations, laying the groundwork for future research in this field.

Data availability

The data can be re-generated through the provided scripts.

Code availability

The code is publicly available at https://github.com/cvanelteren/boiler_room.

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