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REGULAR ARTICLE

Social networks, norm-enforcing ties and cooperation

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Abstract
We study cooperation and group pressure on social networks by introducing a new concept termed norm-enforcing ties. By combining network characteristics and agents' actions, direct and indirect norm-enforcing ties extend and refine the concept of social ties as well as the role of the tightness of a group as drivers of group pressure and cooperation. The results show that a strong commitment by agents with collective interests, or a high degree of confrontation between agents minimizes the effect of indirect norm-enforcing ties on cooperation. The analysis in terms of the agent's utility reveals that an increase in indirect norm-enforcing ties does not necessarily lead to a decrease in the critical mass of compliers supporting cooperation. We demonstrate that network-oriented policies are more efficient in promoting cooperation than are standard economic policy instruments when the expected value of direct norm-enforcing ties is sufficiently large compared to the tightness of the group. Otherwise, standard economic policy instruments are more efficient.

Keywords Social norms · Social network · Cooperation · Social dilemma · Network-oriented policies

JEL Classification D85 · D91

1 Introduction

1.1 Motivation

In the presence of a social dilemma, social norms of cooperation may emerge as informal enforcement mechanisms that place collective interests above individual interests (Elster 1989; Bicchieri 2010; Nyborg 2018). The emergence and prevalence

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of such norms cannot be understood without considering the underlying social network structure and reciprocity rules (Granovetter 1973; Young 2015; FeldmanHall et al. 2018). The decision to cooperate is often voluntary, especially if it is technically infeasible or if costs are too high to rely on formal enforcement policies, such as fines or subsidies. In such cases, group pressure plays a crucial role in promoting cooperation so that agents comply with norms to avoid their group's disapproval (Akerlof 1997; Fehr et al. 2002; Ali and Miller 2016; Bicchieri 2016; Gätcher et al. 2017). The key element that distinguishes this study from the existing literature is that it considers the structure of the social network and the behavior of agents to explain sustained cooperation. It departs from the observation that the existing literature has been concerned primarily with describing the relationship between group pressure and cooperation based on the social network structure but does not analyze how the joint profiles of agents' actions and link structure relate to the strength of group pressure and support for cooperation. Thus far, models of group pressure have offered little insight into determining the extent to which the consideration of the joint profiles of agents' actions and the links structure between norm-complying agents allows agents to increase group pressure by coordinating their effort. Consequently, explaining social norm enforcement by the theory of conformity, where pressured agents are induced to match the behavior of pressuring agents (Bernheim 1994), is likely to be incomplete and may lead to a misspecification of group pressure. Furthermore, additional group-level mechanisms, such as confrontation, can potentially amplify specification errors.

The previous literature identified network structure (Axelrod and Hamilton 1981; Nowak 2006; Ohtsuki et al. 2006; Calvó-Armengol and Jackson 2010; Allen et al. 2017) or the available information about other agents' behavior (Battigalli and Dufwenberg 2007; Chaudhuri 2011; Fehr and Schurtenberger 2018; Harrell and Wolff 2023) as an important driver for group pressure. However, previous studies have neither developed a modeling approach nor a measure to determine the influence of these two elements on cooperation. Within the framework of a sequence of simultaneous choice games, this paper presents a refinement of the concept of group cohesiveness by considering whether agents have demonstrated cooperative or non-cooperative behavior in the past. For this purpose, this paper presents a new concept, termed "norm-enforcing ties", as a means to analyze group pressure and cooperation in social networks, together with its implications for the design of public policies.

1.2 Cooperation within groups: norm-enforcing ties as an extension of social ties and cohesiveness

The economic literature predominantly relies on the "set of dyads" (group size) to present social interaction between two agents that cause group pressure (Bramoullé et al. 2020; Urschev and Zenou 2020). Dyads are interpreted as avenues for observation and interaction between agents, for example, the observation of other agents' behavior and peer pressure. Yet, among sociologists—with roots in Simmel and Wolff (1950) and Coleman (1988)—it is widely acknowledged that the effective enforcement of norms also depends on another characteristic of social networks.

This is given by the "set of triads" (group cohesiveness), because it is the third agent that allows groups to coordinate actions against norm violations. Group size and group cohesiveness take into account all existing social ties within a group, but they do not offer a complete understanding of how social norms support the formation of cooperation. For example, consider a scenario with a close-knit group comprising three agents (closed triad), where one agent (i) complies with the norm (complier) and the other two (j and k) do not (deviators). In this situation, there are two social ties, that is two dyads involving agent i that contribute to norm enforcement. The triad does not play a role because there is no avenue for coordinating actions against deviators. In contrast, in a scenario with two compliers (i and j) and one deviator (k), there are three social ties that actively contribute to norm enforcement: the two dyads involving agent k and the triad involving agents i and j. Hence, the presence of triads is a necessary yet insufficient condition for enhancing the enforcement of norms. Along this line, our concept of norm-enforcing ties (Sect. 2.1) differentiates between direct norm-enforcing ties (all agents i's dyads involve compliers) and indirect norm-enforcing ties (all agents i's triads involve two compliers). The measure of norm-enforcing ties combines the agents' actions (compliance with the norm or not) with measurable network characteristics (group size and group cohesiveness) and allows us to quantify the capacity of compliers to exercise and coordinate group pressure on deviators. To analyze the influence of norm-enforcing ties on cooperation, we consider two additional factors that are important for cooperation at the group level: the agents' commitment to the collective interests (Sect. 2.2) and group confrontation (Sect. 2.3).

1.3 Scaling up cooperation: from groups to networks

In a recent empirical study, Piskorski and Gorbatâi (2017) not only validated the hypothesis that agents embedded in cohesive groups are less likely to deviate from the norm but also found that an agent's norm-complying behavior is reinforced when the neighbors[1] of that agent are part of cohesive groups that are formed by norm-complying neighbors of that agent. The concept of norm-enforcing ties lends itself to a theoretical underpinning of this empirical finding, as it allows us to extend the analysis of the role of norm-enforcing ties from the group to the network level. In this way, we shift the focus of our study from a more variable or fragile topology at the group level to a more robust topology at the network level. For this purpose, we calculate the expected value and variance of norm-enforcing ties at the network level. These statistical metrics allow us to identify the minimum and maximum influence of indirect norm-enforcing ties on cooperation for different types of networks of any size.

[1] The term "neighbor" refers to agents, e.g., family, acquaintances, or friends, whose actions matter for agent i's decisions.

1.4 Outline of our analysis

Based on a socioeconomic model at the group level, we determine the minimum number of compliers (critical mass) where the deviator's disutility from group pressure is equal to the agents' threshold in terms of the utility of their private net benefits. In general, the level of the critical mass of compliers is less demanding as the tightness of indirect norm-enforcing ties increases. We illustrate our main theoretical findings for the case of a negative externality (public bad) in Figs. 1, 2, 3 and show that, for any group or network, the importance of indirect norm-enforcing ties in affecting agents' thresholds of private net benefits increases with the group cohesiveness of compliers. At the network level, we determine the extent to which an increase in the expected cohesiveness of the network heightens the expected tightness of indirect norm-enforcing ties. Similarly, we determine the functional relationship between the expected tightness of direct norm-enforcing ties and indirect norm-enforcing ties. Analyzing the sign and magnitude of changes in norm-enforcing ties at the network level allows us to derive conditions for the design of efficient policies that aim to enhance cooperation. We find that policies that promote group cohesiveness are more efficient than those that promote direct norm-enforcing ties if the expected tightness of direct norm-enforcing ties is at least twice the value of expected group cohesiveness. Conversely, policies should focus on increasing direct norm-enforcing ties. Finally, our findings indicate that formal enforcement policies are the only efficient policy option for networks with relatively few or many social ties.

1.5 Organization of the paper

The remainder of this paper is organized as follows. Section 2 presents the theoretical framework and underlying assumptions. Section 3 presents the socioeconomic model. Section 4 provides a numerical example for identifying thresholds and equilibria. Section 5 analyzes the influence of norm-enforcing ties on individual decision-making and presents graphical illustrations of the main results. Section 6 analyzes the tightness of norm-enforcing ties at the network level and discusses the implications for policy design. Section 7 concludes.

2 Theoretical framework and assumptions

This section presents the concepts, building elements, and measures used to study cooperation in social networks. It focuses on promoting and impairing factors of cooperation at the group level and justifies the underlying assumptions of the modeling approach.

2.1 Norm-enforcing ties: concept, building elements, and measure

2.1.1 Concept of norm-enforcing ties

Consistent with previous research (Shweder et al. 1997; Tomasello 2016; Yudkin et al. 2021), we interpret norm-enforcing ties as agents' interactions that increase their perceived obligation to realize an action, such as cooperation in social dilemmas. Norm-enforcing ties are related to expectations shared by groups: the greater the tightness of the norm-enforcing ties within a group, the more agent i's neighbors expect cooperation from agent i. Norm-enforcing ties emerge and spread through interactions between agents. They may take the form of an implicit informal contract between group members that encourages the subordination of agents to collective interests.

2.1.2 Group size and group cohesiveness

Group size and group cohesiveness measure the total number of dyads and triads agent i has, respectively. Social networks are formally represented by $g = (V, L)$, where $V : \{1, ..., n\}$ is the set of agents and L is the set of links (dyads) among them. The elements in set L consist of the values of the indicatrix link function $\ell : V \times V \rightarrow \{0, 1\}$, where $\ell_{ij} \in \{0, 1\}$ indicates whether any pair of agents $(i, j) \in V$ are neighbors, $\ell_{ij} = 1$, or not, $\ell_{ij} = 0$. Agent i's group is defined by their[2] neighbors and is denoted by $N_i(g) = \left\{ j \in V \backslash \{i\} : \ell_{ij} = 1 \right\}$. The size of the group is given by $k_i = \left| N_i(g) \right| \in [1, n-1]$.[3]

Economic theory focuses mainly on dyads to study cooperation in social networks (Bramoullé et al. 2020). In contrast, sociological theory also considers group cohesiveness, since this concept helps identify the mechanisms by which dyads are affected by triads at the group level, such as impartial mediation (Simmel and Wolff 1950) or the formation of coalitions (Caplow 1969). For example, in a triad, a form of coalition interaction emerges when two agents (the majority) request cooperation from a third agent (the minority) under the threat of group pressure (Miller 2007). The cohesiveness of agent i's group depends on its total number of triads, m_i, which is defined by.

$$m_i = \left| \left\{ \ell_{uv} : u, v \in N_i(g), \ell_{uv} = 1 \right\} \right| \in \left[\underline{m}_i, \overline{m}_i \right], \tag{1}$$

where $\underline{m}_i = 0$ occurs when agent i's neighbors cannot interact at all, for example, agent i's group has the form of a star, and $\overline{m}_i = \left(k_i \left(k_i - 1 \right) \right) / 2$ occurs when agent i's neighbors form a completely cohesive group so that every neighbor can interact

[2] Instead of binary male–female pronouns, we use the plural form.

[3] A gentle introduction into social networks and economic behavior is given by Jackson et al. (2017) and a more rigorous introduction by Jackson (2010).

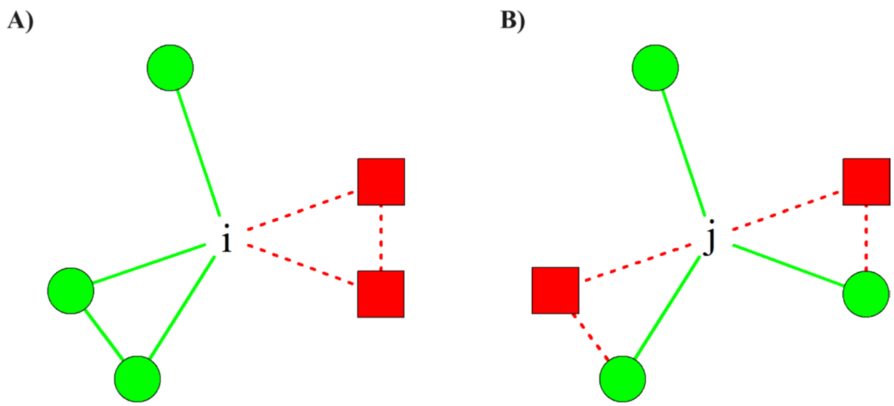

Fig. 1 Norm-enforcing ties as an extension of social ties and cohesiveness. The green circles and red squares represent agent i's ($j's$) neighbors, who are compliers and deviators, respectively. Norm-enforcing ties are represented by a continuous line (green), whereas the remaining social ties are represented by a discontinuous line (red). In Panel A, agent i has three direct norm-enforcing ties and one indirect norm-enforcing tie. In Panel B, agent j has three direct norm-enforcing ties, and no indirect norm-enforcing ties

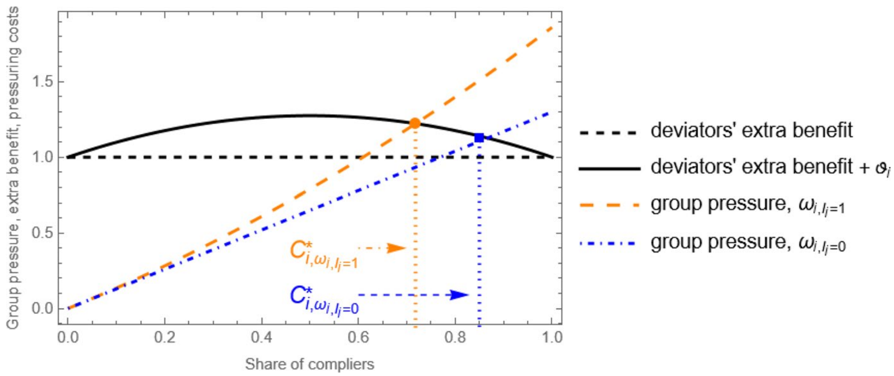

Fig. 2 Effects of indirect norm-enforcing ties on the location of the critical mass of compliers, C_i^*. The solid black line represents the sum of the deviator's extra benefits and the pressuring costs. The dashed orange and dotted-dashed blue lines represent group pressure when I_i is maximal and minimal, respectively. The vertical dotted blue and orange lines represent the locations of C_i^* when $I_i = 0$ and $I_i = 1$, respectively

with all other neighbors. Group cohesiveness is measured by the individual clustering coefficient[4] (Jackson 2010) that is defined as.

$$\tau_i = \frac{m_i}{\overline{m}_i} \in [0, 1]. \tag{2}$$

[4] Other statistical measures of cohesiveness can also be found in the literature (Jackson 2010, Jackson et al. 2012) but they either do not relate to agent i's group or they are not based on closed triads.

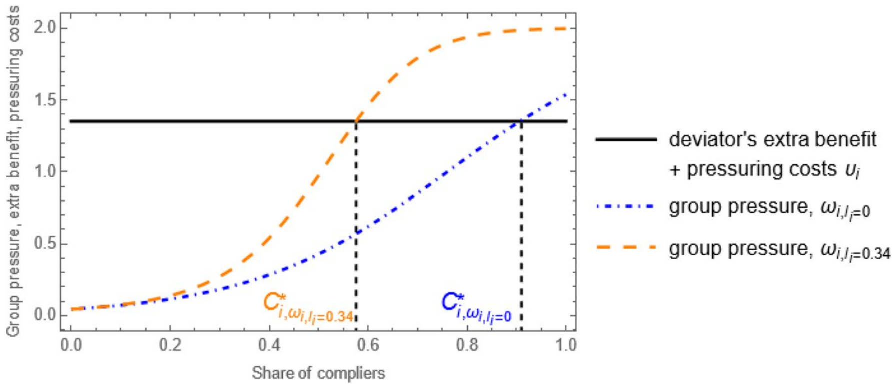

Fig. 3 Effects of indirect norm-enforcing ties on the location of C_i^*. The solid black line represents the sum of the normalized deviators' extra benefits and the pressuring costs. The dashed orange and dotted-dashed blue lines represent group pressure when I_i is maximal and minimal, respectively. Vertical dashed black lines represent the locations of C_i^* when $I_i = 0$ and $I_i = 0.34$, respectively. The parameter values are $S = 2$, $\beta_1 = 10$, $\beta_2 = 5$, $\beta_3 = 0.3$, $\gamma_i(k_i) = 1$, $v_0 = 0.35$, and $v_1 = v_2 = 0$

It indicates the total number of triads with respect to the maximum number of triads within agent i's group. In the remainder of the paper, we maintain the term "cohesiveness" as it describes the idea of tightness of the group more intuitively than the term "clustering.

2.1.3 Actions: individual versus collective interests

Let a community consist of $n \in \mathbb{N}$ identical agents, whose action profiles are denoted by the vector $\mathbf{a} = (a_i)_{1 \leq i \leq n} \in \mathbb{R}^n_{\geq 0}$. For analytical convenience, and without loss of generality, let agents face a binary choice between their actions, such that $\forall i \in V$, $a_i \in \{0, 1\}$. The action $a_i = 0$ (complier) indicates that agent i adheres to the social norm, while $a_i = 1$ (deviator) indicates that agent i deviates from it. Each agent i receives private benefits from individual actions, $a_i \in \mathbb{R}_{\geq 0}$, and suffers economic losses from a negative externality in the form of a public bad as a result of the aggregate actions of all agents, $A = \sum_{i=1}^{n} a_i$.[5, 6]. For example, the public bad may originate from the agents' action in form of air or water pollution, noise, self-medication with antibiotics (thereby creating resistance), light contamination, or congestion of public infrastructure. The net benefits of agent i include the costs of the negative externality and are denoted by $\pi_i(a_i, A)$, where $\pi_i : \mathbb{R}^2_{\geq 0} \rightarrow \mathbb{R}$ is a continuous, twice differentiable, and strictly concave function with $\partial\pi_i / \partial a_i > 0$ and $\partial\pi_i / \partial A < 0$. We assume that the agents' net benefits are anonymous and social welfare is given by the sum of individually separable net benefits, that is, $W = \sum_{i=1}^{n} \pi_i$.

Let $a_i = 0$ and $a_i = 1$ denote agent i's actions that uniquely maximize private net benefits and social welfare (collective interest), respectively. As described widely in the literature (Cornes and Sandler 1996; Chaudhuri 2011; Baldassarri 2015) the presence of a public bad leads to a social dilemma that for $\forall i \in V$ and any A can be characterized at the individual level by $\pi_i(a_i = 0, A) < \pi_i(a_i = 1, A)$ but at the collective level by $W(a_i = 0, A) = \sum_{i=1}^{n} \pi_i(a_i = 0, A) > W(a_i = 1, A) = \sum_{i=1}^{n} \pi_i(a_i = 1, A)$.

This social dilemma arises because the action profile that maximizes social welfare is not optimal for self-interested agents seeking to maximize their private net benefits. The higher the number of agents who choose $a_i = 0$, the lower the negative externality—for example, less congested public infrastructure or a lower concentration of air pollutants. Once $a_i = 0$ has been determined, and is known to all agents, it may emerge as a social norm[7] to promote collective interests within the community.

2.1.4 Measure for norm-enforcing ties

The measure[8] for norm-enforcing ties takes account of two different types of links: (1) links between any agent i and their norm-complying neighbors, and (2) links between the agent i's norm-complying neighbors (only links between compliers). The first type of links is called "direct norm-enforcing ties", depends on dyads, and captures the significance of the social norm within agent i's group, that is, the dissimilarity between the agent's own actions and those of the group. Direct

[5] The analysis in this study concentrates on the case of negative externalities. However, our theoretical framework can be easily adjusted to consider positive externalities such as the production of a public good.

[6] If all agents are deviators, it holds that $A = n$, and if all agents are compliers, it holds that $A = 0$.

[7] In our context, norms describe ways to behave in specific situations that are socially shared and informally enforced by agents. Consequently, shared knowledge about how to behave to maximize social welfare is a prerequisite for norms to emerge and prevail. Given the focus of this paper, we prefer to abstain from analyzing the emergence of a social norm since it may distract from our focus on the influence of direct and indirect norm-enforcing ties on cooperation. For studies that cover the emergence of social norms see for example, (Young 1993, Henrich and Boyd 2001, Bicchieri and Xiao 2009, Krupka and Weber 2013, Acemoglu and Jackson 2015).

[8] The code, written in Python and R, allows us to calculate norm-enforcing ties in groups for different types of networks of any size and can be downloaded at https://doi.org/10.5281/zenodo.13371113.

norm-enforcing ties, k_i^0, indicate the number of compliers that form part of agent i's group and are computed as.

$$k_i^0 = \left| N_i^0(g) \right| = k_i - \sum_{j \in N_i(g)} a_j, \tag{3}$$

where $N_i^0(g) = \left\{ j \in V \backslash \{i\} \,:\, \left(1 - a_j\right)\ell_{ij} = 1 \right\}$ denotes the set formed by all compliers within agent i's group, such that $N_i^0(g) \subseteq N_i(g)$ and $k_i^0 \leq k_i$. Superscript 0 relates to the chosen action of norm compliance, that is, $a_i = 0$. The second type of links is called "indirect norm-enforcing ties", depends on triads, and captures the capacity of norm-complying neighbors to coordinate group pressure on agent i when deviating from the social norm. The computation of the number of indirect norm-enforcing ties, m_i^0, is given by.

$$m_i^0 = \left| \left\{ \ell_{uv} \,:\, u, v \in N_i^0(g), \ell_{uv} = 1 \right\} \right| \in \left[\underline{m}_i, \overline{m}_i \right]. \tag{4}$$

This indicates the number of triads involving two of agent i's neighbors who comply with the norm. Since not all triads are formed by compliers, it holds that $m_i^0 \leq m_i$. According to Eq. (4), $m_i^0 = 0$ occurs, for example, when $k_i^0 = 0$ or $m_i = \underline{m}_i = 0$. This implies that m_i^0 depends on k_i^0 and m_i. More precisely, it holds that indirect norm-enforcing ties tend to increase with the number of compliers and the number of triads involving compliers that form part of agent i's group, i.e., $\partial m_i^0 / \partial k_i \approx m_i^0\left(k_i^0 + 1\right) - m_i^0\left(k_i^0\right) \geq 0$ and $\partial m_i^0 / \partial m_i \geq 0$.[9, 10] More importantly, differences in m_i^0 may appear even in groups with identical k_i, k_i^0 and m_i. See Fig. 1 for an illustration. The groups $N_i(g)$ and $N_j(g)$ have identical dyads, $k_i = k_j = 5$, acceptance of the social norm, $k_i^0 = k_j^0 = 3$, and triads, $m_i = m_j = 2$. However, they differ in the number of indirect norm-enforcing ties, $m_i^0 = 1 > m_j^0 = 0$, because agent j's neighbors act in such a way that norm-complying neighbors are not linked.

[9] In mathematical terms our notation is not correct since k_i is a natural number and the derivative $\partial m_i^0 / \partial k_i$ is not well defined. For this reason, $\partial m_i^0 / \partial k_i$ should be interpreted as an approximation given by $\partial m_i^0 / \partial k_i \approx m_i^0\left(k_i^0 + 1\right) - m_i^0\left(k_i^0\right) \geq 0$. Another way to interpret $\partial m_i^0 / \partial k_i$ would be to think of it as an arithmetic derivative that operates strictly within the realm of integers. It measures how changes in the prime factorization of an integer translate into a discrete "rate of change". Throughout the paper we consider $\partial m_i^0 / \partial k_i \approx m_i^0\left(k_i^0 + 1\right) - m_i^0\left(k_i^0\right) \geq 0$. Although this approximation may be inaccurate for a particular group its accuracy is high if the derivative represents the average k_i within the network. Thus, when we use a derivative with respect to k_i we interpret it as the average effect of a change in the degree of agent i 's group.

[10] The sign of the first derivative is not strictly positive, because an increase in the number of agent i's norm-complying neighbors, k_i^0, does not lead to an increase in m_i^0 if a new neighbor adhering to the social norm is not linked to the existing norm-complying neighbors. Similarly, the sign of the second derivative is not strictly positive because an increase in the number of triads within agent i's group, m_i, does not lead to an increase in m_i^0 if the new triad does not involve two norm-complying neighbors.

2.2 Group pressure: concept, building elements, and measure

A predominant idea in the literature is that there is a very limited social distance[11] at which agents are expected to enforce norms (Manski 1993; Bicchieri 2016; Nyborg 2018). Therefore, we focus on group pressure (only neighbors can exert pressure) instead of social pressure (any agent can exert pressure). Groups portray the circle of trust of agent i (Duernecker and Vega-Redondo 2017); therefore, the behavior of agents who lie outside the circle has virtually no influence on agent $i's$ behavior[12] (Banfield 1958; Platteu 2000).

2.2.1 Building elements of group pressure

Group pressure supports cooperation and has the following key ingredients: (a) norm-enforcing ties, and (b) the level of agents' commitment to collective interest. With respect to norm-enforcing ties, we focus on the two building elements that translate into group pressure: (1) the acceptance of the social norm within agent i's group, and (2) the level of coordination among agent i's norm-complying neighbors. The strength of the social norm within agent i's group is computed as follows.

$$C_i = \frac{k_i^0}{k_i} \in [0, 1]. \tag{5}$$

The measure C_i indicates the tightness of direct norm-enforcing ties at the group level, as it measures the proportion of agent i's dyads that involve norm-complying neighbors. The level of coordination among agent i's norm-complying neighbors is computed by.

$$I_i = \frac{m^0}{\overline{m}_i} \in [0, 1]. \tag{6}$$

The measure I_i is based on a modification of the individual clustering coefficient by considering only agents that are compliers. It indicates the tightness of indirect norm-enforcing ties at the group level, by measuring how close $N_i^0(g)$ is to a completely cohesive group. Note that the measures τ_i and I_i, defined in Eqs. (2) and (6), involve triads. However, the measure of τ_i is different from the definition of I_i because the former measures the links among agent i's neighbors, regardless of whether they are compliers, whereas I_i only measures the links among agent i's norm-complying neighbors. Hence, $I_i \leq \tau_i$ always holds, because not all neighbors

[11] In a connected social network, the social distance between two agents refers to the number of links required to connect them. Social distance is equal to one when agents are neighbors. It is equal to two when agents have neighbors in common but are not linked to each other, and so forth.

[12] Another reason for selecting group pressure instead of social pressure is motivated by the results from Balafoutas and Nikiforakis (2012). In their paper, the authors conducted a natural field experiment and observed that only 35 out of 300 agents were willing to exercise costly social pressure on strangers (agents who are not neighbors) to enforce social norms. A possible explanation for the low reciprocity rate may be that there are no social ties between agents, whereas our study is based on a social network in which agents are connected and interact.

are compliers, that is $N_i^0(g) \subseteq N_i(g)$. Based on Eq. (6) we make the following assumption.

Assumption 1 Compliers that are linked always coordinate group pressure.[13]

Next, we define how direct and indirect norm-enforcing ties translate into group pressure.

2.2.2 Measure for group pressure

The strength of group pressure, ω_i, on agent i is defined by,

$$\omega_i\left(C_i, I_i, \pi_i\left(a_i = 1, A\right) - \pi_i\left(a_i = 0, A\right)\right), \tag{7}$$

where the group pressure function $\omega_i : \mathbb{R}^3_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ is a continuous, twice differentiable, and increasing function in C_i, I_i and A, with $\omega_i(0, 0, 0) = 0$ and $\max\left\{\omega_i\right\} \in \mathbb{R}_{>0}$. The group pressure function includes the pressure from individual compliers alone and its intensification if the compliers are linked. If agent i complies with the social norm, $a_i = 0$, norm-complying neighbors do not exert pressure on agent i, that is $a_i\omega_i = 0$. Otherwise, $\omega_i\left(C_i, I_i, \pi_i\left(a_i = 1, A\right) - \pi_i\left(a_i = 0, A\right)\right)$. The difference $\left(\pi_i\left(a_i = 1, A\right) - \pi_i\left(a_i = 0, A\right)\right) \in \mathbb{R}_{>0}$ denotes the extra benefits that an agent obtains from deviation. The extra benefits of a deviator indicate the difference between the net benefits an agent obtains from choosing to be a deviator compared

[13] The coordination of group pressure among compliers may depend not only on the existence of a link between them (Coleman 1988) but also on factors related to the tightness of their links. For example, among other factors, homophily ("birds of a feather flock together") may favor coordination (McPherson et al. 2001). Consequently, the effective number of indirect norm-enforcing ties, $\tilde{m}_i^0$, may be lower than the nominal number of indirect norm-enforcing ties, m_i^0, such that $\tilde{m}_i^0 \leq m_i^0 \leq m_i$. We recognize that triads and homophily are related and intensify the similarity of actions within a group (Kossinets and Watts 2006). However, because the principal objective of this paper is to present and analyze norm-enforcing ties, we focus on group cohesiveness as a driving factor for coordination and do not consider the homophily. At first glance, this might be viewed as a shortcoming. However, assuming $\tilde{m}_i^0 = m_i^0$, does not exclude the analysis of the case where $\tilde{m}_i^0 < m_i^0$ by considering different values of m_i^0 as a function of C_i. The analysis of social networks, presented in Sect. 6, particularly Theorem 1 and Appendix H, shows that the share of direct norm-enforcing ties and the type of social network are approximately related to indirect norm-enforcing ties. Thus, given the type of network (random, scale-fee or complete) and any share of compliers C_i, we can calculate the expected share of indirect norm-enforcing ties m_i^0 (Theorem 1). The analysis of equilibria and thresholds in Sect. 5 is based on variations in C_i that are synonymous with changes in m_i^0. Thus, the case $\tilde{m}_i^0 < m_i^0$ can be analyzed by considering values of C_i that are lower than those that correspond to m_i^0. Likewise, one can consider types of networks whose maximal number of triads formed by all agents, regardless of whether they are compliers, is lower for a given number of C_i. Thus, Theorem 1 and Appendix H warrant that Assumption 1 is innocuous because the analysis can be easily extended to the case in which not all compliers coordinate group pressure with other compliers.

to those from choosing to be a complier. If the deviators extra benefits are negative the agents choose to be a complier.[14]

Conceptual frameworks and empirical evidence developed in game theory and laboratory experiments suggest that group pressure is the result of negative reciprocity; that is, the group exerts pressure in proportion to the severity of the deviation (Fehr et al. 2002; Dohmen et al. 2009; FeldmanHall et al. 2018). Hence, compliers are not only motivated by the deviation itself, but also by the fact that the deviators' extra benefits result in higher costs for compliers. In other words, deviators inflict economic losses on compliers, and the privation suffered by compliers provides incentives to exercise group pressure. For the actual realization of group pressure, we make the following assumption.

Assumption 2 All agents are perfectly informed about their neighbors' actions. There is no time delay between detecting deviators and exercising group pressure.[15]

2.3 Costs of exerting pressure and group confrontation: concepts and measure

Exerting pressure on deviators is costly for compliers because it can lead to reprisals (Fehr and Gätcher 2000 and 2002; Calvó-Armengol and Jackson 2010; Balafoutas and Nikiforakis 2012). Let ϑ_i denote agent i's costs of exerting pressure on their neighbors who are deviators. The more deviators a complier is linked to, the higher the complier's total cost of exerting pressure. Likewise, the more compliers are within agent i's group the higher the coordination costs between them. For agent i, the pressuring costs, ϑ_i, are defined by.

$$\vartheta_i\left(k_i, C_i\right), \tag{8}$$

where $\vartheta_i : \mathbb{R}^2_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ is a continuous, twice differentiable, and nondecreasing function in k_i, and is increasing and/or nonincreasing with respect to C_i with $\vartheta_i\left(k_i, 1\right) = 0$.

The pressuring costs are also likely to be affected by the degree of confrontation between compliers and deviators of the group. A high degree of confrontation may occur when deviators observe that they are not isolated agents but form part of

[14] Group pressure is a function of the link structure, the number of compliers, their position within in the network and the corresponding deviator's extra benefits. The combinations of these four factors give rise to a specific group pressure. Some of these combination may lead to identical pressure, but they differ at least in one of the four factors. Thus, the strength of group pressure does not allow to deduce the link structure of the network, the number of compliers, their positions within the network and/or the deviator's extra benefit. Only if all four factors are known group pressure is uniquely defined, but the reverse does not hold. Since the measure of group pressure takes account of all four factors, the proposed measure of group pressure is not only applicable to certain link structures (types of networks) but to any.

[15] Under imperfect monitoring, coordination of group pressure requires specification of a mechanism that determines how agents coordinate their actions. However, because this extension does not offer any additional insights into the analysis of norm-enforcing ties, we abstain from its specification. For any specification of the agents' coordination effort, imperfect monitoring likely leads to a reduction in group pressure. However, as mentioned in footnote 12, reduced group pressure can be analyzed within the existing framework. It does not lead to a loss of generality of our analysis because imperfect monitoring is analogous to a decrease in direct norm-enforcing ties or a change in the type of network.

a larger group of deviators. A larger group of deviators strengthens their identity, which in turn reinforces their willingness to defend their choice of norm deviation. This situation may result in the formation of well-balanced subgroups of deviators and compliers. More strongly defended viewpoints imply that compliers have higher pressuring costs, since deviators may be more reluctant to change their actions.

The concepts of norm-enforcing ties and group pressure assume that agents tend to match their actions to those of other agents in the group. The fact that agent i's pressuring costs depend on the number of compliers and deviators, coordination and resistance, motivates the assumption that the specification of the cost function should allow for flexible functions including in form of a bell with respect to C_i. If the cost function is bell-shaped, we define the value at which the confrontation between the subgroups and, therefore, the pressuring costs are maximal. The maximum value is achieved when the subgroups are of equal size.

Definition 1 [Value of maximal group confrontation] Within a group, confrontation occurs only if compliers and deviators coexist. If the pressuring cost function is bell-shaped with respect to C_i the value at which confrontation within the group is maximal is denoted by $\tilde{C}_i$.

In the presence of a social dilemma and pressuring costs, we make the following assumption regarding compliers' motivation.

Assumption 3 Compliers are willing to pressure deviators based on their norm-enforcing code, even at a cost to themselves, and they do not free ride on each other. Deviators do not exercise group pressure.[16]

The norm-enforcing code is shared by all compliers. The strength of the norm-enforcing code depends on agents' commitment to the collective interest; that is, choosing the action that, if chosen by all agents, would lead to social welfare maximization (Alger and Weibull 2013).[17, 18] If compliers are highly committed, the

[16] Reinterpreting and respecifying the compliers' pressure as a net pressure function of compliers and deviators would allow for an analysis of the effect of deviators' group pressure. As a result, a complier's pressure function would start its transition with an increase in the share of compliers from low to high pressure later, and it requires more compliers to reach the maximal group pressure compared to the case where deviators do not exercise group pressure. Basically, it leads to a countereffect of the group pressure of compliers on deviators, originating from the group pressure of deviators on compliers. The specification of a net pressure function within the existing modeling framework is possible because the form of the complier's pressure function is flexible. By appropriately selecting the parameter values, the behavior of the compliers' pressure function can portray the behavior of the net pressure function. However, we do not include this analysis since it does not seem to produce new qualitative insights.

[17] We assume that agents are intrinsically motivated but not in form of an absolute value. Instead, the analytical and empirical framework allows for the graduation of intrinsic motivation in the form of the agent's commitment to the collective interest. In Sect. 5 the agent's commitment can be adjusted by varying the parameters β_2 and β_3. The specification of flexible function allows us to maintain the generality of the analysis.

[18] The level of agents' commitment to collective interest is high if they share similarly high values of fairness and justice (Enke 2019). One expects that the higher the level of the agents' commitment to the collective interest, the more likely agents consider the effects of their individual actions on the public bad and exercise group pressure on deviators.

group pressure increases rapidly with the number of compliers, and they already start pressuring even if the number of compliers is low. Lowly committed agents start pressuring only if the number of compliers is high. Without intrinsic motivation, compliers may not necessarily exercise group pressure and may free ride on each other. In the latter case, we must distinguish between compliers who exert pressure and those who do not. Embedding a social dilemma between compliers into a more general social dilemma between compliers and deviators is beyond the scope of this study.[19]

At the end of this section, Table 1 presents a summary of the most important functions, variables, and parameters of the theoretical framework.

3 The socioeconomic model

The socioeconomic model defines (1) the agents' utility, taking into account both promoting and impairing factors for cooperation; (2) agents' decision rule, with a threshold that marks the difference between cooperation and noncooperation; and (3) conditions for the existence and stability of equilibria at the group and network levels.

3.1 Utility

The agent i's utility is given by.

$$u_i^{a_i\in\{0,1\}} = \pi_i\left(a_i, A\right) - a_i\omega_i - \left(1 - a_i\right)\vartheta_i. \tag{9}$$

As defined above, the evaluation of the first term of Eq. (9) yields $\pi_i(0, A) < \pi_i(1, A)$, for all $A \in [0, n]$. Since compliers do not receive group pressure, it holds that $u_i^0 = \pi_i(0, A) - \vartheta_i$, and deviators do not exert pressure, so that $u_i^1 = \pi_i(1, A) - \omega_i$.

3.2 Context of the decision process

To simplify our study of the effects of norm-enforcing ties on cooperation, the decision-making process is embedded in the following context.

3.2.1 Setup

The context of the decision process is characterized by.

[19] If some compliers fail to exert pressure on deviators, other compliers might pressure them to exercise group pressure. This behavior can be explained by the existence of a meta-norm (Axelrod 1986). However, to keep our analysis focused on norm-enforcing ties, we did not consider the so-called second-order dilemma of public goods.

- *Social networks*. Networks are of any size and are described by the joint distribution of links and agents' actions. The number of agents and the link structure do not change over time.[20] Links are undirected and unweighted, and no agent is isolated. At the outset of the sequence of the simultaneous choice game, the group size and cohesiveness of the agents are distributed randomly in line with topological characteristics of the network across agents.
- *Social norm*. The action that maximizes social welfare is known and achievable to all agents.
- *Initial profile of actions*. An initially randomly distributed subset of agents chooses to comply with the norm, whereas the complement of this subset is formed by the deviators.
- *Timeline*. Within each sequence of the game, all agents decide whether to comply or deviate simultaneously and to act nonstrategically. The game ends when an equilibrium is reached.

3.2.2 Individual decision-making

Agents' decisions are based on previous actions taken at the group level and the magnitude of the negative externality, without considering the actions that other agents take at this moment. The calculation of agent i's best-response function is limited because agent i has no information about the influence of the agents' decisions lying outside the group of agent i's neighbors. Thus, any best-response function based only on the current actions of agent i's neighbors is erroneous by construction, and there is no guarantee that the underlying decision process leads to more efficient outcomes than assuming nonstrategic behavior.[21] Additionally, we focus on the likely situation in which the number of agents is sufficiently large so that the marginal effect of agent i's action on the negative externality in the form of a public bad is negligible. Thus, agents do not consider the influence of their actions on the negative externality.

The agent's decision rule is given by.

$$u_i^0 \geq u_i^1. \tag{10}$$

[20] The literature also considers the case where the behavior of the agents gives rise to new social networks whose formation process follows a particular pattern generating a random, scale-free or complete network (Jackson et al. 2008, Currarini et al. 2010, Jackson 2010, Boucher 2016, Christakis et al. 2020). However, this aspect is not considered explicitly in this study, as it is beyond its scope. Indirectly, however, this aspect is considered because the analysis of social networks in Sect. 6 shows that the share of direct norm-enforcing ties and the type of social network are related to indirect norm-enforcing ties. Thus, given a type of network and share of compliers, we can calculate the maximal share of indirect norm-enforcing ties of a random, scale-free or complete network. In other words, the paper does not model the link formation process itself but allows to relate possible outcomes of the link formation process with the strength of group pressure.

[21] Moreover, we do not consider strategic behavior because the determination of the optimal strategic response to, for instance, hundreds of other agents, each of whom occupies a unique position in the social network, could stretch the assumption of rationality beyond its limits owning to the interdependency of the agents' strategic decision problem.

Table 1 Enumeration and description of the most relevant functions, variables and parameters of the theoretical framework

Functions, variables and parameters	
$N_i(g) = \{j \in V\backslash\{i\} : \ell_{ij} = 1\}$	Agent i's group
$k_i = \lvert N_i(g)\rvert$	The size of agent i's group
$m_i \in [\underline{m}_i, \overline{m}_i]$	The number of triads of agent i's group
$\tau_i \in [0, 1]$	The cohesiveness of agent i's group measured by the individual clustering coefficient
$a_i \in \{0, 1\}, A = \sum_{i=1}^{n} a_i$	Set of agent i's possible actions and the aggregate actions of all agents. The value A indicates the magnitude of the negative externality
$\pi_i(a_i, A)$	Agent i's net benefit
k_i^0	The number of compliers that form part of agent i's group
$N_i^0(g)$	The set of all compliers within agent i's group
$m_i^0 =\in [\underline{m}_i, \overline{m}_i]$	The number of triads that involves two compliers of agent i's neighbors
C_i	The tightness of direct norm-enforcing at the group level
I_i	The tightness of indirect norm-enforcing ties at the group level
ω_i	The tightness of group pressure on agent i at the group level
ϑ_i	Agent i's pressuring costs
$u_i^{a_i \in \{0,1\}}$	Agent i's utility (to be introduced below)
Functions and parameter values (to be introduced below)	
S	Maximal attainable group pressure
$\beta_1, \beta_2, \beta_3$	Parameters of the group pressure function
v_1, v_2, v_3	Parameters of the pressuring cost function
$\tilde{C}_i$	Value at which confrontation within the group is maximum when $v_2 \geq v_1 \geq 0$

Thus, agent i chooses to comply with the norm if the utility derived from cooperation, u_i^0, is at least as high as the utility derived from noncooperation, u_i^1. The equality between u_i^0 and u_i^1 represents an individual threshold[22] that marks the difference between cooperation and noncooperation, as stated in Definition 2.

Our analysis focuses on the effect of norm-enforcing ties on individual thresholds and equilibria of the game, but we do not model the evolution of k_i, C_i, m_i^0 and A over time. The analysis of the trajectories of these four state variables requires implementation of complex numerical approximation techniques that are beyond the scope of this paper.

Definition 2 [Individual threshold] An individual threshold for cooperation is the proportion of agent i's group that must comply with the norm before agent i

[22] Since Granovetter (1978), the use of thresholds has become common practice for analyzing social dilemmas. Other authors such as Bicchieri (2006) refer to thresholds as "conditional cooperation". In our model, agents are neither pure cooperators nor pure deviators; whereas other authors condition cooperation on the existence of individual thresholds (Torren-Peraire et al. 2024).

complies. This is denoted by $C_i^* \in (0, 1]$, where $C_i < C_i^*$ leads to $u_i^0 < u_i^1$ and $C_i \geq C_i^*$ to $u_i^0 \geq u_i^1$.

Individual thresholds are specific for each agent because they result from the links between the members of agent i's group and the location of compliers and deviators within the group. Different compositions of locations can yield different thresholds.

3.3 Equilibrium

The existence and stability of equilibria at the group and network levels are determined as follows.

Definition 3 [Existence of groupwise equilibrium]. An equilibrium where agent j and agent j's neighbors exercise costly pressure exists and is temporarily groupwise stable if there exists a profile of actions $\mathbf{a}^G = \left(a_i\right)_{1 \leq i \leq k_j+1} \in \{0, 1\}^{k_j+1}$ such that $\forall a_i \in \Omega = \{0, 1\}, \forall j \in \left\{N_j(g) \cup \{j\}\right\} \subseteq V$: $u_i^{\hat{a}_i} \leq u_i^{a_i}$ where, $\hat{a}_i \in \Omega \backslash \left\{a_i\right\}$.

Equilibrium conditions require that each agent of the group $N_j(g) \cup \{j\}$ chooses the action that offers at least the utility of the alternative action, given all neighbors' actions. In other words, agent j and all their neighbors have no incentive to modify their current actions. However, because the group is embedded in the large social network, the stability of a groupwise equilibrium does not imply an equilibrium at the network level. Any agent lying outside the group may choose a different action than before, which in turn alters the profile of actions. Unlike the case for groups, the existence of an equilibrium at the network level can be determined.

Definition 4 [Existence and stability of a network equilibrium]. An equilibrium in which agents exercise costly pressure is stable at the network level if there exists a profile of actions $\mathbf{a}^N = \left(a_i\right)_{1 \leq i \leq n} \in \{0, 1\}^n$ such that $\forall a_i \in \Omega = \{0, 1\}, \forall i \in V : u_i^{\hat{a}_i} \leq u_i^{a_i}$, where $\hat{a}_i \in \Omega \backslash \left\{a_i\right\}$.

Definition 4 allows us to identify multiple equilibria, including not only the all-deviator, $A = \left(\sum_{i=1}^n a_i = 1\right) = n$, and all-complier, $A = \left(\sum_{i=1}^n a_i = 0\right) = 0$, equilibria, but also interior equilibria, $0 < A^* < n$, where compliers and deviators coexist.[23] In the case of an interior equilibrium, none of the agents of the entire social network have an incentive to modify their current actions. The case $A = n$ represents a Nash equilibrium in which none of the agents have economic incentives to change the status quo; therefore, a social norm is not likely to be established. The case $A = 0$ represents the situation in which the equilibrium coincides with the unique Pareto-efficient allocation of actions; that is, the community achieves social welfare maximization as a result of the emergence and prevalence of the social norm. Any interior

[23] We cannot rule out that cyclical equilibria exist. However, a more detailed analysis is beyond the scope of this paper.

equilibria, A^*, can be interpreted as a second-best solution of the social dilemma because the resulting negative externality is below $A = n$ but still above $A = 0$.

4 Numerical example for identifying thresholds and equilibria

This section illustrates the influence of norm-enforcing ties on the location of a groupwise equilibrium and the agent's decision, taking into account the tightness of direct and indirect norm-enforcing ties at the group level, the degree of group confrontation, and pressuring costs. To illustrate the influence of norm-enforcing ties on the individual threshold, we have chosen simple forms of the employed functions. Let agent i 's net benefit function be given by $\pi^{a_i} = 1 + a_i - 0.01(A/n)$, group pressure by $\omega_i = 1.3C_i + 0.7I_i$, and its cost for compliers by $\vartheta_i = \left(1 - C_i\right)C_i$. The function π^{a_i} also shows that the deviator's extra benefits $\left(\pi_i\left(a_i = 1, A\right) - \pi_i\left(a_i = 0, A\right)\right)$ are constant and equal to one. Thus, according to Definition 3, a group equilibrium requires for $\forall a_j \in \Omega = \{0, 1\}\ \forall j \in \left\{N_j(g) \cup \{j\}\right\}$ that.

$$\pi_j\left(\hat{a}_j, A\right) - \hat{a}_j\omega_j - \left(1 - \hat{a}_j\right)\vartheta_j \leq \pi_j\left(a_j, A\right) - a_j\omega_j - \left(1 - a_j\right)\vartheta_j \text{ where } \hat{a}_j \in \Omega \backslash \left\{a_j\right\}. \tag{11}$$

Based on the specification of the functions $\pi_i, \omega_i, \vartheta_i$ Eq. (11) becomes[24]

$$\begin{aligned} &1 + \hat{a}_i - 0.01\frac{A}{n} - \hat{a}_i\left(1.3C_i + 0.7I_i\right) - \left(1 - \hat{a}_i\right)\left(1 - C_i\right)C_i \\ &\leq 1 + a_i - 0.01\frac{A}{n} - a_i\left(1.3C_i + 0.7I_i\right) - \left(1 - a_i\right)\left(1 - C_i\right)C_i \end{aligned} \tag{12}$$

According to Definition 4, Eq. (12) also defines an equilibrium at the network level if the inequality holds not only for all agents of the neighborhood but also for all agents of the network.

Agent i chooses to be a complier if $u_i^0 - u_i^1 \geq 0$ which translates to $\pi_i\left(a_i = 0, A\right) - \vartheta_i - \left(\pi_i\left(a_i = 1, A\right) - \omega_i\right) = \omega_i - 1 - \vartheta_i \geq 0$. Based on the chosen specification, Fig. 2 presents the graphs of $\pi_i, \omega_i, \vartheta_i$ as a function of the share of compliers (direct norm-enforcing ties). The influence of the tightness of indirect norm-enforcing ties at the group level is presented in Fig. 2 by an area where the upper boundary line of group pressure corresponds to the minimal tightness of indirect norm-enforcing ties at the group level, $I_i = 0$, and the lower boundary line of group pressure corresponds to the maximal tightness of indirect norm-enforcing ties at the group level $I_i = 1$. Agent i decides to comply if $u_i^0 - u_i^1 \geq 0$, that is, if $\omega_i \geq 1 + \vartheta_i$. Thus, the solution of $\omega_i = 1 + \vartheta_i$ indicates the critical mass of compliers necessary for agent i to become a complier. The critical mass is denoted by C_i^*, and yields $C_1^* = 0.721$ and $C^*_{i,I_i=0} = 0.855$ for the cases of $I_i = 0$ and $I_i = 1$, respectively. The location of the solution is marked in Fig. 2 by an orange circle in the

[24] The index j refers to all neighbors of agent i and agent i itself. For this reason, we make use of the index j instead of i.

former case and by a blue square in the latter case. If the solution of $\omega_i = 1 + \vartheta_i$ for a particular $I_i \in [0,1]$ holds for all agents of a group, it indicates a groupwise equilibrium (Definition 3). If the solution holds for all agents of the social network, it indicates a stable network equilibrium (Definition 4).[25]

The solution of $\omega_i = 1 + \vartheta_i$ also presents an individual threshold with respect to the tightness of direct and indirect norm-enforcing ties at the group level. Once it holds that $\omega_i > 1 + \vartheta_i$, agents decide to comply, because group pressure is higher than the sum of the deviator's extra benefits and pressuring costs. Fig 2 illustrates that the individual threshold is a function of direct and indirect norm-enforcing ties, the specification of the functions $\pi_i, \omega_i, \vartheta_i$ and the type of social network. Advancing findings of Sect. 6 (Theorem 1, Appendix H) allows us to relate direct norm-enforcing ties and the type of network to the tightness of indirect norm-enforcing ties at the group level. Utilizing this relationship Fig. 2 shows that a random network where $I_i = 0$ requires a substantially higher share of compliers than a complete network where $I_i = 1$. The equilibria-supporting share of compliers for a scale-free network are situated between these two extremes.

5 Flexible functions of group pressure and pressuring costs and their influence on thresholds

To generalize the findings in Sect. 4, we define group-pressure and pressuring-cost functions in a flexible form where different forms present specific conditions that agents face. In this way, we analyze the influence of the specifications of these functions on the location of the threshold.

5.1 Flexible functions

With respect to the group pressure function $\omega_i \equiv \omega_i\left(C_i, I_i, A\right)$ we define its flexible form as.

$$\omega_i = \frac{S}{\left(1 + \beta_1 e^{-\beta_2(C_i-(\beta_3-I_i))}\right)}\left(\pi_i\left(a_i = 1, A\right) - \pi_i\left(a_i = 0, A\right)\right). \tag{13}$$

where $S \in \mathbb{R}_{>0}$ denotes the maximal attainable group pressure agents can receive from their norm-complying peers. A high value of $\beta_1 \in \mathbb{R}_{\geq 0}$ indicates that agent i is not highly motivated to exercise strong group pressure whereas a high value of $\beta_2 \in \mathbb{R}_{\geq 0}$ indicates the opposite. Parameter $\beta_3 \in \mathbb{R}_{\geq 0}$ determines the minimum necessary tightness of direct norm-enforcing ties at the group level at which group pressure is sufficiently strong to affect the deviators' utility. In other words, it affects the number of compliers from where on group pressure increases with an increase in

[25] The latter is the case if the social network is regular so that all agents have the same degree (e.g., lattices or complete networks).

compliers. Hence, in the case of Eq. (13), the strength of the agent's commitment to collective interests is reflected by the values of the parameters β_2 and β_3. Depending on the chosen parameter values $\beta_{i\in\{1,2,3\}}$ the function is concave or sigmoidal[26] and can grow slowly or rapidly as the number of norm-complying peers increases. This mirrors real-world scenarios in which the influence can either build up gradually or decrease after it has reached a peak. See Appendix A for further details on the specifications of the group-pressure function.

The flexible form of pressuring-cost function $\vartheta_i \equiv \vartheta_i\left(k_i, C_i\right)$ is specified as.

$$\vartheta_i = \gamma_i\left(k_i\right)\left(v_0 - v_1 C_i + v_2\left(1 - C_i\right)C_i\right), \tag{14}$$

where $\gamma_i\left(k_i\right) \in \mathbb{R}_{>0}$ increases in k_i, and $v_{i\in\{0,1,2\}} \in \mathbb{R}$ are parameters. This flexible form allows us to consider four different cases.

Case 1 Fixed costs: Agents have individual pressuring costs v_0 that cannot be shared with other compliers, that is, the costs are fixed, and it holds that $v_1 = v_2 = 0$. This could be the case if an agent needs to install a device or contract a guard to monitor the actions of their peers. In this case, compliers face only individual pressuring costs.

Case 2 Decreasing costs: The term $v_0 - v_1 C_i$, with $v_0 \geq v_1 \geq 0$, indicates the extent to which the individual costs of exerting pressure can be shared with other compliers. Moreover, it holds that $v_2 = 0$. Thus, pressuring costs ϑ_i are nonincreasing in the tightness of direct norm-enforcing ties at the group level, C_i. The latter effect may be the result of cost sharing among compliers, either because of technical reasoning or because of lower coordination costs among compliers due to a high level of indirect norm-enforcing ties. If compliers can share the costs of group pressure, economies of scale could reduce individual pressuring costs. This would be the case if an installed device can monitor not only the actions of agent i's group but also of agent j's group.

Case 3 Bell-shaped costs: The term $v_2\left(1 - C_i\right)C_i$, with $v_2 \geq v_1 \geq 0$, indicates that the higher the confrontation of the subgroups of deviators and compliers, the higher the pressuring costs. This leads to bell-shaped pressuring costs which are maximal at $\tilde{C}_i = \arg\max_{C_i}\left(\vartheta_i\right) = \frac{1}{2}\left(1 - \frac{v_1}{v_2}\right)$. Well-balanced subgroups of deviators and compliers (confrontation) support the deviators' identity which in turn increases the resistance of deviators to adhere to the norm. For example, consider a scenario where two opposing sides in a group clash, making it harder for the norm-conforming side to apply pressure without facing pushback. As a result, the compliers' pressuring costs increase. As shown in Appendix B, $\tilde{C}_i \in (0, 0.5]$.

Case 4 U-shaped costs: When $v_1, v_2 < 0$ pressuring costs are U-shaped, reflecting the fact that there are economies of scale as the number of compliers increases, but it is reversed by coordination costs as the share of compliers increases even more. A U-shaped cost function arises if the benefits from economies of scale are

[26] Other functional forms also satisfy the requirement that group pressure increases with norm-enforcing ties and reaches its maximum value when all agents are compliers. However, they do not offer any qualitative insights that differ from those presented here.

overcompensated by an increase in coordination costs as the number of compliers increases.

Based on the different forms of the functions ω_i and ϑ_i we analyze how changes in the network structure or in the behavior of agents i's neighbors affect the location of agent i's thresholds and possible location of equilibria. We analyze the extent to which the sign and magnitude of these effects are influenced by group confrontation or by the level of the agents' commitment to collective interest. We summarize our results in Proposition 1.

Proposition 1 [Comparative statics] *If the pressuring costs are constant, decreasing, or bell-shaped, $v_{i\in\{0,1,2\}} \in \mathbb{R}_{\geq 0}$, an increase in indirect norm-enforcing ties, I_i, leads to a decrease in the critical mass C_i^* (substitutability), and an increase in group size, k_i, leads to an increase in the critical mass C_i^* (complementarity). If the pressuring costs are U-shaped, $v_0 > 0, v_{i\in\{1,2\}} \in \mathbb{R}_{<0}$ depending on the shares of compliers, the critical mass decreases or increases with the tightness of indirect norm-enforcing ties at the group level (complementary, substitutive). The sign of the changes in the critical mass with an increase in group size is opposite to that of an increase in the tightness of indirect norm-enforcing ties at the group level.*

Proof See Appendix C.

Proposition 1 summarizes the effects different forms of the pressuring costs (cases 1—4) have on the critical mass of compliers if the indirect norm-enforcing ties or the group size increases. In Appendix C, we show that I_i and C_i^* are substitutes, $\partial C_i^*/\partial I_i < 0$, and k_i and C_i^* are complements, $\partial C_i^*/\partial k_i > 0$. However, this general finding is not supported when the pressuring costs are U-shaped. In this case, I_i and C_i^* are substitutes, and k_i and C_i^*, are complements if the share of compliers is low. However, if the share of compliers is high, it holds that I_i and C_i^* are complements and that k_i and C_i^* are substitutes.

5.2 Influence on thresholds: graphical illustrations

For a graphical representation of the influence different shapes of the pressuring costs (cases 1 and 3) and type of networks have on the critical mass of compliers we start by normalizing the above-described functions u_i^0, u_i^1, ω_i and ϑ_i with respect to the deviator's extra benefits, $\pi_i(1,A) - \pi_i(0,A)$, such that the threshold is defined by $u_i^0 - u_i^1 = \omega_i - 1 - \vartheta_i = 0$ and the deviators' extra benefits are 1. We maintain the previous notation for utilities, group pressure, and pressuring costs, in order to reduce notational burden, but we implicitly understand that these functions have been normalized. For all the following examples, we consider $S = 2$ so that group pressure is at most twice the value of the normalized deviator's extra benefits.[27] The employed parameter values of the functions ω_i and ϑ_i are specified in the captions of Figs. 3 and 4. We concentrate on two important factors for cooperation at the group level—direct and indirect norm-enforcing ties and group confrontation—and analyze their effects on the agent's thresholds.

[27] The maximum value of S has been chosen such that its value influences but does not dictate the outcome of the agent's decision.

5.2.1 Effects of direct and indirect norm-enforcing ties on the critical mass of compliers

We start by considering Case 1 (fixed costs) where there is no group confrontation and compliers incur fixed costs only. Fig 3 illustrates the functions $1 + \vartheta_i$ (solid black line) and ω_i (dashed orange and dotted-dashed blue lines). The intersections between $1 + \vartheta_i$ and ω_i indicate the location of the agent's threshold, C_i^*.

In Fig. 3 (bell-shaped costs), the locations of thresholds $C^*_{i,I_i=0}$ and $C^*_{i,I_i=0.34}$ (vertical dashed black lines) represent how individual thresholds are determined as a result of C_i and how they change as a result of $I_i = 0$ and $I_i = 0.34$, respectively. The comparison between the locations of $C^*_{i,I_i=0} = 0.91$ and $C^*_{i,I_i=0.34} = 0.58$ allows the signpost of the minimum and maximum values of I_i on C_i^*, and indicates the interval of influence of I_i on C_i^*. As mentioned above, the findings of Sect. 6 (Theorem 1, Appendix H) allow us to relate direct norm-enforcing ties and the type of the network with the tightness of indirect norm-enforcing ties at the group level.[28] The threshold $C^*_{i,I_i=0} = 0.91$ results from group pressure, where only direct norm-enforcing ties but no indirect norm-enforcing ties are present (dotted-dashed blue line), for example, the group has the form of a star, or is part of a random network. The threshold $C^*_{i,I_i=0.34} = 0.58$ results from group pressure, where compliers form a cohesive group (complete network) with $\tau_i = 1$ (dashed orange line). This result is in line with Proposition 1, which predicts substitutability between I_i and C_i^* when $C_i^* \geq 0.5 \geq \tilde{C}_i$. Utilizing this relationship, Fig. 3 shows that a random network where $I_i = 0$ requires a substantially higher share of compliers than a complete network where $I_i = 0.34$. The equilibria-supporting share of compliers for scale-free networks are situated between these two extremes.

5.2.2 Effects of group confrontation on the critical mass of compliers

Next, we analyze Case 3 (bell-shaped costs), in which pressuring costs are predominantly the result of group confrontation. For Fig. 4, we maintained the parameter values employed in Fig. 3, except for the group confrontation, $v_2 > 0$. Confrontation within the group implies higher pressuring costs; therefore, the tightness of indirect norm-enforcing ties at the group level necessary to attain an agent's threshold needs to be higher. Fig 4 illustrates the case in which group confrontation likely leads to the all-deviator equilibrium because pressuring costs dominate group pressure up to the value of $C^*_{i,I_i=0.63} = 0.79$. If compliers do not coordinate group pressure, norm compliance must be very close to the maximum value of one, $C^*_{i,I_i=0} = 0.97$. Again, the locations of $C^*_{i,I_i=0}$ and $C^*_{i,I_i=0.74}$(vertical dashed black lines) indicate the minimum and maximum influence of I_i on C_i^*. The minimum and maximum influence of I_i on C_i^* correspond to random and complete networks, respectively, and equilibria

[28] In Sect. 6 (Theorem 1 and Appendix E), we show that the expected strength of indirect moral ties can be computed as $I_i \simeq \tau_i C_i^2$. Since $\tau_i \in [0, 1]$, it holds that $I_i \in \left[0, C_i^2\right]$. Thus, for the example illustrated in Fig. 3, the minimum value of indirect norm-enforcing ties is $I_i = 0$ and their maximum value is $I_i = \left(C_i^* = 0.58\right)^2 = 0.34$.

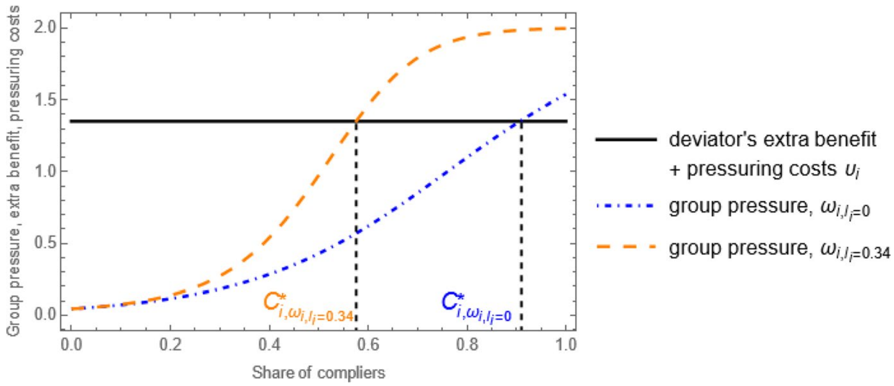

Fig. 4 Effects of group confrontation on the location of the critical mass of compliers C_i^*. The horizontal dashed black line represents the normalized deviator's extra benefits, and the solid black line represents the sum of the deviators' extra benefits and the pressuring costs. The dashed orange and dotted-dashed blue lines represent group pressure when I_i is maximal and minimal, respectively. Vertical dashed black lines represent the locations of C_i^* when $I_i = 0$ and $I_i = 0.63$. The parameter values are $S = 2$, $\beta_1 = 10$, $\beta_2 = 5$, $\beta_3 = 0.3$, $\gamma_i(k_i) = 1$, $v_0 = 0.1$, $v_1 = 0$, and $v_2 = 5$

related with scale-free networks are situated between these two extremes. Note that the interval of influence of I_i on C_i^* has been reduced by more than half compared to the situation depicted in Fig. 3. In line with Proposition 1, we observe substitutability between I_i and C_i^* because $C_i^* \geq 0.5 \geq \tilde{C}_i$.

Fig 4 shows that the critical mass of compliers must be high in the presence of group confrontation. The agent decides to comply only if a very high level of compliers is reached. However, as shown in Appendix D, if the level of the agents' commitment to the collective interest is high ($\beta_2 = 45, \beta_3 = 0.1$) even a low critical mass of compliers allows the support of cooperation. Moreover, if the agents' commitment to the collective interest is high, the influence of indirect norm-enforcing ties on the level of the critical mass is rather limited compared to the case where no group confrontation is present.

6 Norm-enforcing ties at the network level: Policy implications

In this section, we evaluate the importance of norm-enforcing ties in policy design. We assume that the regulator lacks detailed knowledge about the agents' behavior and their underlying network structure but can use surveys to collect data about the total number of compliers and the agents' cohesiveness at the network level. These data allow for the determination of the type of social network (e.g., random, scale-free, or complete) and the expected value and variance of norm-enforcing ties at the network level. These statistical insights enable us to compare the efficiency of policies based on subsidies or fines (formal enforcement) with network-oriented instruments aimed at tightening indirect norm-enforcing ties at the group level (informal enforcement).

6.1 Expected value and variance of norm-enforcing ties at the network level

Within our conceptual framework of social networks with fixed links, the share of compliers C_i and local cohesiveness τ_i can be considered at every moment of time as independent variables that are randomly distributed over the social network.[29] Thus, we can take the social network and profile of actions as given and predict the expected tightness of norm-enforcing ties at the group-level ties, C and I, at the network level. For its calculation we measure cohesiveness at the network level by the global clustering coefficient τ, defined by the total number of triads with respect to the maximum number of triads of the entire network. The results that hold for networks of any size, joint distribution of links and agents' actions, are summarized in the following theorem.

Theorem 1 [*Expected tightness of norm-enforcing ties at the network level*] *At the network level, the expected tightness of direct and indirect norm-enforcing ties are C and $I \simeq \tau C^2$, respectively, where $C = E\left[a_i\right]$ and $\tau = E\left[\tau_i\right]$.*

Proof See Appendix E.

Assumption 1 establishes that the level of coordination coincides with agents' capacity for coordination. Theorem 1 shows that an increase in the expected group cohesiveness, τ, heightens the expected tightness of indirect norm-enforcing ties, I, at the network level. The magnitude of these effects depends on the expected tightness of direct norm-enforcing ties, C at the network level, such that $\partial I/\partial\tau \simeq C^2$. Similarly, we find that an increase in C produces positive and nonlinear effects on I. The magnitude of these effects depends jointly on τ and C such that $\partial I/\partial C \simeq 2\tau C$. If $C = 2\tau$, the effects are identical, because $\partial I/\partial C \simeq \partial I/\partial\tau$.

Analyzing the sign and magnitude of changes in τ and C allows us to evaluate the efficiency of different policy options for increasing indirect norm-enforcing ties as a function of direct norm-enforcing ties and expected group cohesiveness at the network level. We compare two alternative formulations: (1) formal enforcement policies aimed at increasing indirect norm-enforcing ties, I, by increasing direct norm-enforcing ties, C, and (2) informal enforcement policies aimed at increasing indirect norm-enforcing ties, I, by strengthening the expected group cohesiveness of the network, τ. For example, network-oriented policies may offer financial support to associations whose membership is open only to norm-complying agents. The association may assist its members by offering support for their economic activities, or for organizing seminars and workshops (Cumming 2018), or other forms of members' privileges. In situations with negative externalities, one can imagine network-oriented policies articulated by means of fiscal deductions or subsidies for compliers' associations or nongovernmental support organizations. Likewise,

[29] When actions and social interactions depend on each other (e.g., Boucher 2016), one cannot easily distinguish between the cases where links are formed because agents are similar, or agents develop similar behavior from the formed links.

community-engagement programs based on volunteer activities or neighborhood improvement projects may help compliers to develop new links with each other.

Our comparison shows that conditions exist for designing efficient formal and informal enforcement policies to promote coordination between compliers at the network level. These are summarized in the following theorem.

Theorem 2 [*Conditions for efficient policy implementation*] *Provided that the implementation costs of formal and informal enforcement policies are identical, an increase in τ (informal enforcement) is more efficient in promoting coordination among compliers than is an increase in C (formal enforcement) if $C > 2\tau$. Otherwise, if $C < 2\tau$, then an increase in C is more efficient. When $C = 2\tau$, both policy options are equally efficient.*

Proof See Appendix F.

Next, we analyze the extent to which norm-enforcing ties at the group level are similar to their expected values at the network level. In other words, we compute the variance of C_i and I_i in the network as a measure of the dispersion of norm-enforcing ties. We summarize the main results in the following theorem.

Theorem 3 [*Variance in norm-enforcing ties*] *The variance in direct norm-enforcing ties depends on the profile of actions and group size. It is maximal at $C = 0.5$, and minimal at $C = 0$ or $C = 1$. The variance in indirect norm-enforcing ties depends on the profile of actions and group cohesiveness. It is maximal at $C = 1$ and $\tau = 0.5$ (or $\tau = 1$ and $C = 0.5$), and minimal at $C = \tau = 0$.*

Proof See Appendix G.[30]

The variance of norm-enforcing ties is partially controlled by the type of network. When cohesiveness is very high or maximal (e.g., very dense or complete networks) the variance in norm-enforcing ties is minimal. The same occurs when cohesiveness is low and the regularity of the network[31] is high, for example, lattices, circles, and random networks. However, the literature shows that real-world social networks are to some extent cohesive and highly irregular (Broido and Clauset, 2019). Hence, these networks are characterized by a significant variance in norm-enforcing ties. Based on the survey mentioned at the beginning of this section, a social planner can estimate C and τ but not C_i and τ_i. In this case, the magnitude of the variance in norm-enforcing ties allows a social planner to deduce information about the agents' choices and/or the underlying social network structure of the group. If the variance in norm-enforcing ties is zero, a social planner has complete

[30] The code, written in R, that allows calculation of the variance of norm-enforcing ties for networks of different types and any size can be downloaded at https://doi.org/10.5281/zenodo.13371113.

[31] The term "regularity" refers to the distributions of group size, $\{k_i\}_{1 \le i \le n}$, and group cohesiveness, $\{\tau_i\}_{1 \le i \le n}$, within the network. In regular networks, all agents have equal or similar group sizes and group cohesiveness.

information at the group level. However, if it is positive, the planner has incomplete information, which limits the design of efficient policies. To advance our analysis of policy design and implementation, we next analyze the influence of different types of networks on indirect norm-enforcing ties and determine efficient policy options, whether formal or informal, to increase the tightness of indirect norm-enforcing ties at the network level.

6.2 Influence of the type of network on indirect norm-enforcing ties

By Theorem 1 it holds that $\tau C^2 \leq \tau$ for any network, because $C \in [0, 1]$. Consequently, we only need to compute τ to determine the upper and lower limits of I. More precisely, we can determine the extent to which τ allows us to narrow the possible values of I to promote cooperation. For illustrative purposes, we focus on three representative network topologies: complete networks (CN), sparse random networks (RN), and real-world social networks presented by scale-free networks (SN). They differ significantly in the value of τ. In CN, group cohesiveness is maximal for all groups, such that $\tau = 1$. In RN, group cohesiveness is very low for all groups, such that $\tau \approx 0$. In contrast, in SN, group cohesiveness has a wide range of possible values. The influence of different types of networks on indirect norm-enforcing ties is summarized in the following proposition.

Proposition 2 [Type of network and indirect norm-enforcing ties] *For any $C \in [0, 1]$, the expected tightness of indirect norm-enforcing ties in CN is maximal, $I_{CN} = C^2$. In RN, it is minimal, $I_{RN} \in \left[\frac{2C^2}{(n-1)}, \frac{2C^2}{\sqrt{n}}\right]$. In SN, it always ranges between RN and CN, $I_{SN} \in \left(0, \frac{4C^2}{5}\right]$.*

Proof See Appendix H.

CN topologies represent the upper limits of I because all compliers are linked and can coordinate group pressure. RN and SN topologies are characterized by many possible network configurations.[32] However, the interval of τ is much larger in SN than in RN owing to the documented "small-world" phenomenon (Broido and Clauset 2019)—that is, in SN, agents tend to form communities that consist of different aggregations of separated groups ("cliques"), and links within and among cliques are facilitated by agents with the highest group sizes ("hubs"). Moreover,

[32] The number of network configurations in both SN and RN fluctuates between $\left(\begin{pmatrix} n \\ 2 \\ n \end{pmatrix}\right)$ and $\left(\begin{pmatrix} n \\ 2 \\ n\sqrt{n} \end{pmatrix}\right)$ (see Appendix F). Since it can be a large number, depending on n, the influence of the type of network on norm-enforcing ties is difficult to study analytically. Simple representations of networks, such as stars, trees, lattices or circles, do not take into account the complexity of social networks (Jackson et al. 2017). To overcome this limitation, the use of numerical simulations has become common practice in the literature on social networks, (e.g., Morsky and Akçay 2019). However, Theorem 1 allows the analytical study of the influence of network topology on indirect norm-enforcing ties.

hubs are agents that contribute disproportionately to an increase in the cohesiveness of the network, as each connected pair of agents is more likely to be linked to a hub than to any other agent in the network (Watts and Strogatz 1998). In contrast, the formation of *RN* is characterized by the setting in which every agent initially does not know any other agent. All links between agents are randomly formed with the same probability. As a result of this formation pattern, hubs are absent in RN, and the group size and group cohesiveness of all agents are very similar. Consequently, RN topologies represent the lower limits of I because the compliers' capacity for coordination is strongly limited.

The wide variety of SN topologies opens the door for the implementation of different informal enforcement policies. Regulators or compliers may take the initiative in implementing these policies.

7 Conclusions

Although cooperation within social networks has attracted substantial interest in economics and social sciences, little attention has been paid to how agents' behavior, in combination with the structure of their links, affects the strength of social influence. The concept of norm-enforcing ties adds another element in determining the drivers of cooperation. Apart from its conceptual formulation, this study offers a measure that allows measurement of the tightness of norm-enforcing ties at the group level. Therefore, this study aims to guide theoretical and empirical research on how to align collective and individual interests to identify patterns of social interaction that support cooperation within groups. Our results identify the agents' threshold of net benefits at which they switch from noncooperation to cooperation. We further determine the extent to which group confrontation and the type of pressuring costs condition whether indirect norm-enforcing ties or group size are complements or substitutes for the critical mass of compliers. In general, the tightness of indirect norm-enforcing ties is a complement, and group size is a substitute for the critical mass of compliers. Only when the pressuring costs are U-shaped can it be for a certain range of the share of compliers that the relationship between these variables is reversed. Moreover, the influence of indirect norm-enforcing ties decreases with group confrontation and the level of agents' commitment to collective interests. Furthermore, our analysis shows that informal enforcement policies are more efficient in promoting coordination among compliers than are formal enforcement policies if the share of compliers is at least twice the value of group cohesiveness at the network level. Otherwise, formal enforcement policies are more efficient.

This paper assumes that compliers' exercise costly group pressure but do not free ride on each other. This supposition may be neglectable if the share of free-riding compliers is small, but as it increases, it may induce all compliers not to exercise group pressure. In this case the only possible outcome of the game is the all-deviator equilibrium.

As an extension of this paper, it may be interesting to determine the critical mass of free-riding compliers that sentences the outcome of the game to be an all-deviator equilibrium. Another extension of this line of research may involve testing the validity of the theoretical framework in a laboratory setting or through field experiments. For example, conducting a laboratory or field experiment on charity-giving allows for the assessment of the influence of norm-enforcing ties. In this setup, the participants were informed of the donations made by others. These participants may be acquaintances of the respondent, but they are not connected to each other. By gradually increasing social ties among acquaintances and observing the actual donations made by the respondents, we can evaluate the tightness of both direct and indirect norm-enforcing ties. A natural application of our theoretical framework can also incorporate the concept of norm-enforcing ties into a game played on a social network. The objective would be to examine the extent to which complex interactions between network properties and agents' actions can help resolve social dilemmas. To achieve this, future research must assess the suitability of available analytical and numerical techniques to determine the optimal trajectory for cooperation.

Appendix A

When facing a social dilemma, agents are torn between giving preference to individual or collective interests. The outcome of the agents' decisions affects the strength of group pressure exercised by compliers. The weight of the preferences for one alternative or the other is captured by parameters $\beta_1 \in \mathbb{R}_{>0}$ and $\beta_2 \in \mathbb{R}_{\geq 0}$ of Eq. (13). On the one hand, parameter β_1 indicates the weight that group members attach to individual interests and therefore any increase in this parameter decreases group pressure, such that $\partial\omega_i/\partial\beta_1 < 0$ and $\beta_1 \gg K$, $\beta_1 >> e^{-\beta_2(C_i-(\beta_3-I_i))}$ lead to $\omega_i \approx 0$. On the other hand, parameter β_2 indicates the weight that group members attach to collective interests. An increase in this parameter leads to higher group pressure. For β_1 sufficiently large and fixed, we obtain that $\partial\omega_i/\partial\beta_2 > 0$, where $\beta_2 = 0$ leads to $\omega_i \approx 0$ and $\beta_2 \gg 0$ leads to $\omega_i \approx K$. Parameter $\beta_3 \in \mathbb{R}_{\geq 0}$ determines the minimum necessary tightness of direct norm-enforcing ties at the group level at which group pressure gains sufficient momentum to become noticeable to deviators.

Appendix B

Maximizing $\vartheta_i = \gamma_i(k_i)\left(v_0 - v_1 C_i + v_2(1 - C_i)C_i\right)$ with respect to C_i shows that $\tilde{C}_i = \arg\max_{C_i}(v_i) = \frac{1}{2}\left(1 - \frac{v_1}{v_2}\right)$, for any k_i. Since $v_2 \geq v_1 \geq 0$ it holds that $\tilde{C}_i \in (0, 0.5]$. To guide the intuition of this result, note that the expected number of links that connect compliers with deviators is maximum at $C_i = 0.5$. Thus, pressuring costs are expected to be maximally close to this point because of group confrontation. However, the location of this maximum depends on the ratio v_1/v_2 that graduates the degrees of confrontation within agent i's group, where $v_1 = v_2$ implies no confrontation and $v_2 >> v_1 \geq 0$ implies a high degree of confrontation (maximal if v_1/v_2 approaches zero and $\tilde{C}_i$ tends to 0.5). As C_i increases further, $C_i > \tilde{C}_i$, the expected number of links between compliers and deviators decreases, as does the group confrontation and pressuring costs.

Appendix C

Proof of Proposition 1

Provided that the denominator of equation (15) is not equal to zero for the points of interest we can conduct comparative statics of Eqs. (13) and (14) for I_i and k_i at individual thresholds. It shows for $u_i^0 = u_i^1$ that.

$$\frac{\partial C_i^*}{\partial I_i} = \begin{cases} \frac{-\partial\omega_i / \partial I_i}{-\partial\vartheta_i / \partial C_i + \partial\omega_i / \partial C_i} < 0 \;\; if\; C_i^* \geq \tilde{C}_i \\ \frac{-\partial\omega_i / \partial I_i}{-\partial\vartheta_i / \partial C_i + \partial\omega_i / \partial C_i} \gtrless 0 \;\; if\; C_i^* < \tilde{C}_i \end{cases}$$
$$\frac{\partial C_i^*}{\partial k_i} = \begin{cases} \frac{dv\vartheta_i / dk_i}{-\partial\vartheta_i / \partial C_i + \partial\omega_i / \partial C_i} > 0 \;\; if\; C_i^* \geq \tilde{C}_i \\ \frac{d\vartheta_i / dk_i}{-\partial\vartheta_i / \partial C_i + \partial\omega_i / \partial C_i} \gtrless 0 \;\; if\; C_i^* < \tilde{C}_i \end{cases}, \tag{15}$$

where $\partial\omega_i / \partial C_i = \frac{\beta_1\beta_2 K e^{\beta_2(C_i+I_i-\beta_3)}}{\left(e^{\beta_2(C_i+I_i-\beta_3)}+\beta_1\right)^2} > 0,\ \partial\omega_i / \partial I_i > 0,\ d\vartheta_i / dk_i > 0$, and for constant, decreasing or bell-shaped pressuring costs, $v_{i\in\{0,1,2\}} \in \mathbb{R}_{\geq 0}$, we obtain that.

$$\frac{\partial\vartheta_i}{\partial C_i} = \gamma\left(k_i\right)\left(v_2\left(1-2C_i\right)-v_1\right)\begin{cases} \leq 0 \;\; \text{if}\, C_i^* \geq \tilde{C}_i \geq 0.5 \\ \leq 0 \;\; \text{if}\, 0.5 > C_i^* \geq \tilde{C}_i,\ \text{it implies that}\ v_2 \leq \frac{v_1}{1-2C_i} \\ \geq 0 \;\; if\, 0.5 > \tilde{C}_i \geq C_i^*,\ \text{it implies that}\ v_2 \geq \frac{v_1}{1-2C_i} \end{cases}. \tag{16}$$

To determine the signs in equation (15), we use the relationship between C_i^* and $\tilde{C}_i$. If $C_i^* \geq \tilde{C}_i$ we know that C_i^* is located to the right of the zenith of the pressuring costs and therefore the marginal pressuring costs are nonincreasing. For the opposite case, $C_i^* \leq \tilde{C}_i$ we know that C_i^* is located to the left of the zenith of the pressuring costs and therefore, the marginal pressuring costs are nondecreasing.

The substitutability between I_i and C_i^*, $\partial C_i^*/\partial I_i < 0$, and complementarity between k_i and C_i^*, $\partial C_i^*/\partial k_i > 0$, require the denominators in equation (15) to be positive. Equation (16) allows us to determine the sign of $\left(-\partial\vartheta_i / \partial C_i + \partial\omega_i / \partial C_i\right)$ unequivocable for $C_i^* \geq \tilde{C}_i$ but not for $C_i^* \leq \tilde{C}_i$ Note that $\partial\vartheta_i / \partial C_i < 0$ always holds when $C_i^* \geq \tilde{C}_i$. However, when $0.5 > \tilde{C}_i \geq C_i^* > 0$, the inequality $v_2 > \frac{\varphi\beta_2 K + \gamma_i(k_i)v_1}{\gamma_i(k_i)(1-2C_i)}$ is a necessary and sufficient condition for $\left(-\partial\vartheta_i / \partial C_i + \partial\omega_i / \partial C_i\right) < 0$ to hold, where $\varphi = \frac{\beta_1 e^{-\beta_2(C_i+I_i-\beta_3)}}{\left(1+\beta_1 e^{-\beta_2(C_i+I_i-\beta_3)}\right)^2}$. This condition depends on the composition of the parameter values $v_1, v_2, \beta_1, \beta_2, \beta_3$ which makes its interpretation difficult.

A numerical sensitivity analysis[33] provides further insight and allows us to rule out that $\partial C_i^*/\partial I_i > 0$, $\partial C_i^*/\partial k_i < 0$. Fig 5 shows the contour plot of $\omega_i - 1 - \upsilon_i$ which corresponds to the graphs of the functions, $\omega_i, 1, \upsilon_i$ presented in Fig. 3.

The threshold is given by the nullcline, that is, where $\omega_i - 1 - \upsilon_i = 0$. The nullcline on the right side of the figure is downward-sloping indicating that the share of compliers C^* and indirect norm-enforcing ties are substitutes. However, the nullcline at the upper-left corner is upward sloping which indicates that the share of compliers C^* and indirect norm-enforcing ties are complementary. Although this nullcline represents a threshold it does not present an admissible solution of the equation $\omega_i - 1 - \upsilon_i = 0$. As demonstrated in Theorem 1 the set of admissible values is represented by the area below the discontinuous red line. Theorem 1 establishes a functional relationship between the share of compliers and the tightness of indirect norm-enforcing ties at the group level. The tightness of indirect norm-enforcing ties at the group level is at most approximately equal to C^2. Using the same parameter set as before, Fig 6 shows the graphs of the functions $\omega_i, 1, \upsilon_i$. This confirms that the share of compliers and indirect norm-enforcing ties complement the set of indirect norm-enforcing ties and the share of compliers, as indicated by the nullcline in the upper-left corner of Fig 5. The threshold C^* increases with the tightness of indirect norm-enforcing ties at the group level, that is, the movement from the blue square to the orange circle in Fig 6.

For the case of U-shaped pressuring costs, however, one can also find admissible combinations of the threshold and indirect norm-enforcing ties where they are complements. Fig 7 shows an example of this case for the set of parameter values displayed on the side panel.

Figure 8 confirms that this set of parameter values leads to complementary between the threshold and indirect norm-enforcing ties—presented by the increase in the threshold as the indirect norm-enforcing ties increases from 0.43 to 0.51.

The numerical analysis of the changes in the critical mass as a result of changes in the group size shows that the signs of the changes are opposite to the changes in the tightness of indirect norm-enforcing ties at the group level. For brevity, a sensitivity analysis with respect to an increase in the group size is not presented here. Its influence on the critical mass can be easily verified by changing the slider of the parameter g (group size) of Fig 5, 6, 7, 8 utilizing the Mathematica® code available at https://doi.org/10.5281/zenodo.13371113.

[33] The Mathematica® code for Fig. 5, 6, 7, 8 can be downloaded at https://doi.org/10.5281/zenodo.13371113. The code reproduces the figures and allows to analyze the effects of changes in the parameters on the group pressure function and its related costs. The results of the sensitivity analysis can be visualized by moving the corresponding sliders of the figures that present the values of the parameters. The same link also contains the code for Figs. 2, 3, 4 and 9.

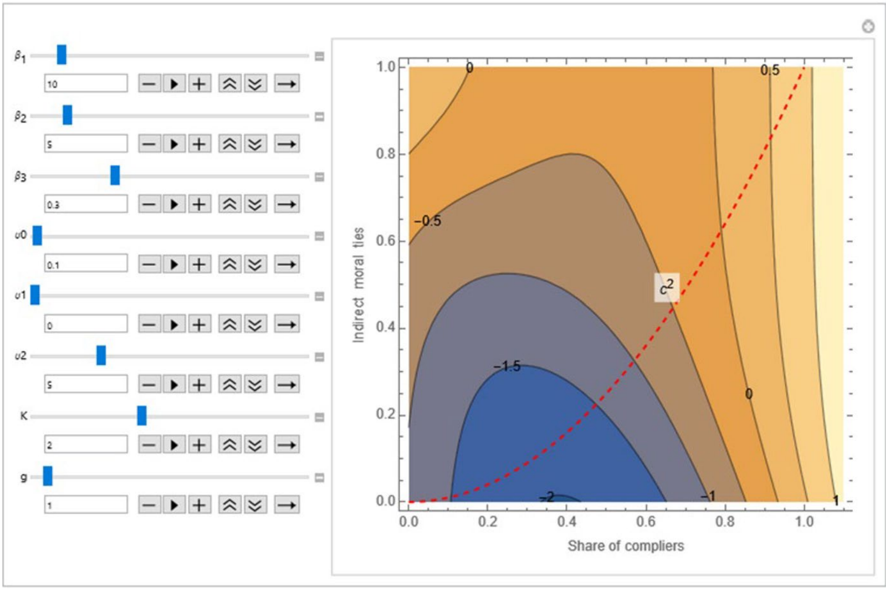

Fig. 5 Contour plot of the equation $\omega_i - 1 - \upsilon_i = 0$ with the same parameter set as in Fig. 3

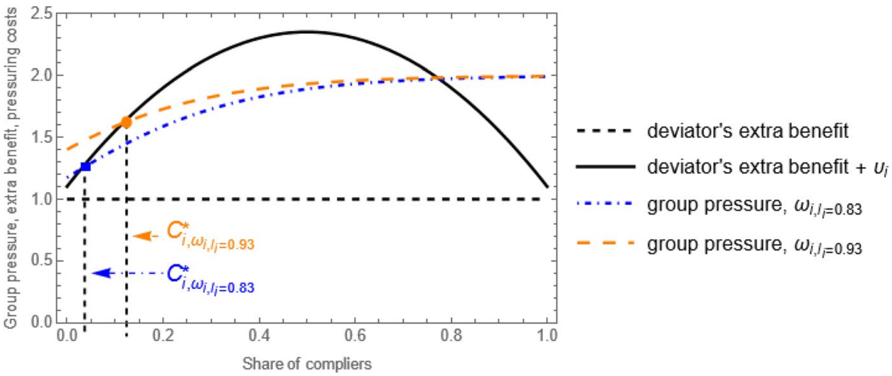

Fig. 6 Graph of the functions ω_i, 1, υ_i with the same parameter set as in Fig. 3

Appendix D

The social dilemma can be overcome even in the presence of a high group confrontation if the agents' commitment to the collective interest is very high. Figure 9 illustrates the case in which agents' level of commitment to collective interest is very high. The transition of group pressure from zero to its maximum occurs quickly. It starts when the tightness of direct norm-enforcing ties at the group level is still very low. Moreover, Fig. 4 illustrates the possible emergence

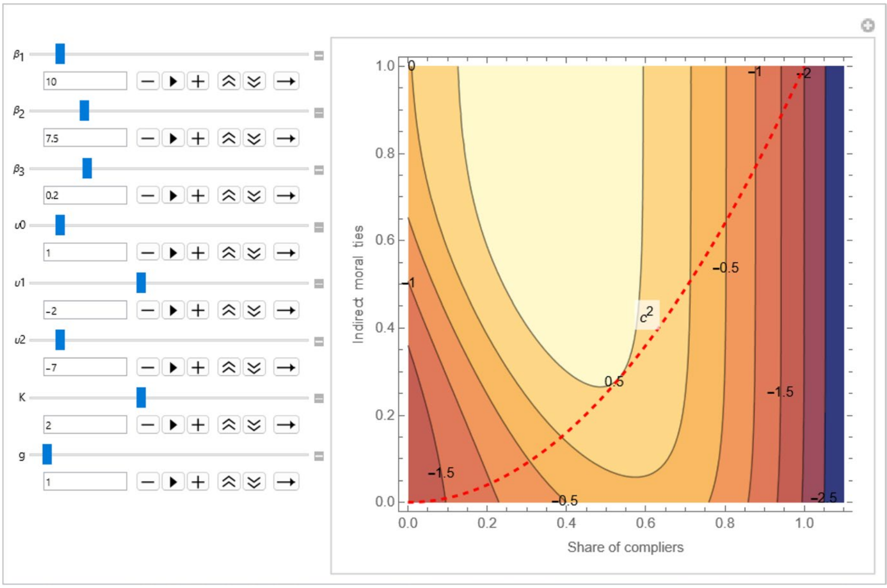

Fig. 7 Contour plot of the equation $\omega_i - 1 - \upsilon_i = 0$ for the parameter values shown in the side panel

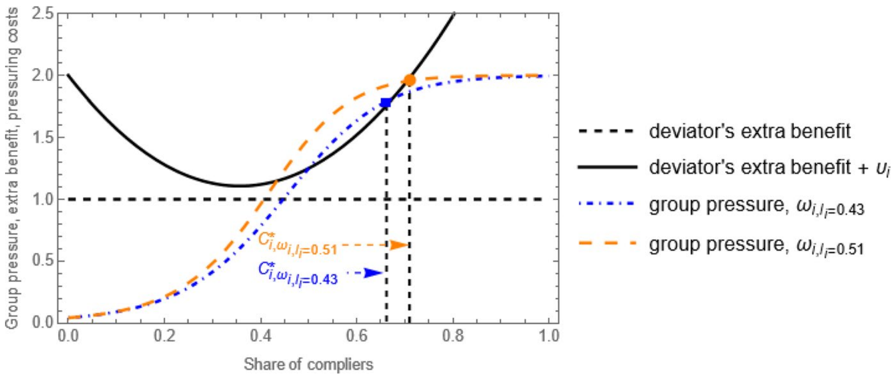

Fig. 8 Graph of the functions $\omega_i, 1, \upsilon_i$ with the same set of parameters as in the side panel of Fig 7

of multiple individual thresholds, from one to three, where the influence of I_i on C_i^* is minimal. In line with Proposition 1, for thresholds $C^*_{i,I_i=0} = 0.23$ and $C^*_{i,I_i=0.04} = 0.19$ we still observe conditional substitutability between I_i and C_i^* because $C_i^* < \tilde{C}_i$ and $\left(-\partial\upsilon_i/\partial C_i + \partial\omega_i/\partial C_i\right) > 0$.

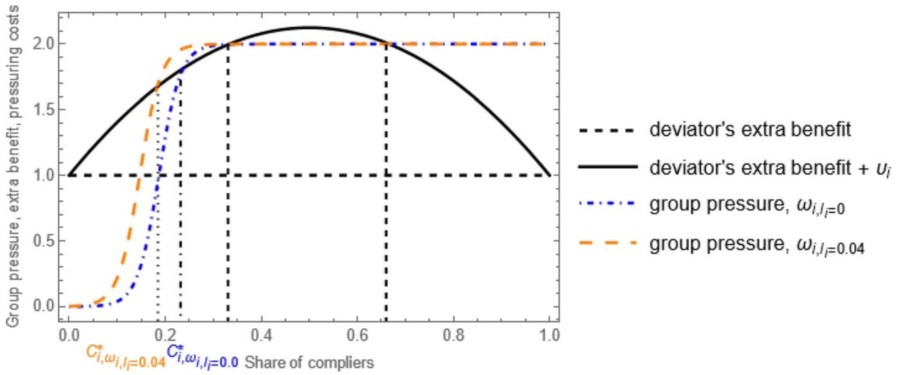

Fig. 9 Effects of the level of the agents' commitment to the collective interest, β_2, on the location of C_i^*. The solid black line represents the sum of the deviator's extra benefit normalized to one and the pressuring costs. The horizontal dashed black line represents the deviator's extra benefits. The dashed orange and the dotted-dashed blue lines represent group pressure when $I_i = 0.04$ and $I_i = 0$, respectively. The dashed black vertical lines represent the locations of individual thresholds, when $I_i = 0$ and $I_i = 0.04$. Parameter values are $S = 2$, $\beta_1 = 50$, $\beta_2 = 45$, $\beta_3 = 0.1$, $\gamma_i(k_i) = 1$, $v_0 = v_1 = 0$, and $v_2 = 4.5$

Appendix E

Proof of Theorem 1

Recall that actions and links are independent random variables. The expected tightness of direct norm-enforcing ties at the group level is $C = E[C_i] = E[a_i]$, that is, it depends on the agents' profile of actions, $\mathbf{a} = (a_i)_{1 \le i \le n} \in \{0,1\}^n$. Since agents face a binary choice, $a_i \in \{0,1\}$, the profile of actions $\mathbf{a}$ follows a binomial distribution, $a_i \sim Bin(n,q)$, where $n \in \mathbb{N}$ denotes the number of agents and q the probability of success (cooperation), such that $C = q$. To calculate the expected tightness of indirect norm-enforcing ties at the group level, I, we need to find the probability p_i that a link between two agents connects two compliers (u,v) in $N_i(g)$. To find p_i, we imagine a box with k_i marbles. The box contains $C_i k_i$ marbles that are compliers and the rest, $k_i(1 - C_i)$, are deviators. We want to find the probability p_i of drawing two consecutive marbles that are compliers, which is given by.

$$p_i = \frac{\frac{(C_i k_i)!}{2!(C_i k_i - 2)!}}{\frac{k_i!}{2!(k_i-2)!}} = \frac{(C_i k_i)!(k_i - 2)!}{k_i!(C_i k_i - 2)!} = \frac{(C_i k_i)(C_i k_i - 1)}{k_i(k_i - 1)} \simeq C_i^2 \in [0,1]. \quad (17)$$

Let SC_i represent success, that is, the case in which an existing link connects two compliers (u,v) in $N_i(g)$. The variable SC_i follows a binomial distribution, such that $\mathrm{E}[SC_i] = n_i p_i$. Note that n_i represents the number of attempts to connect two neighbors within $N_i(g)$ and that $0 \le n_i \le \frac{k_i(k_i-1)}{2}$. Using the upper limits of n_i, which is $\overline{n}_i = \frac{k_i(k_i-1)}{2}$, we can normalize SC_i as follows $\widetilde{SC}_i = \frac{n_i p_i}{\overline{n}_i} \in [0,1]$. The ratio

$\tau_i = \frac{n_i}{\bar{n}_i} \in [0, 1]$ is the group cohesiveness in $N_i(g)$. As we measure the number of links among compliers within a group, $\tilde{SC}_i$ represents the expected tightness of indirect norm-enforcing ties at the group-level agent i has, such that $\tilde{SC}_i = I_i = \tau_i p_i$. Using Eq. (17), it yields $\tilde{SC}_i = I_i = \tau_i C_i^2$. At the network level, the expected tightness of indirect norm-enforcing ties at the group level, I, can be calculated as the product of two independent random variables, τ_i and C_i, such that $\tilde{SC}_i = I = E[\tau_i]E[C_i^2] = \tau(C^2 + Var(C_i))$. For the derivation of Theorem 2, we approximate $I = \tau(C^2 + Var(C_i))$ by $I = \tau C^2$. Note that $Var(C_i)$ is zero or very close to zero when networks are regular, very dense or sparse, or when C tends to either 0 or 1. Hence, for all these cases, the approximation error is very small. Moreover, Theorem 2 demonstrates that this approximation does not affect the determination of efficient policies. $\square$.

Appendix F

Proof of Theorem 2

Provided that the policy implementation costs are identical, we compare the efficiency of informal and formal enforcement policies in promoting coordination among compliers. As shown in Theorem 2 the effects of increases in τ (informal enforcement) on I, or of increases in C (formal enforcement) on I are given, respectively, by.

$$\frac{\partial I}{\partial C} = 2\tau C + \frac{\partial Var(C_i)}{\partial C}, \text{and } \frac{\partial I}{\partial \tau} = C^2 + Var(C_i)\frac{\partial I}{\partial \tau} = C^2 + Var(C_i), \tag{18}$$

where.

$$\begin{aligned} \frac{\partial Var(C_i)}{\partial C} &= \frac{1}{n}\left[\frac{\partial}{\partial C}(C_i - C)^2 + \frac{\partial}{\partial C}(C_j - C)^2 + \dots + \frac{\partial}{\partial C}(C_n - C)^2\right] \\ &= \frac{1}{n}\left[2(C - C_i) + 2(C - C_j) + \dots + 2(C - C_n)\right] \\ &= \frac{2}{n}\left[nC - \sum_{i=1}^{n} C_i\right] = 2C - 2C = 0. \end{aligned} \tag{19}$$

Since $\frac{\partial Var(C_i)}{\partial C} = 0$, informal enforcement is more efficient than formal enforcement if the following condition holds.

$$\frac{\partial I}{\partial \tau} \geq \frac{\partial I}{\partial C} \rightarrow C \geq \left(2\tau - \frac{Var(C_i)}{C}\right). \tag{20}$$

Note that $Var(C_i)$ tends to zero when networks are regular, very dense, or sparse, or when C either tends to 0 or 1. In all of these cases, the condition presented in equation (20) can be simplified to $C \geq 2\tau$. In the main text, we approximate $\partial I / \partial C = 2\tau - Var(C_i) / C$ by 2τ. However, meeting the inequality $C \geq 2\tau$ guarantees that the exact inequality $C > 2\tau - Var(C_i) / C$ always holds. In other words, the inequality $C \geq 2\tau$ marks the lower limits of C for informal enforcement to always be more efficient for any value of $Var(C_i) / C$. However, if $Var(C_i) > 0$, then the level of C at which informal enforcement becomes more efficient decreases. Hence, the approximation $I = \tau C^2$ employed in Theorem 2 does not affect the lower limits of C for informal enforcement to be more efficient than for formal enforcement when promoting coordination among compliers. □.

Appendix G

Proof of Theorem 3

Recall that $C_i, \tau_i \in [0, 1]$. The variance of the tightness of direct norm-enforcing ties at the group level is given by.

$$Var(C_i) = \frac{1}{n} \sum_{i=1}^{n} \left(C_i - C\right)^2, \tag{21}$$

where $C = E[C_i] = E[a_i]$ (see Theorem 1). This variance of C_i reaches its minimal value, $Var(C_i) = 0$, when $C = 0$ or $C = 1$, and its maximal value, $Var(C_i) = \frac{1}{4}$, when $C = 0.5$. Maximal variance occurs when C_i takes only the values of 0 and 1, $C_i \in \{0, 1\}$, and the probability of taking either 0 or 1 is equal to one half, such that $\mathrm{P}(C_i = 0) = \mathrm{P}(C_i = 1) = \frac{1}{2}$. The proof is provided by the variance of the binomial distribution, $Var(C_i) = C - C^2$.

The variance of the tightness of indirect norm-enforcing ties at the group level is computed as the variance of the product of two independent random variables, τ_i and C_i, as follows.

$$Var(I_i) = Var(C_i^2)Var(\tau_i) + Var(C_i^2)\tau^2 + Var(\tau_i)\left(E\left[C_i^2\right]\right)^2, \tag{22}$$

where $\tau = E[\tau_i]$. This variance is bounded, $0 \leq Var(I_i) \leq \frac{1}{4}$. It reaches its minimal value, $Var(I) = 0$, when $C = \tau = 0$ or $C = \tau = 1$, and its maximal value, $Var(I) = \frac{1}{4}$, when $C = \tau = 0.5$. Maximal variance of group cohesiveness occurs when τ_i takes only the values of 0 and 1, $\tau_i \in \{0, 1\}$, and the probability of taking either 0 or 1 is equal to one half, such that $\mathrm{P}(\tau_i = 0) = \mathrm{P}(\tau_i = 1) = \frac{1}{2}$. Given that $C_i, \tau_i \in \{0, 1\}$, then $Var(C_i^2) = Var(C_i) = C - C^2$, $C = E[C_i] = E[C_i^2]$, and $Var(\tau_i) = \tau - \tau^2$. Thus, equation (22) can be rewritten as $Var(I_i) = \left(C - C^2\right)\tau + \left(\tau - \tau^2\right)C^2$. It is easy to observe that this variance is maximal when $C = 1$ and $\tau = 0.5$ (or $\tau = 1$ and $C = 0.5$) and minimal when $C = \tau = 0$. □.

Appendix H

We introduce the background information on social networks (Part 1) before proceeding with the proof of Proposition 2 (Part 2).

Part 1 of Appendix H: Necessary condition for the power-law distribution to emerge.

Observation H1 *[Power-law distribution]. Social networks are nonregular, sparse networks, and the power-law distribution is a statistically plausible model for explaining their group size sequence,* $\{k_i\}_{1\le i\le n}$, *such that* $\mathrm{P}(k) \propto k^{-\gamma}$ *for* $k \ge 1$ *with* $2 < \gamma < 3$.

In a recent study, Broido and Clauset (2019) analyzed nearly 1000 social, biological, technological, transportation, and information networks and found that the lognormal and the power-law distributions are good approximations of these networks. However, our study is based on a power-law distribution, because its statistical properties are easy to interpret analytically.

Definition H1 [Regular networks] Regular networks are those in which all agents have the same group size, $Var(k) = \frac{1}{n}\sum_{i=1}^{n}\left(k_i - k\right)^2 = 0$. Nonregular networks have $Var(k) > 0$.

The regularity of a social network depends on its power-law exponent, $2 < \gamma < 3$, with $\gamma \to 3$ leading to more regular social networks. In the literature, sparse networks are defined as follows.

Definition H2 [Sparse networks] Sparse networks are characterized by a low total number of links, $0 < |L| << |L|^{\max}$, where $|L|$ denotes the total number of links in the network and $|L|^{\max} = \frac{n(n-1)}{2}$ its maximal number.

Although sparsity is an important characteristic of social networks, the threshold between sparsity and nonsparsity is not well defined in the literature. Next, we show that the sparsity of social networks is specifically bounded by the network size.

Proposition H1 *[Sparsity and social networks] The condition* $n \le |L| \le n\sqrt{n}$ *is a necessary condition for the power-law distribution of social networks to emerge.*

Proof Let $F(k) = \mathrm{P}(K \ge k)$ denote the cumulative distribution function of the power-law distributed variable k (in this case, group size). In the continuous case, $F(k) = \int_k^{\infty} P(k)dk = \left(\frac{k}{k_{\min}}\right)^{1-\delta}$. The integral of $P(k)$ over two different group sizes (k_1, k_2) is computed as $F(k) = \int_{k_1}^{k_2} P(k)dk$, where $k_1 < k_2$, and it provides the probability that a randomly chosen agent i has a group size between these two values, such that $k_1 < k_i < k_2$.

To calculate k_{max}, we assume that in a social network of n agents we expect at most one agent whose group size exceeds k_{max}; then $F(k) = \int_{k_{max}}^{\infty} P(k)dk = \left(\frac{k_{max}}{k_{min}}\right)^{1-\gamma} = \frac{1}{n}$. It yields $k_{max} = k_{min} n^{\left(\frac{1}{\gamma-1}\right)}$. Solving the last equation in the limits of the power-law exponent $2 \le \gamma \le 3$, we obtain that

$$\begin{cases} k_{max} = nk_{min}, \text{ if } \gamma = 2 \\ k_{max} = \sqrt{n} k_{min}, \text{ if } \gamma = 3 \end{cases} \tag{23}$$

Since neither self-loops nor multiple links are considered, it holds that $1 < k_{max} \le n - 1$. Equation (23) indicates that k_{min} needs to be bounded between $1 \le k_{min} < \sqrt{n}$. Using the Barabasi and Albert model (1999) as the reference model for power-law networks, we know that the average group size is $k = 2k_{min}$, and the total number of links is $|L| = \frac{nk}{2}$. According to equation (23), we obtain the condition for the power-law distribution of social networks to emerge, which is $n \le |L| \le n\sqrt{n}$. □.

According to Definition H2 and Proposition H1, the condition for sparsity $0 < n \le |L| \le n\sqrt{n} << |L|^{max}$ holds when n is sufficiently large (e.g., $n \ge 1000$). This means that social networks represent only a small fraction of all possible networks. Let $G_{|L|}$ be the set of all networks of size n with any number $0 \le |L| \le |L|^{max}$ of links. Let $\tilde{G}_{|L|}$ be the set of all possible social networks, which implies size n with $0 < n \le |L| \le n\sqrt{n}$ links (Proposition H1). Then, we can easily observe that $\tilde{G}_{|L|} \subset G_{|L|}$.

Part 2 of Appendix H: Proof of Proposition 2

In a complete network (CN), all agents are linked such that $\forall i \in V$, $\tau_i = \tau = 1$. The expected tightness of indirect norm-enforcing ties in CN is maximal, $I_{CN} = C^2$, due to $\tau = 1$.

To calculate the lower and upper limits of average group cohesiveness in social networks (SN), we use two different power-law networks generative models: the Barabasi and Albert (BA) model (1999) and the pseudo-fractal (PF) model (Dorogovtsev et al. 2002). The lower limit of τ in SN is given by the BA model. In this model, average group cohesiveness is $\tau = \frac{(k_{min}-1)(\log n)^2}{8n}$ (Klemm and Eguíluz 2002; Fronczak et al. 2003; Szabó et al. 2003). Since $k_{min} \in \left[1, \sqrt{n}\right)$ (Proposition F1), then $\tau \in \left[0, \frac{(\log n)^2}{8\sqrt{n}}\right]$.

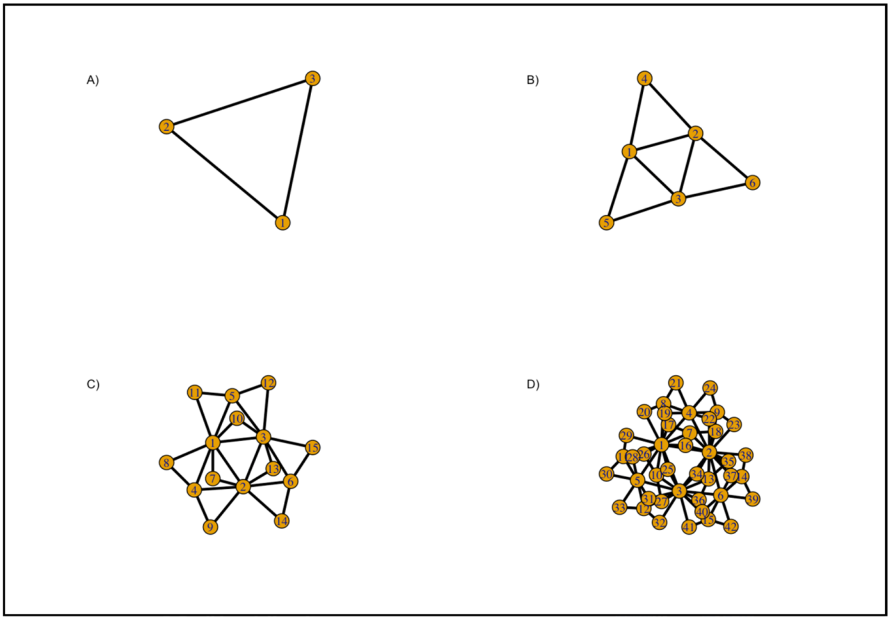

Fig. 10 The pseudo-fractal network generative model (Dorogovtsev et al. 2002). Starting from a single link that connects two agents at time $t = 1$, every link in the network generates at each time step a new agent that connects to both of the end-agents of the link. Figure 10 shows the structure of the pseudo-fractal network at times $t = \{2, 3, 4, 5\}$ which corresponds to networks in panels A, B, C and D, respectively

Using the PF model, the upper limit of τ in the SN can be approximated.[34] This model is used to generate a SN with remarkably high average group cohesiveness, e.g., a network of scientific collaborators (Foster et al. 2011). The pseudo-fractal model is deterministic because network growth depends exclusively on calendar time $t \in \mathbb{R}_{\geq 0}$. Thus, the network size is $n = \frac{3(3^t+1)}{2}$, total number of links is $|L| = 3^{t+1}$, and average degree is $k = \frac{4}{1+3^{-t}}$ (Figure 10). The distribution of group cohesiveness follows a power-law distribution that depends on individual group size, with $\tau_i = \frac{2}{k_i}$. The resulting average group cohesiveness approaches a constant value $\tau = \frac{4}{5}$. According to these network generative models, the expected tightness of indirect norm-enforcing ties in SN ranges in-between $I_{SN} \in \left[0, \frac{4C^2}{5}\right]$.

The Erdös-Rényi model (Erdös and Rényi 1960) is the original random-network (RN) generative model. Although the topology of the RN is not observed in social networks, the model is interesting because its characteristics can be studied

[34] Klemm and Eguíluz (2002) proposed an alternative model to reproduce power-law networks with higher average group cohesiveness, $\tau = 5/6$, but we based our analysis on pseudo-fractal networks because they are more easy to analyze analytically.

analytically. The RN network is typically denoted by $g = (n, p)$ for its two components: (1) $n \in [2, \infty)$ the number of isolated agents; and (2) $p \in [0, 1]$ the probability that a link between any pair (i, j) in g exists. All links have identical probability p to exist. Average group size is $k = (n-1)p$, total number of links is $|L| = \frac{nk}{2}$, and average group cohesiveness is $\tau = \frac{\binom{n}{3}p^3}{\binom{n}{3}p^2} = p$.

To compare RN and SN, the networks have to be of identical size n subject to the sparsity condition, $n \leq |L| \leq n\sqrt{n}$ (Proposition H1). This condition leads to $k \in \left[2, 2\sqrt{n}\right]$ and $\tau \in \left[\frac{2}{(n-1)}, \frac{2}{\sqrt{n}}\right]$. Consequently, the expected tightness of indirect norm-enforcing ties in sparse RN is minimal, $I_{RN} \in \left[\frac{2C^2}{(n-1)}, \frac{2C^2}{\sqrt{n}}\right]$, because $\tau \approx 0$; especially in RN with large n. $\square$.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

Acemoglu D, Jackson MO (2015) History, expectations, and leadership in the evolution of social norms. Rev Econ Stud 82(2):423–456

Akerlof G (1997) Social distance and social decisions. Econometrica 65:1005–1027
Alger I, Weibull J (2013) Homo moralis—preference evolution under incomplete information and assortative matching. Econometrica 81:2269–2302
Ali SN, Miller DA (2016) Ostracism and forgiveness. Am Econ Rev 106:2329–2348
Allen B, Lippner G, Chen Y-T, Fotouhi B, Momeni N, Yau S-T, Nowak MA (2017) Evolutionary dynamics on any population structure. Nature 544(7649):227–230
Axelrod R (1986) An evolutionary approach to norms. Am Polit Sci Rev 80:1095–1111
Axelrod R, Hamilton WD (1981) The evolution of cooperation. Science 211(4489):1390–1396
Balafoutas L, Nikiforakis N (2012) Norm enforcement in the city: a natural field experiment. Euro Econ Rev 56:1773–1785
Baldassarri D (2015) Cooperative networks: altruism, group solidarity, reciprocity, and sanctioning in Ugandan producer organizations. Am J Sociol 121:355–395
Banfield E (1958) The Norm-enforcing Basis of a Backward Society. Free Press, New York
Battigalli P, Dufwenberg M (2007) Guilt in Games. Am Econ Rev 97(2):170–176
Bernheim BD (1994) A Theory of Conformity. J Polit Econ 102:841–877
Bicchieri C (2006) The Grammar of Society: The Nature and Dynamics of Social Norms. Cambridge University Press, New York
Bicchieri C (2010) Norms, preferences, and conditional behavior. Polit, Philos Econ 9:297–313
Bicchieri C (2016) Norms in the wild. How to diagnose, measure, and change social norms. Oxford: Oxford University Press, 264 pages, ISBN 978–0190622053
Bicchieri C, Xiao E (2009) Do the right thing: but only if others do so. J Behav Decis Mak 22(2):191–208
Boucher V (2016) Conformism and self-selection in social networks. J Public Econ 136:30–44
Bramoullé Y, Djebbari H, Fortin B (2020) Peer effects in networks: a survey. Annu Rev Econ 12:603–629
Broido AD, Clauset A (2019) Scale-free networks are rare. Nat Commun 10(1):1017
Calvó-Armengol A, Jackson M (2010) Peer pressure. J Eur Econ Assoc 8:62–89
Caplow T (1969) Two Against One: Coalitions in Triads. Prentice-Hall, Englewood Cliffs
Chaudhuri A (2011) Sustaining cooperation in laboratory public goods experiments: a selective survey of the literature. Exp Econ 14:47–83
Christakis N, Fowler J, Imbens GW, Kalyanaraman K (2020) Chapter 6–An empirical model for strategic network formation. In: Graham B, de Paula Á (eds) The Econometric Analysis of Network Data. Academic Press, Cambridge
Coleman J (1988) Social capital in the creation of human capital. Am J Sociol 94:S95–S120
Cornes R and Sandler T (1996) Game theory and public goods. In: The Theory of Externalities, Public Goods, and Club Goods, 300–326. Cambridge University Press, Cambridge
Cumming GS (2018) A review of social dilemmas and social-ecological traps in conservation and natural resource management. Conserv Lett 11:e12376
Currarini S, Jackson MO, Pin P (2010) Identifying the roles of race-based choice and chance in high school friendship network formation. Proc Natl Acad Sci 107(11):4857–4861
Dohmen T, Falk A, Huffman D, Sunde U (2009) Homo reciprocans: survey evidence on behavioural outcomes. Econ J 119:592–612
Duernecker G, Vega-Redondo F (2017) Social networks and the process of globalization. Rev Econ Stud 85:1716–1751
Elster J (1989) Social norms and economic theory. J Econ Perspect 3:99–117
Enke B (2019) Kinship, cooperation, and the evolution of norm-enforcing systems. Q J Econ 134:953–1019
Fehr E, Gächter S (2000) Fairness and retaliation: the economics of reciprocity. J Econ Perspect 14:159–181
Fehr E, Gächter S (2002) Altruistic punishment in humans. Nature 415:137–140
Fehr E, Schurtenberger I (2018) Normative foundations of human cooperation. Nat Hum Behav 2(7):458–468
Fehr E, Fischbacher U, Gächter S (2002) Strong reciprocity, human cooperation, and the enforcement of social norms. Human Nat: Interdiscip Biosoc Perspect 13:1–25
FeldmanHall O, Son J, Heffner J (2018) Norms and the flexibility of norm-enforcing action. Personal Neurosci 1:1–14
Gächter S, Gerhards L, Nosenzo D (2017) The importance of peers for compliance with norms of fair sharing. Euro Econ Rev 97:72–86
Granovetter MS (1973) The strength of weak ties. Am J Sociol 78:1360–1380
Granovetter M (1978) Threshold models of collective behavior. Am J Sociol 83:1420–1443

Harrell A, Wolff T (2023) Cooperation in networked collective-action groups: information access and norm enforcement in groups of different sizes. Soc Psychol Quart 86(4):476–496
Henrich J, Boyd R (2001) Why people punish defectors: weak conformist transmission can stabilize costly enforcement of norms in cooperative dilemmas. J Theor Biol 208(1):79–89
Jackson M (2008) Network formation. In: Durlauf S, Blume L (eds) The New Palgrave Dictionary of Economics. Macmillan, London
Jackson M (2010) Social and Economic Networks. Princeton University Press, Princeton
Jackson M, Rodriguez-Barraquer T, Tan X (2012) Social capital and social quilts: network patterns of favor exchange. Am Econ Rev 102:1857–1897
Jackson M, Rogers B, Zenou Y (2017) The economic consequences of social network structure. J Econ Lit 55:49–95
Kossinets G, Watts D (2006) Empirical analysis of an evolving social network. Science 311:88–90
Krupka EL, Weber RA (2013) Identifying social norms using coordination games: why does dictator game sharing vary? J Eur Econ Assoc 11(3):495–524
Manski C (1993) Identification of endogenous social effects: the reflection problem. Rev Econ Stud 60:531–542
McPherson M, Smith-Lovin L, Cook J (2001) Birds of a feather: homophily in social networks. Ann Rev Sociol 27:415–444
Miller DE (2007) Dyad/Triad. In: The Blackwell Encyclopedia of Sociology, Ritzer G (Ed). https://doi.org/10.1002/9781405165518
Morsky B, Akçay E (2019) Evolution of social norms and correlated equilibria. Proc Natl Acad Sci 116:8834–8839
Nowak MA (2006) Five rules for the evolution of cooperation. Science 314(5805):1560–1563
Nyborg K (2018) Social norms and the environment. Annu Rev Resour Econ 10:405–423
Ohtsuki H, Hauert C, Lieberman E, Nowak MA (2006) A simple rule for the evolution of cooperation on graphs and social networks. Nature 441(7092):502–505
Piskorski J, Gorbatâi A (2017) Testing Coleman's social-norm enforcement mechanism: evidence from wikipedia. Am J Sociol 122:1183–1222
Platteu JP (2000) Institutions Amsterdam, Hardwood Academic Publishers and Routledge Social Norms and Economic Development
Shweder RA, Much N, Mahapatra M, Park L (1997) The "big three" of morality (autonomy, community, divinity) and the "big three" explanations of suffering. Moral Health 119:119–169
Simmel G, Wolff K (1950) The Sociology of Georg Simmel. Free Press, Glencoe
Tomasello MA (2016) Natural History of Human Morality (Harvard University Press, 2016)
Torren-Peraire D, Savin I, Van den Bergh J (2023) An agent-based model of cultural change for a low-carbon transition. Available at SSRN 4344035
Ushchev P, Zenou Y (2020) Social norms in networks. J Econ Theory 185:104969
Watts DJ, Strogatz SH (1998) Collective dynamics of 'small-world'networks. Nature 393(6684):440–442
Young HP (1993) The evolution of conventions. Econometrica 61(1):57–84
Young HP (2015) The Evolution of social norms. Annu Rev Econ 7:359–387
Yudkin DA, Gantman A, Hofmann W, Quoidbach J (2021) Binding norm-enforcing values gain importance in the presence of close others. Nat Commun 12:2718

References for the Appendices

Broido AD and Clauset A (2019). Scale-free networks are rare. Nature Communications 2019 Vol 1017
Barábasi AL, Albert R (1999) Emergence of scaling in random networks. Science 286:509–512
Dorogovtsev SN, Goltsev AV, Mendes JF (2002) Pseudofractal scale-free web. Phys Rev E 65(6):066122
Erdos P, Rényi A (1960) On the evolution of random graphs. Publ Math Inst Hung Acad Sci 5(1):17–60
Foster DV, Foster JG, Grassberger P, Paczuski M (2011) Clustering drives assortativity and community structure in ensembles of networks. Phys Rev E–stat, Nonlinear, Soft Matter Phys 84(6):066117
Fronczak A, Fronczak P, Hołyst J (2003) Mean-field theory for clustering coefficients in Barábsi-Albert networks. Phys Rev E 68:046126
Klemm K, Eguíluz V (2002) Growing scale-free networks with small-world behavior. Phys Rev E 65:057102
Jackson M (2010) Social and economic networks. Princeton, Princeton University Press

Jackson M, Rogers B and Zenou Y (2017) The economic consequences of social network structure. Journal of Economic Literature, 55: 49–95
Szabó G, Alava M, Kertész J (2003) Structural transitions in scale-free networks. Phys Rev E 67:056102