Received: 17 December 2021 | Accepted: 3 January 2022

DOI: 10.1111/ajae.12372

ARTICLE

Public policy design and common property resources: A social network approach

Jorge Marco[1] | Renan Goetz[2]

[1]University of Los Andes, Bogotá, Colombia

[2]University of Girona, Girona, Spain

Correspondence
Renan Goetz, University of Girona, Carrer de la Universitat, 10, 17003 Girona, Spain.
Email: renan.goetz@udg.edu

Funding information
Spanish Government; Ministerio de Ciencia e Innovación (MCIN)/Agencia Española de Investigación(AEI), Grant/Award Number: PID2020-118268RB; SDGnexus Network, Grant/Award Number: 57526248; German Federal Ministry for Economic Cooperation (BMZ)

Abstract

This paper analyzes the extent to which two factors—social networks and the severity of the scarcity of a common property resource—affect norm-complying behavior that favors cooperation. It assumes that those who comply with the social norm exercise social pressure on defectors. We develop an analytical framework that allows us to determine the minimum (maximum) share of norm-complying agents at which social networks start (stop) having an influence on cooperation. Knowing these shares allows policymakers to identify the conditions under which legal and/or informal enforcement policies for cooperation are effective and how different types of social networks affect the design of these policies. We find that stable steady states exist in which compliers and defectors coexist (partial cooperation), but the stability of such states requires that the costs of coordination among compliers to exercise social pressure are high. Full cooperation is another possible steady state but is unlikely to prevail if the agents do not perceive the scarcity of the common property resource as severe. A numerical study, empirically calibrated for an aquifer in Spain, shows that subsidizing the compliers' costs of exerting social pressure may impede the attainment of a steady state based on partial cooperation. Although social networks can promote cooperation, their influence is limited. The minimum share of compliers for attaining cooperation can be reduced by informal enforcement policies by not more than 26%. We show that combinations of different types of informal enforcement policies should be applied cautiously because they may cancel each other out.

KEYWORDS

common property resources, cooperation, public policy, social networks, social norms

JEL CLASSIFICATION
C73, D70, D85, Q20

1 | INTRODUCTION

Common property resources such as aquifers are being depleted and degraded in many parts of the world (Ravenscroft & Lytton, 2022). Some communities cooperate to extract common property resources in a sustainable way, whereas others do not. Sustained cooperation and sustainable management are traditionally explained by compliance with social norms (Elster, 1989; Fehr & Gächter, 2002; Fehr & Gintis, 2007). For instance, a social norm may correspond to the socially optimal extraction of the resource, whereas deviations from the social norm may correspond to privately optimal extraction of the resource. The decision to comply with social norms is often voluntary, especially if it is technically infeasible or too costly to rely on laws and enforcement. Nevertheless, agents who adhere to social norms may apply social pressure to agents who do not adhere to them (Ali & Miller, 2016; Fehr et al., 2002). Understanding how social norms emerge and prevail is fundamental for explaining ongoing cooperation.

The economic literature (Acemoglu & Jackson, 2017; Bramoullé & Kranton, 2007; Jackson, 2014) has identified the structure of social interactions (often referred to as social networks) as a driving factor in the emergence of social norms. However, this literature has paid hardly any attention to the influence of the severity of the social dilemma, for example, the scarcity of a common property resource. The literature on direct reciprocity, for instance in the form of social pressure, suggests that repeated interactions can alleviate the social dilemma of common property resources but has assumed that the stock of the resource is constant over time (García & van Veelen, 2016; Grujic et al., 2012; Hilbe, Chatterjee, & Nowak, 2018). This assumption is incompatible with the findings by Hilbe, Šimsa, et al. (2018). They show that the interaction between reciprocity and payoffs depends on the severity of the social dilemma.

Based on these findings, our study aims to develop an analytical framework that takes account of the interdependencies among agents' decisions, the scarcity of the resource, and the share of norm-complying agents. Our approach is based on the theory of evolutionary games. In contrast with a standard evolutionary game, it does not only consider networks where every agent is connected to all other agents but takes into account realistic pattern of social interactions that reflect the complexity, vicinity, and segregation patterns of social networks (Jackson et al., 2017). The evolutionary game approach is extended by combining the dynamics of a renewable common property resource with the dynamics of the normcomplying agents. This setup yields a so-called bioeconomic system where a formal institution (for instance, a regulatory entity) may sanction non-complying agents, whereas an informal institution (norm-complying agents) exercises social pressure on non-complying agents. Either of the two institutions may formalize network-oriented enforcement policies that strengthen the effect of social interactions on cooperation.

Agents make decisions at the micro-scale of the network (the neighborhood) and take account of the decisions made by their neighbors. However, each agent's decision is affected by all other agents' decisions as they modify the entire network (the macro-scale), which is described by the characteristics of the social network, the scarcity of the resource and the share of norm-complying agents. Unfortunately, the enormous number of interactions between the micro-scale and macro-scale impedes efforts to obtain analytical results. For this reason, we opt for an approximation method similar to mean-field analysis where we model the effects of all agents on an individual agent in a representative manner. Based on this approximation method, the proposed framework allows us to quantitatively and qualitatively determine the scope of cooperation and the design of optimal policies for social networks of any type and size. This study offers answers to the following two important questions:

a. "To what extent does the underlying pattern of social interactions (the type of social network) influence equilibrium outcomes and cooperation?" This question has received little attention, although economists widely agree that social interactions are important for sustained cooperation. The economic literature has introduced the concept of a social tipping point, which refers in our context to the minimum share of norm-complying agents needed to induce cooperation among all agents (Barrett & Dannenberg, 2017; Nyborg, 2020). We find that social tipping points, even in combination with information about the state of the common property resource, are imprecise predictors for cooperation. Instead, we propose a new concept which we call frontier lines. It not only considers the share of norm-complying agents and the scarcity of the resource but also the underlying type of social network. The concept of frontier lines allows us to delineate the "area of network influence" by determining the maximum and minimum influence from where social networks start (stop) having influence on cooperation.
b. Based on the answer to the first question, we address a second question: "To what extent do the location and size of the area of network influence affect the design of optimal enforcement policies?" To answer this question, we first analyze the conditions under which legal (e.g., fines or subsidies) and informal (e.g., network-oriented) enforcement policies are a viable option and second determine the optimal design of legal and informal enforcement policies in order to achieve the socially optimal outcome (full cooperation).

With the answers to these two questions, we extend the literature with an analytical framework for modeling the interactions among the agents, network characteristics, and the dynamics of the resource. This framework permits us to consider a diversity of realistic situations by evaluating the effect of changes in the parameters on the outcome of the model. It offers three policy-relevant results. First, we compare the effectiveness of legal versus informal enforcement at the steady state and "off" the steady state. Second, we find that even an extremely high share of compliers does not guarantee cooperation. Third, the type of social network is important for norm-complying behavior, but its influence could be quite limited. In the following paragraphs, we present a more detailed preview of these results.

Our study extends the literature by evaluating legal and informal enforcement policies, not only in a steady state but also outside this state. For this purpose, we determine the basins of attraction of the bioeconomic system, which allows us to identify the effectiveness of the different enforcement policies. The determination of the area of network influence opens the door for informal enforcement policies in the form of network-oriented policies designed to increase cooperation. These policies may include creating an association whose membership is open only to norm-complying agents. The association may assist its members by offering support for their economic activities, training workshops, or members' privileges. Yet, as shown in this study, even an initially very high number of norm-complying agents may lead to non-cooperation in the long run when agents do not perceive the social dilemma as a pressing problem.

We employ our analytical framework for the case of a groundwater-extracting community of farmers located in Spain. The Western La Mancha Aquifer has suffered overexploitation for many decades (Esteban & Albiac, 2011). In the empirical part of this study, we analyze the extent to which different characteristics of a social network contribute to sustainable management of the aquifer. The results show that, depending on the type of network and the scarcity of the resource, informal enforcement policies can reduce the minimum number of norm-complying agents required to support full cooperation by 26% at most. Moreover, the results show that a locally stable second-best solution (partial cooperation), where norm-complying and noncomplying agents coexist, occurs within the area of network influence only if social pressure is costly. The size of the area of network influence depends substantially on the agents' responsiveness with respect to the social dilemma.

This result underlines the importance of public opinion-making (e.g., public campaigns, lobbying, regulations etc.) as a catalyst for the formation of social norms within a social network. Furthermore, the results show the extent to which taking into account both social networks and the scarcity of the resource allows the social planner to reduce the number of agents that need to be targeted through formal mechanisms in order to achieve full cooperation. Finally, the study offers a rule of thumb for designing policies if the regulator/community has incomplete information about the underlying social network structure.

The paper is organized as follows. The rationale of the modeling approach and its relation with the previous literature is explained in Section 2, the model in Section 3, and implications for policy design in Section 4. Section 5 concludes.

2 | PREVIOUS LITERATURE

Frequently, norm compliance or cooperation is modeled within the framework of evolutionary games (Besley, 2020; Smith & Price, 1973). These assume well-mixed communities where agents do not act fully rationally and where every agent is linked with all other agents (complete networks). Bounded rationality seems reasonable if the social network is either large or topologically complex. Determining the optimal strategic response to, for instance, thousands of other agents, each of whom occupies a unique position in the social network, could stretch the assumption of rationality beyond its limits due to the complexity of the strategic decision problem.

Besides trust and reputation, the literature has identified social pressure as an effective instrument to promote cooperation within a community (Jackson et al., 2012; Karlan et al., 2009; Tavoni et al., 2012). In the case of social pressure, agents who do not comply with the social norm (referred to as defectors) might be exposed to social pressure from their neighbors who are complying with the norm (referred to as compliers). The share of compliers alone, however, is a poor indicator of social pressure because it does not consider how compliers can coordinate their actions with the aim of increasing social pressure on defectors (Coleman, 1988). Thus, characteristics of social networks, such as network density (Karlan et al., 2009; Kyriakopoulou & Xepapadeas, 2021), network size (Wolitzky, 2013), and social distance (Tabellini, 2008), are frequently related to trust, reputation, coordination, and social pressure to get a better picture of the driving factors for cooperation. Although network characteristics provide key information about the underlying pattern of social interactions, they do not take account of agents' behavior. Because each of the two explanatory approaches falls short of being convincing, we employ the concept of moral ties proposed by Goetz and Marco (2022). Moral ties are based on the combination of two metrics: the share of compliers and local cohesiveness (Coleman, 1988; Jackson, 2016). They capture the pattern of the agents' interaction and behavior within the community and allow measurement of the capacity of agent i's norm-complying neighbors to both exert and coordinate social pressure on agent i (Coleman, 1988). We complement the concept of moral ties as a driver of social pressure with the agents' perception of the scarcity of the resource.

Based on the case of a community of farmers who extract groundwater from a common property resource, we analyze the effects of both social networks and the scarcity of the resource on cooperation among the farmers. This modeling approach requires describing both the evolution of the water table (as a result of natural recharge of the aquifer and the aggregate extraction of all farmers) and the evolution of the share of compliers (together with the compliers' capacity to coordinate their behavior). These two components are the building elements of an evolutionary game that will form the basis for our empirically oriented study.[1] At each period of time, every agent decides whether or not to cooperate based on the utility derived from this decision. Before we present the full economic model, we turn our attention to the building elements of the game.

3 | THE MODEL

We consider that each of the $n >> 2$ identical agents of the community has access to a common property resource and receives payoffs from resource extraction. The social dilemma has two defining characteristics. At every moment of time, defectors (D) receive higher payoffs than compliers (C) from resource extraction regardless of what other agents do. But if all agents were compliers, the aggregate stream of future payoffs of each agent would be maximized. The social dilemma could be overcome if the socially optimal extraction emerged as a social norm. Adherence to the social norm would be voluntary, but compliers could pressure defectors to comply with it. Social pressure, explained in more detail below, depends on its costs, the scarcity of the resource, and the compliers' capacity to coordinate their efforts to exercise social pressure.

In this section we define the underlying assumptions of the game, its building elements (utility, social networks, and social pressure), its setup and timeline, and the dynamics of the bioeconomic system.

3.1 | Assumptions

The game is based on the following assumptions.

- *A1. Individual payoffs and utility*. All compliers receive identical payoffs from resource extraction, but their utility may differ because the costs of social pressure depend on the number of non-complying neighbors.[2] Likewise, all defectors receive identical payoffs from resource extraction, but their utility depends on the social pressure imposed on them.
- *A2. Monitoring*. All agents are perfectly informed about their neighbors' actions. There is no time delay between detecting defectors and exercising social pressure. Legal institutions observe the state of the resource but have incomplete information about the underlying social network because they can observe characteristics of the social network at the macro-scale but not at the micro-scale/neighborhood. However, they could detect defectors and obtain further information about the social network by exercising additional effort, for example, by carrying out surveys.
- *A3. Bounded rationality*. Agents do not act strategically and their decisions to be a complier or defector are based only on the comparison of current utility.
- *A4. Coordination of social pressure*. Compliers who are part of a defector's neighborhood and linked among each other can coordinate their social pressure. They do not free ride on each other.

The differences in the agents' utility, as stated in Assumption A1, are supported by the fact that social networks are frequently highly non-regular. Thus, the number of neighbors and their local cohesiveness vary greatly across agents and every agent occupies a unique position within the social network (Jackson et al., 2017). Assumption A2 emphasizes that legal institutions can observe characteristics of the network at the macro-scale, for example, the type of social network. Moreover, they know how the water table would evolve if all agents were defectors or compliers. Thus, they can deduce the average share of compliers from the observed changes in the water table from year to year. Assumption A3 takes into account that the agent's decision problem is highly complex because every agent's action affects and is affected by the actions of all other agents. These interdependencies are significantly more important in social networks that tend to be large and complex with notable differences at the micro-scale. In such cases, it does not seem realistic that every agent considers the large number of interactions among all agents. Therefore, we assume, as in Gale and Kariv (2003), that the agents' rationality is bounded. Accordingly, individual choices to be either a complier or defector are taken non-strategically based on current utility. The nonstrategic behavior of the agents as the result of the complexity of the decision problem implies that agents are not forward looking and, therefore, an intertemporal preference rate does not need to be considered for the game. Thus, the discount factor of all agents is equal to one.[3] Assumption A4 considers the case where compliers who are linked among each other coordinate their behavior so that the social pressure exercised increases. Moreover, it states that compliers cooperate in order to increase social pressure, but they do not free ride on each other.[4] As suggested by laboratory experiments, social pressure is the result of negative reciprocity, where an agent is willing to use costly social pressure when another agent transgresses (Dohmen et al., 2009; Fehr et al., 2002; Fehr & Fischbacher, 2003). Compliers are not only motivated by the defectors' transgression but also by differences in extraction rates. Defectors may inflict economic losses on compliers, and therefore the deprivation suffered by the compliers can be viewed as a motivation for social pressure.

3.2 | Utility, social networks, and social pressure

In this section, we present the following three elements of the game: utility, social networks, and social pressure.

Utility

Agents' payoffs are determined by the amount of the resource extracted. Let $w_i^C(s(t)) \in \mathbb{R}_{\geq 0}$ and $w_i^D(s(t)) \in \mathbb{R}_{\geq 0}$ denote the water demand function at time t if agent i is a complier or defector, respectively. The available amount of the resource is denoted by $s \in [0, s_{\max}]$, where $s_{\max} \in \mathbb{R}_{>0}$ indicates the maximum available amount of the resource and $s(t) = 0$ resource depletion. The complier's water demand function $w_i^C(s)$ represents the social norm because it corresponds to the socially optimal water demand of a farsighted social planner.[5] The defector's water demand function $w_i^D(s)$ represents the privately optimal water demand because it corresponds to the demand of a short-sighted farmer.[6] The water-demand functions $w^C(s)$ and $w_i^D(s)$ are generic functions and present two different types of behavior: socially and privately optimal. Because the socially optimal water-demand function takes account of the intertemporal user costs of the resource, whereas privately optimal water-demand function does not, it holds that $w_i^D(s) > w_i^C(s)$.[7] In other words, at any moment of time and for any given s, including the steady-state stock, defectors always extract more than compliers. Thus, their payoffs are never less than those of the compliers, $\pi_i^D\left(w_i^D(s)\right) \geq \pi_i^C\left(w_i^C(s)\right)$. The difference between $\pi_i^D\left(w_i^D(s)\right)$ and $\pi_i^C\left(w_i^C(s)\right)$ is henceforth referred to as defectors' extra benefits.

Although compliance with the social norm is voluntary, compliers exercise social pressure at cost $\gamma_i \in \mathbb{R}_{\geq 0}$ (see below for more details). Social pressure reduces the defectors' utility, which in turn favors the compliance with the social norm. We denote the social pressure that is imposed on agent i by the function $\omega_i \in \mathbb{R}_{\geq 0}$ (see below for more details). The utility of agent i adhering to the social norm is given by

$$U_i^C = \pi_i^C\left(w_i^C(s)\right) - \gamma_i. \tag{1}$$

This indicates that the utility of a complier is equal to the difference between their payoffs and the sanctioning costs.[8] The utility of the same agent i who does not adhere to the social norm is given by

$$U_i^D = \pi_i^D\left(w_i^D(s)\right) - \omega_i - \theta_i, \tag{2}$$

where $\theta_i \in \mathbb{R}_{<0}$ denotes a per capita subsidy and $\theta_i \in \mathbb{R}_{\geq 0}$ a per capita fine as a result of legal enforcement.

Social networks

The social network is denoted by $g=(A,L)$ and consists of a set $A=\{1,2,\ldots,n\}$ of agents and a set L of undirected links that are the unordered pairs of elements from A. For any pair of agents, $(i,j)\in A$, the expression $\ell_{ij}=1$ indicates that they are neighbors; otherwise $\ell_{ij}=0$. Any network metric is obtained from the adjacency matrix $g\in[0,1]^{\mathrm{n}\times\mathrm{n}}$. The neighborhood of agent i is denoted by $A_i(g)=\{j\in A\backslash\{i\}:\ell_{ij}=1\}$, and $k_i=|A_i(g)|=\sum_{j=1}^{n}\ell_{ij}$ indicates its size (degree), with $k_i\in[1,n-1]$. The social network is complete when $k_i=n-1$ for all agents. The local cohesiveness of agent i is defined as

$$\tau_i=\frac{|\{\ell_{uv}:u,v\in A_i(g),\ell_{uv}=1\}|}{k_i(k_i-1)/2}\in[0,1]. \tag{3}$$

The denominator of Equation (3) indicates the maximum number of possible links among agent i's neighbors, and the numerator indicates the number of existing links among them. Let $A_i^C(g)$ denote the subset of compliers within agent i's neighborhood, such that $A_i^C(g)\subseteq A_i(g)$. Local cohesiveness of compliers measures the capacity of coordination among compliers, which depends on two metrics: the share of compliers, $c_i=\frac{|A_i^C(g)|}{|A_i(g)|}\in[0,1]$, and the local cohesiveness of the neighborhood of agent i, τ_i. Let τ_{c_i} denote the local cohesiveness of compliers in agent i's neighborhood, which can be quantified as

$$\tau_{c_i}=\frac{|\{\ell_{uv}:u,v\in A_i^C(g),\ell_{uv}=1\}|}{k_i(k_i-1)/2}\in[0,1]. \tag{4}$$

Equation (4) measures how close $A_i^C(g)$ is to being a complete network ($\tau_{c_i}=1$). The term τ_{c_i} also signals the maximum size of the coalition that compliers can form in order to increase social pressure on agent i. Note that $\tau_{c_i}\leq\tau_i$ always holds because $A_i^C(g)\subseteq A_i(g)$.

Social pressure

Social pressure is denoted by the function $\omega_i\equiv\omega_i(c_i,\tau_{c_i},s),\omega_i:\mathbb{R}^3_{\geq 0}\rightarrow\mathbb{R}_{\geq 0}$ and is based on three variables: the share of compliers, the local cohesiveness of compliers, and the level of the remaining stock. The social pressure function relates to the concept of conditional compliers (Besley, 2020; Bowles & Gintis, 2011; Fehr et al., 2002). However, in this study, the conditionality is not only linked to the share of compliers but also to the strength of cohesiveness and the scarcity of the resource. If the link to these conditions does not exist or is very weak, agents exercise little or no social pressure, so that cooperation is not supported, and it is optimal for agents not to adhere to the social norm. In the remaining part of this subsection, we analyze the effects of these three key variables on social pressure.

As described in theoretical and empirical studies (Bowles & Gintis, 2011; Calvó-Armengol & Jackson, 2010; Fehr & Gächter, 2002; Gächter et al., 2017), the higher the share of compliers, the greater the social pressure exerted on agent i, $\omega_{c_i}=\partial\omega_i/\partial c_i>0$.[9] Social pressure is influenced by local cohesiveness, which in turn is favored by the decision to coordinate actions (Goetz & Marco, 2022), $\omega_{\tau_{c_i}}=\partial\omega_i/\partial\tau_{c_i}>0$.[10]

Provided that agents have knowledge about the dynamics of the resource, we consider the level of the remaining stock to be a driving force for cooperation, as in Sethi and Somanathan (1996). The agents' awareness of the effect of their individual extraction on the dynamics of the resource, likely affects their willingness to take responsibility for the state of the resource, in particular if the resource is close to depletion. For this reason, we postulate that the individual responsibility is translated into social pressure, and the scarcer the resource is, the greater the social pressure the compliers exert on defectors (Lade et al., 2013; Tavoni et al., 2012). In other words, social pressure is a decreasing function in s, $\omega_{s_i} = \partial \omega_i / \partial s < 0$.[11] To summarize, social pressure is a continuous, twice differentiable and increasing function in c_i and τ_{c_i}, and is decreasing in s, with $\omega_i(0,0,s) = 0$ and $0 < \omega_i(1,1,0) = \max\{\omega_i\} < < \infty$ (Bicchieri & Muldoon, 2014).

Fehr and Gächter (2000) have observed that compliers are willing to pressure defectors even when it is costly for them and even if no future net benefits are to be expected from their pressure. For this reason, we consider sanctioning costs but do not impose economic rationality, that is, the costs of sanctioning do not have to be less than the resulting benefits from sanctioning.[12] The complier i's sanctioning costs are defined by $\gamma_i : \mathbb{R}^2_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$, a function that is continuous, twice differentiable, and non-decreasing in k_i. Let the function γ_i be given by

$$\gamma_i(k_i, c_i) = \upsilon(k_i)(\alpha_0 - \alpha_1 c_i + \alpha_2(1 - c_i)c_i), \tag{5}$$

where $\upsilon(k_i) > 0$, $\partial \upsilon / \partial k_i > 0$ and $\alpha_0, \alpha_1, \alpha_2$ are nonnegative parameters. The parameter α_0 reflects fixed sanctioning costs. For a given k_i, $\alpha_0 \geq \alpha_1$, and $\alpha_2 = 0$, agent i's sanctioning costs are maximal if all neighbors are defectors. In this case, agent i's sanctioning costs are given by $\gamma_i(k_i, 0) = \alpha_0 \upsilon(k_i)$. Conversely, agent i's sanctioning costs are minimal if all neighbors are compliers, that is, $\gamma_i(k_i, 1) = \upsilon(k_i)(\alpha_0 - \alpha_1)$. However, the assumption $\alpha_2 = 0$ does not allow us to consider the compliers' costs of coordination.

Coordination costs are expressed by the term $\alpha_2(1 - c_i)c_i$, with $\alpha_2 \geq \alpha_1 \geq 0$. These costs are low if there are few compliers.[13] However, as the share of compliers increases up to $c_i = 0.5$, so do the compliers' costs of coordination. This happens because the expected maximum number of links where compliers and defectors are connected is likely to occur when $c_i = 0.5$. However, as the share of compliers increases further, the expected number of links between compliers and defectors decreases. Thus, the coordination costs among compliers decreases as well, because fewer compliers are in a position to exercise social pressure over the diminishing number of defectors. If there are no defectors left, coordination costs are zero. Likewise, if all agents are defectors, there are no compliers left and consequently the costs of coordination are zero as well. The consideration of coordination costs for $\alpha_0 = \alpha_1$ suggests that sanctioning costs are bell shaped where it still holds that $\gamma_i(k_i, 0) = \alpha_0 \upsilon(k_i)$ and $\gamma_i(k_i, 1) = 0$, but $\gamma_i(k_i, c_i)$ is likely to be maximum if $c_i \in (0, 0.5]$.

3.3 | The game

The game is described as follows.

- The structure of the social network $g \in (A, L)$ is static throughout the run of the game but can be modified between different runs. This allows us to analyze the influence of different types of networks on cooperation.
- The size of the social network is finite but large, $0 < < |A| = n < \infty$, and constant during the run of the game.
- The game begins at time $t = 0$ for a given stock $s_0 \in (0, s_{\max}]$. The initial number of compliers, $c_0 \in (0, 1)$, the size of the neighborhood k_i, and local cohesiveness τ_i are distributed randomly across agents.
- *Decision problem*. At each moment $t \in [1, T]$, agent i in g faces a binary choice from the set $\{w_i^C(s(t)), w_i^D(s(t))\}$. Given the specification of the functions $w_i^D(s(t))$ and $w_i^C(s(t))$, the choice of all agents determines the evolution of the stock, which in turn determines the values of $w_i^C(s(t))$ and $w_i^D(s(t))$ in the next period of the game.

- *Action choice*. At each t, all agents take their neighbors' actions as given and simultaneously choose their action. Agents switch to the alternative action only if its utility is higher than the utility of their current action. Cooperation and the available stock vary in time as a result of all agents' actions. The continuous repetition of this step brings the game close to a sequence of one-shot games that are linked by the previous state of the bioeconomic system.
- *End of the game*. The game ends when $t = T$ or $s = 0$, where $c_T \in [0,1]$ and $s_T \in [0, s_{\max}]$ denote the share of compliers and the remaining stock at the end of the game, respectively.

3.4 | The bioeconomic system

Before we analyze the dynamics of the bioeconomic system, we define an approximation method that reduces the complexity and offers analytical tractability.

Approximation method

Based on the remaining level of the resource and their observations at the micro-scale, all agents simultaneously choose between w_i^C and w_i^D. Agents' decisions at the micro-scale modify the local cohesiveness of compliers, the share of norm-complying agents, and the severity of the social dilemma at the macro-scale. The interdependence between micro-scale and macro-scale leads to an enormous number of interrelationships, which makes the game unsuitable for both calculation and simulation, despite the correct focus on the micro-scale. This problem also led Guéant et al. (2015) to the conclusion that models where each agent considers the individual state of all other agents are unusable. To reduce the number of interrelationships, the mathematical literature suggests creating a mean field.[14] This allows approximation of the agents' interactions by portraying the contribution of each agent to the creation of the mean field and the effect of the mean field on each agent. In the context of games, the mean field is given by the probability distribution on the domain of the agents' states (Gomes et al., 2014; Guéant, 2015). In our case, agent i's state is described by a vector formed by the components, k_i, τ_{c_i}, c_i, and s. Mean-field games assume that agents know their own state and the probability distribution of the states over all other agents. The latter assumption, however, is not satisfied in our game, because agents have information about their neighborhood but not beyond. In view of this drawback, mean-field games do not seem to be a suitable approximation method for the micro-scale of our game and we need to look for alternatives.

Given the problems of a quantitative and qualitative analysis based on the agents' behavior at the micro-scale, we suggest approximating the evolution of the share of compliers and the natural resource at the macro level. More precisely, in the spirit of the mean field and in accordance with Assumption A2, we propose to approximate the state of each agent by the expected state of all agents. Our approach employs two features that allow us to study evolutionary games on complex networks in quantitative and qualitative terms; to the best of our knowledge, these features have not been studied before. The first is a judicious simplification and abstraction of the agents' interaction. The proposed modeling approach is probably the simplest representation of an evolutionary game on a complex network that still incorporates most critical features of the game. The second feature is that we replace the number of interactions among agents who have different states by interaction of agents who all have the same states. Thus, the modeling approach reduces a system of partial differential equations of a classical mean field game to a system of two ordinary differential equations. Based on this approximation method, the proposed framework allows for the study of the scope of cooperation and the design of optimal policies for networks of different types and sizes. In particular, it offers the possibility of obtaining quantitative and qualitative results that allow us to evaluate a diversity of realistic contexts by varying the corresponding parameters of the model. For this purpose, we approximate the components c_i, k_i, by their corresponding expected values, $E[c_i] \equiv c$,

$E[k_i] \equiv k$, and τ_{c_i} by τc^2 where $E[\tau_i] \equiv \tau$. The approximation method and the evaluation of its accuracy are presented in more detail in Online Appendix E in Data S1.

System dynamics

As a result of the approximation, the evolution of cooperation can be expressed as

$$\frac{\partial c}{\partial t} \equiv \dot{c} = c\left(U^C - U\right) = c\left(U^C - \left(cU^C + (1-c)U^D\right)\right) = c(1-c)\left(U^C - U^D\right), \tag{6}$$

where $U = (1/n)\sum_{i=1}^{n} U_i$ denotes the average utility of all agents. According to Equations (1) and (2), Equation (6) can be rewritten as follows

$$\dot{c} = c(1-c)\left(\left(\pi^C - \pi^D\right) + \widehat{\omega} + \widehat{\theta} - \widehat{\gamma}\right), \tag{7}$$

where $\widehat{\omega} = \widehat{\omega}(c, \tau c^2, s)$ denotes the approximated social pressure function ω_i, $\widehat{\gamma} = \widehat{\gamma}(c,k)$ the approximated sanctioning costs function γ_i, and $\widehat{\theta}$ the average per capita subsidy or fine. To facilitate the interpretation of Equation (7), we choose the defectors' extra benefits, $\pi^D - \pi^C$, as a reference point that we normalize to one. Thus, dividing Equation (7) by $\pi^D - \pi^C$ yields

$$\dot{c} = \left(\widehat{\omega} - 1 + \widehat{\theta} - \widehat{\gamma}\right)c(1-c). \tag{8}$$

Because the interpretation of the functions $\dot{c}$, $\widehat{\omega}$, $\widehat{\theta}$, and $\widehat{\gamma}$ remains unchanged, we maintain their notations to reduce the notational burden of the study. Equation (8) shows that cooperation increases if social pressure is higher than the sum of the defectors' extra benefits, legal enforcement in the form of a fine or subsidy, and the sanctioning costs, that is, $\widehat{\omega} \geq 1 - \widehat{\theta} + \widehat{\gamma}$. The term $c(1-c)$ relates to the interaction rate between compliers and defectors, and fine tunes the changes in the speed of the evolution of cooperation. It is at its maximum when $c = 0.5$. The degree of cooperation affects the evolution of the stock, which is described by

$$\frac{\partial s}{\partial t} \equiv \dot{s} = R(s) - (1-\psi)\left(\sum_{i=1}^{cn} w_i^C(s) + \sum_{j=cn+1}^{n} w_j^D(s)\right) = R(s) - (1-\psi)\left(cnw_i^C(s) + (1-c)nw_j^D(s)\right), \tag{9}$$

where the parameter ψ denotes the share of the extracted water used for irrigation that percolates back to the aquifer. The growth rate of the resource $R(s) \in \mathbb{R}_{\geq 0}$ could be stock dependent, as it is for forests or fisheries, or it could be constant, for instance indicating the average annual precipitation of an aquifer where $R(s) \equiv R_{fix} \in \mathbb{R}_{\geq 0}$.

Definitions 1 and 2 below characterize steady states and the socially optimal and socially second-best solutions of the game respectively. The stability of steady states is analyzed in the next section.

Definition 1. (Equilibrium conditions): The stationary values of the bioeconomic system are denoted by c^* and s^* respectively. A steady state of this system is obtained when c^* and s^* exist, and it holds that $\dot{s} = \dot{c} = 0$

The dynamics of the bioeconomic system are governed exclusively by $\dot{c}$ and $\dot{s}$. According to Equations (8) and (9), a steady state is characterized by $R(s^*) = (1-\psi)\left(cnw_i^C(s^*) + (1-c)nw_j^D(s^*)\right)$

and $c = 0$, $c = 1$, or $\widehat{\omega} = 1 - \widehat{\theta} + \widehat{\gamma}$. The values $c^* = \underline{c} = 0$ (lower), $c^* = \widetilde{c} \in (0,1)$ (interior), and $c^* = \overline{c} = 1$ (upper) comply with $\dot{c} = 0$, and s^* with $\dot{s} = 0$. The all-complier steady state (full cooperation) is achieved when $c^* = \overline{c} = 1$, and the all-defector steady state is achieved when $c^* = \underline{c} = 0$. An interior steady state (partial cooperation) is reached if $\widehat{\omega}\left(\widetilde{c}, \tau\widetilde{c}^2, s\right) = 1 - \widehat{\theta} + \widehat{\gamma}(k, \widetilde{c})$ and $\dot{s} = 0$.

Definition 2. (Socially optimal and socially second-best solutions): The socially optimal solution of the game is the stable all-complier steady state, $c^* = c_T = 1$. Because $w_i^C(s)$ defines the socially optimal extraction, it guarantees that $0 < s_0 < s^* = s_T \leq s_{\max}$ when $0 < c_0 < c^* = c_T = 1$. In other words, the point $(c^* = \overline{c} = 1, s^*)$ exists. However, if the socially optimal solution cannot be reached, there may exist a socially second-best solution defined by $0 < c^* = c_T < 1$ and $0 < s^* = s_T < s_{\max}$.

The $\dot{c}, \dot{s}$ nullclines lead to the definitions of a "frontier line" and "border line" in the next section. The set of possible locations of the frontier lines allows us to determine the minimum and maximum influence social networks have on equilibrium outcomes and cooperation. This information is highly relevant for public policy design because it permits policymakers to compare the effectiveness of legal and informal enforcement policies.

3.5 | Stock and network effects

We first examine how changes in the stock of the resource and/or in the characteristics of the network affect the dynamics of cooperation. Next, we introduce the concepts of "frontier line" and "border line" to analyze equilibrium outcomes and the existence of second-best solutions. Finally, we characterize the conditions under which informal and legal enforcement policies are available to policymakers and may be best applied.

Stock effects

The effects on cooperation of the remaining amount of stock are observed in Equations (8) and (9). Because compliers extract less than defectors, the future amount of stock is better conserved when there are more compliers. However, if agents perceive that their extractions have only marginal effects on resource depletion and that the resource is abundant, they may be less committed to exerting pressure on defectors. Hence, the assumption $\widehat{\omega}_s < 0$ counteracts the better conservation of the future amount of the stock resulting from an increase in c and/or τ_c. Consequently, the sign of $\dot{c}$ in Equation (8) cannot be determined unambiguously when $\widehat{\omega}_s < 0$. Otherwise, when $\widehat{\omega}_s = 0$, cooperation spreads unambiguously with an increase in c and/or in τ_c. The importance of the remaining stock for sustaining cooperation, even if the share of compliers is high, is formalized in Proposition 3.

Network effects

We approximate expected local cohesiveness among compliers by $\tau_c \simeq \tau c^2$, as in Goetz and Marco (2022), Theorem 2. Because $c \in [0,1]$, the inequality $\tau c^2 \leq \tau$ holds for networks of any topology and size, and we only need to compute τ to determine the maximum and minimum influence that τ_c has on promoting cooperation. We focus on three representative network topologies: complete networks (CN), sparse random networks (RN), and real-world social networks (SN). They differ greatly in the value of τ. The topology of CN represents the upper limits of τ_c, because all compliers are linked and can coordinate actions, such that $\tau = 1$. The topologies of RN and SN are characterized by many possible network configurations. However, the interval of τ is much larger in SN than in RN because agents in SN tend to form cliques, and links within and among cliques are facilitated by agents with the highest degree. Usually, RN topologies emerge in situations where agents initially do not know each other, for example, when a new community is being formed. In RN, the agents' degrees and cohesiveness are similarily low. Therefore, RN topologies represent the lower limits of τ_c, because coordination among compliers is extremely restricted when $\tau \approx 0$. In contrast, the wide variety of possible values of $\tau \in [0, 0.8]$ in SN (Goetz and Marco, 2022) opens the door to designing network-oriented policies that aim to increase social pressure by increasing τ.

The effects that social networks have on cooperation are observed in Equation (8). The dynamics of the bioeconomic system may give rise to positive feedback loops with respect to cooperation because an increase in c or τ leads to an increase in social pressure, $\widehat{\omega}_c > 0$ and $\widehat{\omega}_{\tau_c} > 0$,[15] if the marginal sanctioning costs, $\widehat{\gamma}_c \gtreqless 0$, are less than the marginal social pressure with respect to c. Similar cause–effect relationships of social networks have been found in empirical studies (Bursztyn & Jensen, 2017), showing that the propagation and prevalence of a social norm is not only the result of reiterated interactions between two agents; rather, it comes from reiterated social interaction patterns among many different agents.

Frontier and border lines

Although the solutions $\underline{c}$ and $\overline{c}$ of the nullcline $\dot{c} = 0$ are straightforward, the interior solutions of the nullcline are more intriguing, because $\widehat{\omega}\left(\widetilde{c}, \tau\widetilde{c}^2, s\right) = 1 - \widehat{\theta} + \widehat{\gamma}(k, \widetilde{c})$ presents the cases where agents are on average indifferent between compliance and non-compliance. Thus, the solution of $\dot{c} = 0$ presents a frontier line for the agents' choices and the nullcline $\dot{s} = 0$ the border line between resource depletion and resource replenishment.

The following definition determines all possible locations of the frontier lines in the c,s-plane.

Definition 3. (Set of frontier lines): The set $\mathscr{F} = \bigcup_{\tau \in [0,1]} \mathcal{F}_\tau$, where $\mathcal{F}_\tau = \left\{c, s \in \mathbb{R}^2_{\geq 0} \,|\, \widehat{\omega}(c, \tau c^2, s) - 1 + \widehat{\theta} - \widehat{\gamma}(k, c) = 0\right\}$, defines the area with all possible frontier lines in the c,s-plane. Its cardinality is denoted by $|\mathscr{F}|$. The elements of the set $\mathscr{F}$ are the different sets $\mathcal{F}_\tau$.

The frontier lines with the minimum and maximum τ are given by $\mathcal{F}_{\tau=0}$ and $\mathcal{F}_{\tau=1}$ respectively. For any given s, fewer compliers are necessary to attain the social pressure where $\widehat{\omega}(c, \tau c^2, s) - 1 + \widehat{\theta} - \widehat{\gamma}(k, c) = 0$ if the strength of cohesiveness increases. Thus, the frontier line shifts to the left in the c,s-plane with an increase in τ, so that $\mathcal{F}_{\tau=1}$ is to the left of $\mathcal{F}_{\tau=0}$. In this way, the sets $\mathcal{F}_{\tau=1}$ and $\mathcal{F}_{\tau=0}$ determine the maximum and minimum influence that the type of social network has on cooperation, that is, the frontier lines of RN topologies constitute the right-hand-side boundary of set $\mathscr{F}$, whereas the frontier lines of CN topologies constitute its left-hand-side boundary.

In the following proposition, we show that any second-best solution, if it exists, is always located in the area of network influence where $(c^* = \widetilde{c}, s^*) \in \mathscr{F}$ holds. The frontier line and the border line can be upward or downward sloping. For the sake of concreteness, we concentrate on the case where the border line is upward sloping, and the frontier line is either upward or downward sloping. The case where the border line is downward sloping can be analyzed within this framework; however, it is not discussed here because it does not offer new qualitative insights.[16]

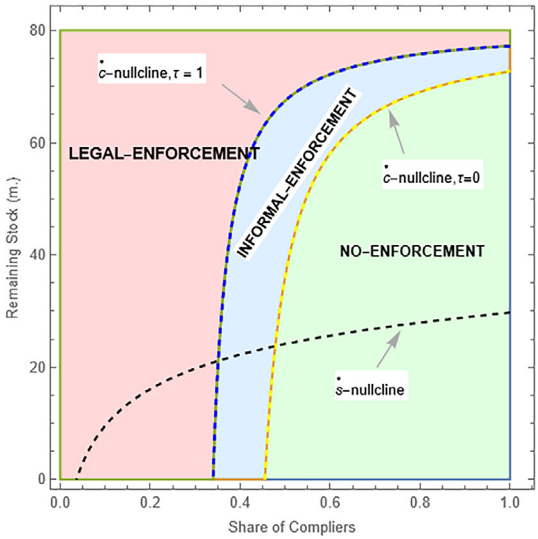

FIGURE 1 Basins of attraction of equilibrium points and the availability of enforcement policies when social pressure is costless. Parameter values refer to Baseline 1 of Table 1 below.

> **Proposition 1.** *(Social networks and second-best): The size of set $\mathscr{F}$ not only determines the maximum and minimum influence of the type of social network on cooperation and equilibrium outcomes but also the possible location of second-best solutions.*

Proof: See Appendix A. For an illustration see also Figure 1 of the following section.

Proposition 1 states that the set $\mathscr{F}$ contains all cases where interior stationary values of the share of compliers exist, and, thus, it also includes all possible interior equilibria of the bioeconomic system where compliers and defectors coexist. As shown in Proposition E1 of Online Appendix E in Data S1, the approximation errors of the functions $\widehat{\omega}$ and $\widehat{\gamma}$ are zero in the case of $\mathscr{F}_{\tau=1}$ (CN topology) and close to zero in the case of $\mathscr{F}_{\tau=0}$ (RN topology). If, additionally, the share of compliers tends toward zero or one, the approximation errors are also zero for the case of $\mathscr{F}_{\tau=0}$. Thus, for any social network, the determination of the boundary elements of the set $\mathscr{F}$ and the location of the area of the network influence can be determined with minimal error. In contrast, the location of second-best solutions, $(c^* = \widetilde{c}, s^*) \in \mathscr{F}$, may vary when the components of the state vectors are highly unevenly distributed so that the approximation is less accurate.

Stability of interior steady states

With respect to the qualitative characteristics of an interior steady state, we find that its stability depends on the sign and slope of the frontier and border line as defined in the next proposition.

> **Proposition 2.** *(Stability of interior steady state): The bioeconomic system is characterized, Part (a), by a sink (attractor) if the frontier line at the steady state $(c^* = \widetilde{c}, s^*)$ is downward sloping and the border line is upward sloping; and, Part (b), by a saddle if the frontier line and border line at the steady state are upward sloping but the slope of the frontier line is greater than the slope of the border line.*

Proof: See Appendix B. For an illustration see also Figure 2 in the following section.

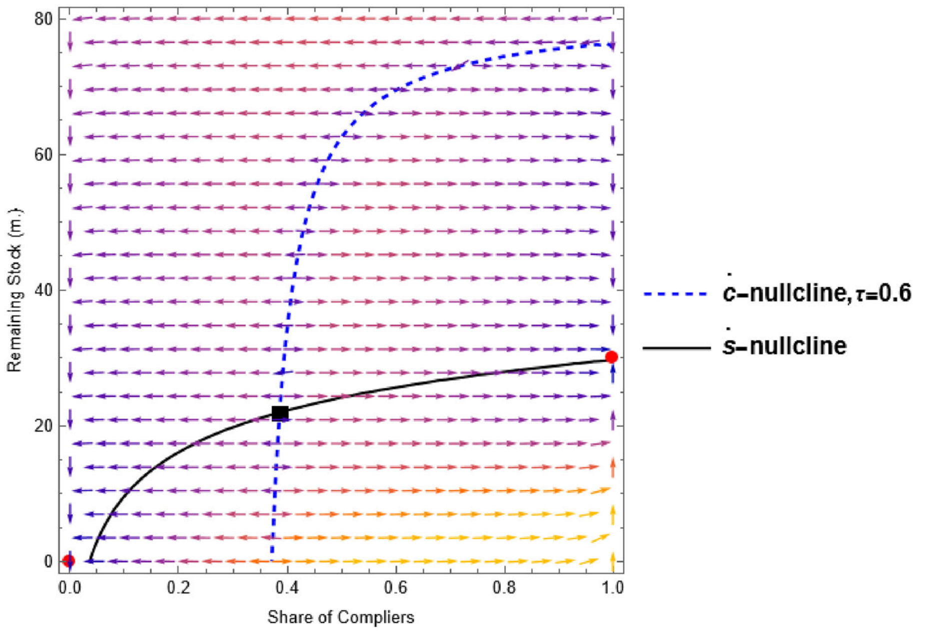

FIGURE 2 Phase diagram of the bioeconomic system, nullclines and steady states in the absence of policy interventions and sanctioning costs. Parameter values: Baseline 1 of Table 1 with $\tau = 0.6$.

For Part (a) of Proposition 2, Appendix B shows that the frontier line is downward sloping only if social pressure is costly and its marginal costs are sufficiently high, that is, high marginal costs of social pressure favor a second-best steady state in the form of a sink. For Part (b) of Proposition 2, Appendix B shows that the frontier line is upward sloping if the social pressure function is more responsive to an increase in the share of compliers than to the sanctioning costs. This is always the case if sanctioning costs are either fixed or barely responsive to an increase in the share of compliers. Thus, social pressure that varies significantly with an increase in the share of compliers favors a second-best steady state in the form of a saddle.[17] In summary, our results indicate that one of two conditions is necessary for second-best solutions to emerge. One option is that the sanctioning costs vary with the share of compliers; the alternative is that changes in the remaining stock have a minor influence on the growth rate of the stock.

Note that the frontier line ($\mathbb{R}^2$) presents a generalization of the concept of a social tipping point ($\mathbb{R}^1$), which depends on the share of compliers but not on the stock or the type of social network (Barrett & Dannenberg, 2017; Nyborg, 2020). This leads to the following observation.

> *Observation* 1. (Social tipping points): Social tipping points as a function of the share of compliers emerge as special cases of frontier lines when there is either no stock or the level of the stock is constant over time and links between compliers are not considered.

Because the structure of the underlying social network and/or stock effects can play a crucial role in promoting cooperation (Hilbe, Chatterjee, & Nowak, 2018; Hilbe, Šimsa, et al., 2018), social tipping points as a function of the share of compliers are unlikely to identify critical transitions between cooperation and non-cooperation in bioeconomic systems. Thus, the concept of frontier lines can be seen as a generalization of the concept of social tipping points.

Basins of attractions and policy options

Consistent with Definition 2, we identify the policies and conditions that best favor cooperation among agents. We define the basins of attraction for the all-defector and all-complier equilibria that allow us to distinguish between the three policy corridors available to policymakers. The policy options themselves are discussed in the following section.

Definition 4. (Basins of attraction): For any given network the sets $\mathcal{R} = \bigcup_{\tau \in [0,1]} \mathcal{R}_\tau$, where $\mathcal{R}_\tau = \left\{c,s \in \mathbb{R}^2_{\geq 0} | \widehat{\omega}(c,\tau c^2,s) - 1 + \widehat{\theta} - \widehat{\gamma}(k,c) < 0 \wedge c < 1\right\}$; and $\mathcal{G} = \bigcup_{\tau \in [0,1]} \mathcal{G}_\tau$, where $\mathcal{G}_\tau = \left\{c,s \in \mathbb{R}^2_{\geq 0} | \widehat{\omega}(c,\tau c^2,s) - 1 + \widehat{\theta} - \widehat{\gamma}(k,c) > 0 \wedge c > 0\right\}$, define $\mathcal{R}$ and $\mathcal{G}$ as the basins of attraction for the all-defector and the all-complier equilibrium respectively.[18]

We briefly characterize the three policy corridors available to policymakers.

No-enforcement corridor

This is independent of the type of social network. Initial values of c and s located in set $\mathcal{G}_{\tau=0}$ indicate that the stable equilibrium outcome is independent of any type of social network because the social norm and social pressure are sufficient for reaching the all-complier equilibrium. For this reason, we refer to this set as the "no-enforcement" corridor.

Informal-enforcement corridor

This depends on the type of social network. Because the set $\mathcal{F}$ depends on the value of τ, it defines the lower and upper limits of network-oriented policies. The objective of informal enforcement policies is to strengthen τ_c by increasing τ and thereby reducing the minimum share of compliers necessary to effectively promote the social norm. For this reason, we refer to set $\mathcal{F}$ as the "network-policy" or "informal-enforcement" corridor with size $|\mathcal{F}|$.

Legal-enforcement corridor

This is completely independent of social interactions. The equilibrium outcome for initial values of c and s located in $\mathcal{R}_{\tau=1}$ corresponds to the all-defector equilibrium. The socially optimal extraction has not been sufficiently accepted within the community and therefore informal enforcement policies will not work. The regulator is only left with the option of legal enforcement, either in the form of direct regulation or economic incentives. For this reason, we refer to the set $\mathcal{R}_{\tau=1}$ as the "legal-enforcement" corridor. The objective of legal enforcement is to strengthen norm compliance by increasing the share of compliers.

The definition of the policy corridors allows us to identify situations when even a very high share of compliers is not sufficient for avoiding the all-defector equilibrium. This finding is summarized in the following proposition.

Proposition 3. *(Severity of the social dilemma):* If $s_{\max} \notin \mathcal{F}_\tau$, $\mathcal{F}_\tau$ *is upward sloping and any* $c < 1$ *forms part of the set* $\left\{c,s \in \mathbb{R}^2_{\geq 0} | (c,s) \in \mathcal{R}_\tau\right\}$, *then any share of compliers except* $c = 1$ *is insufficient for guaranteeing sustained cooperation.*[19]

Proof: See Appendix C.

Proposition 3 shows that resource abundance may lead to insufficient social pressure that cannot be compensated by a high share of compliers. In this case, the all-defector equilibrium cannot be avoided. This situation is relevant for policy design. It may occur when the frontier line does not include the value of $s_{\max}$, and, therefore, agents consider that social pressure is not necessary while the stock of the resource is above a certain threshold level but fail to agree upon this level (Biel & Gärling, 1995). Even though agents are aware of the consequences, non-compliance is likely to outweigh compliance when agents perceive the scarcity of the resource as not severe. For example, the high share of compliers that does not support the socially optimal solution is situated in the upper right corner, as illustrated in Figures 2 and 4. The latter case may occur when agents are not fully informed about the consequences of a poor state of the resource. To overcome this misperception of scarcity, regulators could strengthen extension services and/or improve educational efforts for reaching out to the agents.

4 | POLICY DESIGN

In this section, we illustrate available policy corridors and the location and stability of steady states. The size and location of the policy corridors serve as the basis for the design of optimal enforcement policies to achieve first- and second-best policy options. The sensitivity of interior equilibria/locations of the frontier line with respect to changes in the parameter values is analyzed at the end of this section.

For this purpose, we analyze and design policy instruments for the management of an aquifer, taking into account social interactions among the farmers in a water user association. As detailed in Online Appendix F in Data S1, the functions employed for the simulations of the bioeconomic model, $\pi_i^C(s), \pi_i^D(s), w_i^C(s)$, and $w_i^D(s)$, are obtained from the solution of a mathematical optimization model written in GAMS® and a subsequent econometric analysis of the output of the GAMS model. The required agronomic, economic, and hydrological input data for the model were obtained from published data about the Western La Mancha Aquifer in Spain and are explained in detail in Online Appendix F in Data S1.

The constant overdraft of this aquifer has led to a variety of policy measures designed to curb its deterioration and comply with the European Union Water Framework Directive (Blanco-Gutiérrez et al., 2011; European Comission, 2000). The remaining stock s is quantified by the distance (measured in meters) between the bottom of the well and the water table. The Western La Mancha Aquifer is fed naturally, and we assume that the recharge is constant, that is, the term $R(s(t))$ is equal to $R_{fix} \in \mathbb{R}_{>0}$. Because the extraction is measured in m^3 (cubic meters) and the depth of the water table in m (meters), we need to adapt Equation (9) by introducing the conversion factor $\mu \in \mathbb{R}_{>0}$, which expresses the change in the depth of the water table as a result of the water extraction. Moreover, some of the water extracted for irrigation percolates back into the aquifer. Following Esteban and Albiac (2010, 2011), we set this percolation rate, $\psi \in \mathbb{R}_{>0}$, equal to 20%. Thus, the dynamics of the natural resource can be written as

$$\dot{s} = \mu\left(R - (1-\psi)\left(\sum_{i=1}^{cn} w_j^C(s) + \sum_{j=cn+1}^{n} w_j^D(s)\right)\right). \tag{10}$$

The approximated social pressure function $\widehat{\omega}$ is specified as a logistic function given by $\widehat{\omega} = \Upsilon / \left(1 + s_{\max} e^{-(s_{\max}-s)\left(c-\left(c_f - \tau c^2\right)\right)}\right)$, where $\Upsilon = \max\{\widehat{\omega}\} = 2$ indicates the maximum social pressure. The maximum value of Υ is chosen to be twice the value of the defectors' extra benefits so that its value influences but does not dictate the outcome of the game. Significantly higher or lower values are likely to destroy the essence of the game. The maximum level of the remaining stock $s_{\max} \in \mathbb{R}_{>0}$ affects the growth rate of the social pressure function. The parameter $c_f \in (0,1)$ influences the horizontal displacement of the logistic function, that is, the minimum share of compliers at which social pressure starts to be effective (i.e., the responsiveness threshold).

Policy corridors

Based on the parameter values defined in Baseline 1 of Table 1 below (legal enforcement is absent, $\widehat{\theta} = 0$, and social pressure is costless, $\widehat{\gamma}(k,c) = 0$), Figure 1 illustrates the location of the two nullclines

($\dot{c}=0, \dot{s}=0$). In Figure 1, the area $\mathscr{R}_{\tau=1}$ is marked in red and the area $\mathcal{G}_{\tau=0}$ in green. The set $\mathscr{F}$, with size $|\mathscr{F}|$, is marked in light blue and indicates the area where the type of social network affects the outcome of the game. The boundary of this area, $\mathscr{F}_{\tau=0}$ and $\mathscr{F}_{\tau=1}$, determines the maximum and minimum influence the type of social network has on the agents' decisions and the equilibrium outcome. We consider the case where the cardinality of the set of all initial values of (c,s), $\boldsymbol{P}=|[0,s_{\max}]\times[0,1]|$, is countable and the number of pairs (c,s) is evenly distributed over the plane $[0,s_{\max}]\times[0,1]$. Under this assumption, we can express the influence of the type of network on the agents' decisions by the coefficient $\lambda\in[0,1]$ as a result of $\lambda=|\mathscr{F}|/\boldsymbol{P}$. For the case of Figure 1, λ is approximately 0.2, that is, approximately 20% of all initial values of (c,s) are located in the area of the network that influences the agents' decisions and the equilibrium outcome. As discussed in Online Appendix E.2 in Data S1, the qualitative and quantitative determination of the boundary elements of set $\mathscr{F}$ and the location of the area of network influence are associated with very small errors of the approximated functions.

Figure 1 also shows that the smaller the sets $\mathscr{R}_{\tau=1}$ and/or $\mathcal{G}_{\tau=0}$, the larger the size of the set $\mathscr{F}$, $|\mathscr{F}|$, and therefore the larger the area of network influence for policy design, $\lambda=|\mathscr{F}|/\boldsymbol{P}$.

Location and stability of equilibria

The location of each steady state (c^*,s^*) in the c,s-plane and its stability determine the optimal policy design to achieve socially optimal and socially second-best solutions. The lower and upper steady states, $\underline{c}\equiv(c^*=\underline{c},s^*)$ and $\bar{c}\equiv(c^*=\bar{c},s^*)$, are located in the sets $\mathscr{R}_{\tau=1}$ and $\mathcal{G}_{\tau=0}$ respectively, and any interior equilibrium $\widetilde{c}\equiv(c^*=\widetilde{c},s^*)$ is located in set $\mathscr{F}$. The following proposition defines the qualitative characteristics of possible equilibria.

> **Proposition 4.** *(Equilibria aquifer): When legal enforcement is absent, $\widehat{\theta}=0$, and sanctioning costs are given by $\widehat{\gamma}(k,c)=0$, the interior equlibria is given by a saddle point. When sanctioning costs are given by $\widehat{\gamma}(k,c)=\upsilon(k)(\alpha_0-\alpha_1 c+\alpha_2 c(1-c))$, there may exist up to three interior equilibria, where one is in the form of a sink and two are in the form of a saddle. The boundary steady states are stable.*

Proof: See Appendix D.

Given the limited validity of the mathematical analysis of the stability beyond the vicinity of a steady state (see Appendix B), in Figure 2 we present the phase diagram[20] for the entire c,s-plane and the two nullclines ($\dot{c}=0, \dot{s}=0$) when no enforcement policy is in place.[21] This shows that there exists a stable interior steady state, but its basin of attraction is very small. Thus, there is little chance that arbitrarily chosen initial values of c_0 and s_0, even if they are initially on the stable branch ($\dot{c}$-nullcline), belong to a path that ends up at the interior steady state. There exists a single equilibrium because the equation $\dot{c}=\widehat{\omega}(c,\tau c^2,s)-1$ changes sign only once as c increases from 0 to 1.

Figure 3 illustrates that the introduction of sanctioning costs with bell-shaped coordination costs may lead to as many as three interior steady states, signalized by a black square. The phase diagram shows that the basins of attraction of the steady states $\widetilde{c}_1,\widetilde{c}_3$ are very small, because their narrow margin does not show up in the phase diagram; this is probably because the underlying grid size of the program employed for the generation of Figure 3 is larger than the basin of attraction. Thus, it is very unlikely that the bioeconomic system starting at arbitrarily chosen values of c_0 and s_0 will end up at the interior equilibria $\widetilde{c}_1$ or $\widetilde{c}_3$. In contrast, the basin of attraction of $\widetilde{c}_2$ is larger, so the chances of reaching the second-best solution are considerably larger when $\widetilde{c}_1<c_0<\widetilde{c}_3$. The intuition for this result resides in the fact that the equation $\dot{c}=\widehat{\omega}(c,\tau c^2,s)-1+\widehat{\theta}-\widehat{\gamma}(k,c)$ changes sign more than once because the coordination costs are bell shaped, peak at the mid interval of $c\in[0,1]$ and vanish

TABLE 1 Sensitivity analysis of the interior equilibrium values of the bioeconomic model.

Name of the parameter	Parameter related with	Value of the parameters			Increase by 30%		Increase by 90%		Decrease by 30%		Decrease by 90%	
		Baseline 1: Social pressure is costless										
		Baseline values	$\tilde{c}$	s^*	$\tilde{c}$	s^*	$\tilde{c}$	s^*	$\tilde{c}$	s^*	$\tilde{c}$	s^*
1. No. of agents: n		7500			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2. Conversion factor m^3 to m: μ	Size of the aquifer	0.00000009			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3. Size of the aquifer: S_{max}	Hydrologic conditions	80			−3.82%	−1.84%	−7.69%	−3.29%	6.37%	1.84%	No equilibrium	
4. Recharge aquifer: R	Meterologic conditions	2900			No equilibrium		No equilibrium		119.54%	−45.32%	No equilibrium	
5. Percolation rate: Ψ	Irrigation technology, agricultural practices, cultivated crops	0.2			No equilibrium		No equilibrium		−2.07%	−44.90%	−3.98%	−91.19%
6. Maximal social pressure: Υ		2			1.21%	−1.75%	−3.56%	−2.14%	3.76%	0.30%	119.54%	25.61%
7. Horizontal displacement of the social pressure function: c_f	Awareness and responsiveness to the social dilemma	0.4			4.38%	8.20%	72.12%	18.33%	−25.09%	−10.76%	−78.25%	−59.99%
8. Cohesiveness of the social network: τ	Relative number of connections between neighbors	Fixed: 0,1	0.45	23.41								
9. Lower limit of the cohesivenes of the social network: τ_L		Fixed: 0	0.47	23.62								

(Continues)

TABLE 1 (Continued)

Name of the parameter	Parameter related with	Value of the parameters			Increase by 30%		Increase by 90%		Decrease by 30%		Decrease by 90%	
10. Upper limit of the cohesiveness of the social network: τ_U		Fixed: 1	0.35 (−22.34%) (−26.25%)	21.17 (−9.56%) (−10.37%)								
11. Agents' degree dependent sanctioning costs: υ	Agents' degree	Fixed: 0										
12. Defector's extra benefit + taxes/subidies: $ExtB + \theta$	Difference between private and social optimal behavior + taxes subsidies, number of agents	−1			3.08%	1.45%	11.45%	4.27%	−1.71%	−1.11%	−10.19%	−5.13%
		Baseline 2: Social pressure is costly but coordination is costless										
11. Degree dependent sanctioning costs: υ		0.62	0.46	23.5	1.50%	1.83%	3.47%	2.60%	−0.36%	−0.60%	−1.97%	−1.96%
13. Sanctioning costs: α_0	Fixed part of the sanctioning costs independent of *c*	1										
14. Sanctioning costs: α_1	Linear part of the sanctioning costs	1										
		Baseline 3: Social pressure and coordination are costly										
11. Degree dependent sanctioning costs: υ		0.62										
13. Sanctioning costs α_0		1										

TABLE 1 (Continued)

Name of the parameter	Parameter related with	Value of the parameters	Increase by 30%	Increase by 90%	Decrease by 30%	Decrease by 90%
14. Sanctioning costs α_1		1				
15. Coordination costs of sanctioning: α_2	Quadratic part of the sanctioning costs	2.5 0.48 24.01	1.91% 2.42%	15.77% 3.46%	−1.30% −0.04%	−3.74% −1.33%

The color is used to facilitate the reading of the table by making its structure more visible.

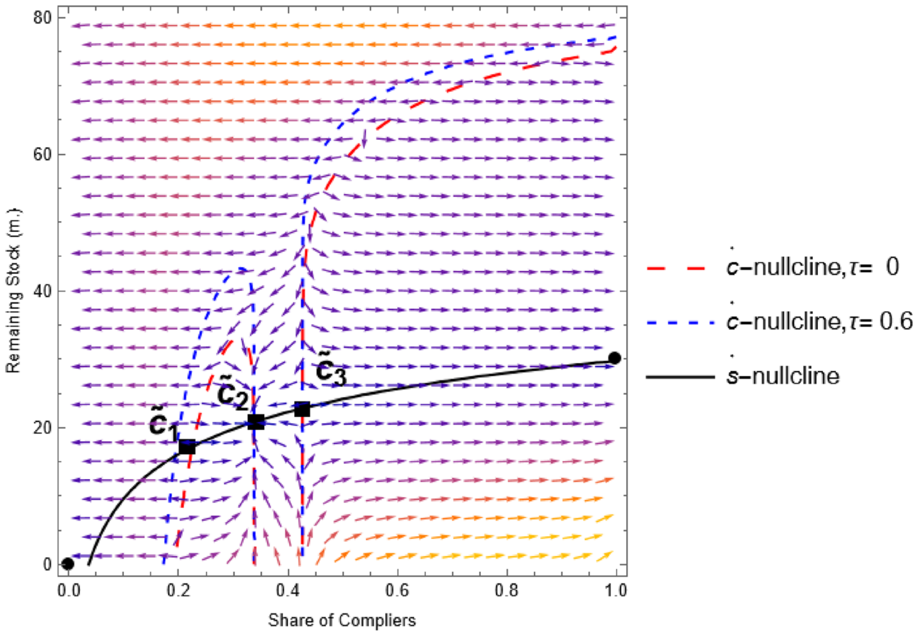

FIGURE 3 Phase diagram of the bioeconomic system, nullclines and steady states when it is costly to exercise and coordinate social pressure. Parameter values: Baseline 3 of Table 1 with $\alpha_2 = 4.25$, $c_f = 0.1$, $\tau = 0.6$.

at the boundary of the interval $c \in [0,1]$. The presence of coordination costs and the emergence of multiple equilibria lead to the following observation.

> *Observation* 2. (Subsidy of sanctioning costs): The introduction of a legal enforcement policy $\widehat{\theta}$ that completely subsidizes compliers for the costs of exerting social pressure, such that $\widehat{\theta} = \widehat{\gamma}$, may eliminate the possibility that the bioeconomic system will reach a stable second-best steady state with a large area of attraction.

The subsidization of sanctioning costs, $\widehat{\theta} = \widehat{\gamma}$ (for instance, incurred for the coordination of compliers), brings the bioeconomic system back to the case where legal enforcement and sanctioning costs are absent, with hardly any chance of achieving a stable interior steady state (see Figure 2).

First- and second-best policy options

Let us assume that, at any moment t, the current values of s and c are given by s_t and c_t, and the expected cohesiveness of the underlying social network is given by $\tau^* \in (0,1]$. Policy options in the form of legal and informal enforcement are available if s_t and c_t are elements of the set $\mathscr{F}_{\tau<\tau^*}$ that form part of the area marked in light blue in Figure 1. This set consists of all frontier lines where $\tau < \tau^*$ —and consequently the point—(c_t, s_t) are to the left of the frontier line with $\tau = \tau^*$. Therefore, the socially optimal solution cannot be achieved. Instead, the bioeconomic system tends to the all-defector equilibrium. This section designs different policy options to achieve the socially optimal solution.

Legal enforcement

Legal enforcement aims to increase the number of compliers. For an arbitrarily small $\varepsilon > 0$, policymakers can employ legal enforcement so that the share of compliers increases from c_t to

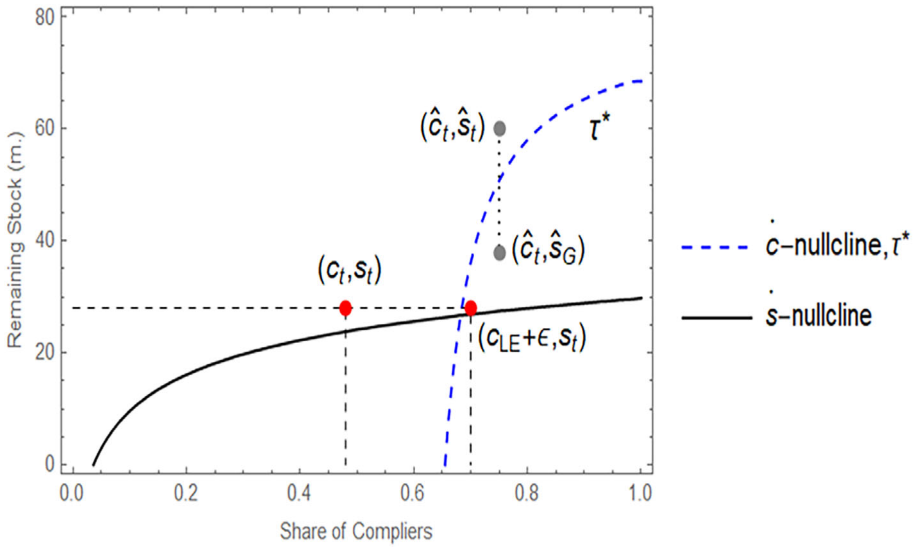

FIGURE 4 Legal enforcement by imposing a fine on $c_{LE} + \varepsilon - c_t$ defectors

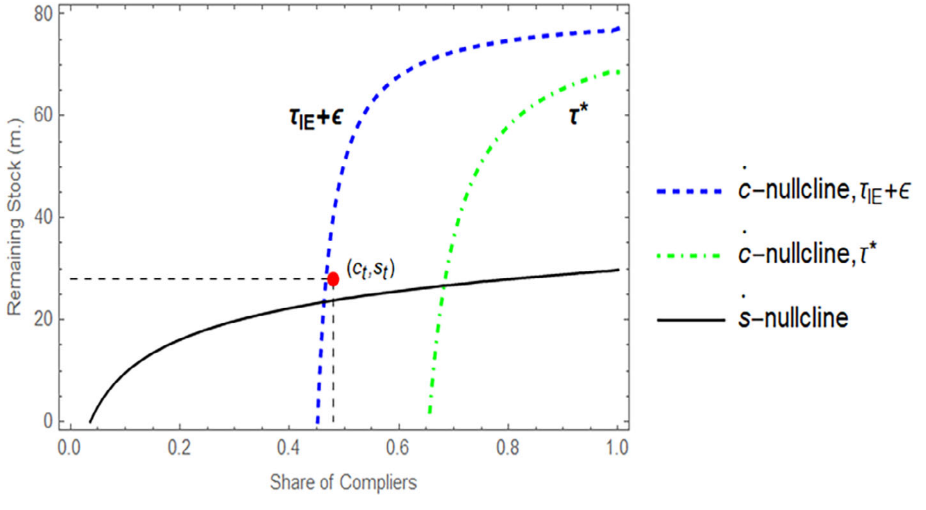

FIGURE 5 Informal enforcement by strengthening the expected cohesiveness beyond τ_{IE}

$c_{LE} + \varepsilon$, where $c_{LE} \in \mathscr{F}_{\tau^*} = \left\{ c, s_t \in \mathbb{R}^2_{\geq 0} \middle| \widehat{\omega}(c, \tau^* c^2, s_t) - 1 + \widehat{\theta} - \widehat{\gamma}(k, c) = 0 \right\}$, that is, the frontier line that has an expected cohesiveness of τ^* and passes through the point (c_{LE}, s_t). If the share of compliers is equal to $c_{LE} + \varepsilon$, Figure 4 shows that the point $(c_{LE} + \varepsilon, s_t)$ is to the right of the frontier line $\mathscr{F}_{\tau=\tau^*}$ and the bioeconomic system tends to the all-complier equilibrium. Legal enforcement is effective if the regulator has detected at least $c_{LE} + \varepsilon - c_t$ defectors. Imposing a fine on this number of defectors opens the pathway for the socially optimal solution. This example clearly demonstrates that it is not necessary to fine all defectors if social pressure is present. It is only necessary to fine the number of defectors that are missing to reach the basin of attraction of the all-complier equilibrium. For the case depicted in Figure 4, the missing number of defectors is slightly less than 50% of all defectors. This percentage varies with the initial share of compliers and the location of the frontier line. Thus, the presence of social pressure allows the social planner to design less stringent enforcement policies compared to the situation when social networks and social pressure are not considered.

Informal enforcement

Alternatively, policymakers can resort to informal enforcement that raises the expected cohesiveness from τ^* to $\tau_{IE}+\varepsilon \le 1$ with $\tau_{IE} > \tau^*$ and $\varepsilon > 0$. We denote the frontier line with $\tau = \tau_{IE}$ that passes through the point (c_t, s_t) by $\mathscr{F}_{\tau=\tau_{IE}}$. A further but arbitrarily small increase of the expected local cohesiveness by ε yields the frontier line $\mathscr{F}_{\tau=\tau_{IE}+\varepsilon}$ that is located to the left of the frontier line $\mathscr{F}_{\tau=\tau_{IE}}$. Consequently, as shown in Figure 5, the point (c_t, s_t) is to the right of the frontier line $\mathscr{F}_{\tau=\tau_{IE}+\varepsilon}$ and the bioeconomic system tends to the all-complier equilibrium.

Apart from legal-only or informal-only enforcement policies, regulators can modify these approaches, for example, by restricting the access to the resource (e.g., seasonal or regional restrictions) or by employing a mix of legal and informal enforcement policies. These policies are presented in Online Appendix G in Data S1.

In the previous paragraphs, we analyzed the design of socially optimal legal and informal enforcement policies. However, they require that the regulator or the community is able to identify neighborhoods where a small increase in c causes defectors to switch from defection (D) to norm-compliance (C). The increase in c is even more effective if the agent who switches from D to C has a high degree. Most likely, the regulator has no precise information about the underlying network structure and agents' choices (C or D). In this case, the regulator cannot select neighborhoods based on the values of c and τ. Yet, either economic or non-economic incentives may induce agents to reveal their choices. With this additional information, the regulator can target geographic zones as a surrogate for neighborhoods where the number of compliers is only slightly less than the number of defectors. All other geographic zones may be neglected. Because the community has information about the structure of the social network and the numbers of compliers and defectors, it can focus on neighborhoods where the number of compliers is slightly less than the number of defectors.

Sensitivity analysis

Table 1 presents changes in the values of the interior equilibrium, $(\widetilde{c}, s^*)$, as a result of an increase/decrease by 30% and 90% of a single parameter value of the Baselines 1, 2 and 3. Baseline 1 considers the case when social pressure is costless, Baseline 2 when social pressure is costly but coordination not and Baseline 3 when social pressure and coordination are costly. Changes in the parameter values are important because changes in the location of the interior equilibrium indicate changes in the location of the frontier line, which imply changes in the area of attraction of the all-complier equilibrium.

For Baseline 1, the results show that the number of agents (Parameter 1 in Table 1) has no direct influence on possible equilibria, because the data were calibrated per hectare (ha) and every agent has exactly one ha. In other words, changes in the number of agents are equivalent to changes in the scale, but they do not change the availability of water and the agents' water demand. Nevertheless, the model allows us to evaluate changes in the number of agents indirectly. As the number of agents decreases, each agent's share of the costs of the externalities related to groundwater extraction increases. This implies that the lower the number of agents, the smaller is the difference between the privately and socially optimal behavior.[22] In other words, the defector's extra benefits decrease. Hence, the variation of Parameter 12 of Table 1 shows that an increase/decrease in the defectors' extra benefits leads to an increase/decrease in the equilibrium values of c and s, $(\widetilde{c}, s^*)$, at the lower end of the one-digit percentage range. If the change in the extra benefits is very substantial (90%), the change in $\widetilde{c}$ is at the lower end of the two-digit percentage range, whereas the change in s^* is still in the one-digit percentage range.

This implies that changes in the number of agents have a significant influence on the outcome of cooperative behavior only if the number of agents is reduced drastically. Otherwise, the influence of changes in the number of agents is of minor importance. Equation (8) shows that the imposition of fines or the payment of subsidies is equivalent to a change in the defector's extra benefits. Thus, we can analyze the effect of different fines/subsidies on the values of $(\widetilde{c}, s^*)$. Given some initial values of c and s, (c_0, s_0), located within the basin of attraction of the all-defector equilibrium, the calculated changes in the values of $(\widetilde{c}, s^*)$ are very helpful for determining the magnitude of the fine or subsidy that is required so that the newly resulting equilibrium values are located within the basin of attraction of the all-complier equilibrium. Parameters 2–5 are related to the hydrological conditions of the aquifer. Like the number of agents n, the conversion factor μ (Parameter 2) is a scaling factor and has no direct influence on the location of the interior equilibrium. The conversion factor does not influence the interior equilibrium condition because changes in μ affect recharge/ha and the average farmers' water demand/ha equally, that is, their equivalence is maintained. However, one would expect that a higher conversion factor leads to a faster drawdown of the water table, which in turn affects the location of the interior equilibrium. Similarly to the change in the conversion factor, one can think of a smaller size of the aquifer as being responsible for a faster drawdown. In this respect, we can analyze the effect of changes in the conversion factor on the location of the equilibrium by varying the size $s_{\max}$ (Parameter 3) of the aquifer. Table 1 shows that variations of $s_{\max}$ have a minor impact on the value of s^* and a higher effect on $\widetilde{c}$, but their impact is always in the lower or middle one-digit percentage range. If $s_{\max}$ decreases by 90%, the two nullclines do not intersect and consequently the existence of any type of equilibrium can be ruled out. Similarly, for changes in the recharge R (Parameter 4), we observe that interior equilibria exist for very small variations of R, but an increase/decrease of 30% or more is not compatible with interior or boundary equilibria. A decrease of 30% of R results in an all-complier equilibrium where the share of compliers is 1 (an increase in 119% compared to Baseline 1) and the stock decreases to 12.6 m (a decrease by 45.32%.). The results of increases in the percolation rate ψ (Parameter 5) are similar to those of increases in recharge R. Yet, for decreases in ψ, we find that interior equilibria exist even for a 90% decrease in the percolation rate. For the existing interior equilibria, Table 1 shows that increases in R or decreases in ψ have a significantly greater effect on the values of s^* than on the values of $\widetilde{c}$. Reduced percolation rates are associated with the application of improved irrigation technologies, as they reduce the waste or ineffective use of water. Thus, promoting water-saving technologies has a slightly positive influence on cooperation and a significant impact on the water table.[23]

The relatively small effects of changes in R or ψ on the value of the existing $\widetilde{c}$ suggest that policies promoting water-saving irrigation technologies, best agricultural management practices, or crop choice have a high impact on the water table of the aquifer but a modest effect on cooperation.

Parameters 6–8 are related to the strength of social pressure. Variations of the maximum value of social pressure, Υ (Parameter 6), lead to changes in the equilibria values at the lower end of the one-digit percent range. However, if Υ decreases by 90%, an interior equilibrium does not exist for values of Baseline 1. In contrast, variations in the responsiveness threshold, c_f (Parameter 7), have a great effect on the location of the values of $\widetilde{c}$ and s^*; at the maximum, the effect is at the higher end of the two-digit percentage range for $\widetilde{c}$ and is substantially lower for s^*. This finding underlines the importance of public awareness of the social dilemma because it is the prerequisite for farmers to exercise social pressure. Public awareness campaigns may move an existing or establish a new reference point of the socially desirable state of the resource. This newly established point may lead to a lower responsiveness threshold c_f and to higher social pressure even when the share of compliers is low. Similarly, variations of cohesiveness, τ (Parameter 8), have significant effects on the location of the values of $\widetilde{c}$ and s^*. An increase in cohesiveness from $\tau = 0.1$ to $\tau = 1$ reduces the critical mass of compliers to reach the greatest lower bound (infimum) of the basin of attraction of the all-complier equilibrium. It reduces the critical mass from 0.45 to 0.35 (22%) and the corresponding stock from 23.4 m to 21.1 m (−9.56%). If we take the value of $\tau = 0$ instead of $\tau = 0.1$ (Parameter 10) as a starting point, the value of $\widetilde{c}$ decreases from 0.47 to 0.35 (−26%) and the value of s^* from 23.62 m to

21.17 m (−10.3%). In other words, the influence of the type of network has an upper limit of 26% on the reduction of the critical mass of compliers. These results underline the importance of network-oriented enforcement policies.[24] The regulator, the president of a water user association, or the compliers themselves may take the initiative to design these policies with the objective of increasing cohesiveness, which translates directly into an increase in social pressure (for example the foundation of a complier associations, NGO, or the organization of field days). Moreover, within the set $\mathscr{F}$, network-oriented policies may be complemented or substituted by legal enforcement policies.

However, there are social networks where cohesiveness is inherently low, and policies aiming to increase cohesiveness may show little effect (Goetz & Marco, 2022). Instead, policymakers may employ policies that aim to augment the responsiveness threshold, c_f. However, the sensitivity analysis shows that the size of the informal enforcement sector $|\mathscr{F}|$ decreases with lower values of the responsiveness threshold (not shown in Table 1). A decrease in the responsiveness threshold simply says that compliers start pressuring defectors even when the share of compliers is low. Yet, cohesiveness of compliers depends on the share of compliers. The lower the share of compliers, the lower is the maximal level of cohesiveness of compliers. Thus, for low shares of compliers, the difference between no cohesiveness ($\tau = 0$) and the possible maximal cohesiveness is small, that is, the informal enforcement corridor in Figure 1 is small. Consequently, the effectiveness of informal policies is limited by the size of the informal corridor $|\mathscr{F}|$. Given the negative side effects of policies related to c_f on informal enforcement policies, policymakers will have to carefully fine tune the dose of each policy.

In Baseline 2, we consider affine-linear sanctioning costs (parameters 13 and 14) in c, with $\alpha_0 = \alpha_1 = 1$ and zero compliers' coordination costs. To analyze the influence of the agent's degree, we vary the parameter 11, that is, the agents' degree-dependent sanctioning costs, υ. Otherwise, we maintain the parameter values of Baseline 1. The variations of υ show that their effect on the values of $\widetilde{c}$ and s^* is at the lower end of the one-digit percentage range. This suggests that an increase in the agent's degree is of minor importance.[25] However, if the additional number of links leads to more cohesiveness, the effect of an increase in degree is substantial and has to be evaluated together with the resulting changes in cohesiveness (Parameter 8).

Finally, in Baseline 3, we introduce coordination costs (Parameter 15) with a starting value of $\alpha_2 = 2.5$. Otherwise, we maintain the parameter values of Baseline 2. Variations in the coordination costs show that they usually affect the values of $\widetilde{c}$ and s^* at the lower end of the one-digit percentage range. Only if α_2 is above 4.1 (increase by 64%) are the changes in the value of $\widetilde{c}$ at the lower end of the two-digit percentage range. As shown above, higher values of α_2 and low values of c_f may lead to multiple interior equilibria where the interior equilibrium (employed in Table 1) is stable; see Figure 3.

The policies mentioned in this section could be based on economic incentives (fines/subsidies). However, as discussed by Palm-Forster et al. (2019, 2022), the application of fines or subsidies may encounter severe difficulties due to its associated costs, limited political acceptability, limited availability of information, or fairness concerns. Alternatively, policies may be based on voluntary approaches that are not linked to economic incentives but motivate agents to participate in the formation of a social norm or to adhere to an existing social norm. These voluntary approaches usually rely on (i) information about individual agents, (ii) framing of the social dilemma problem, or (iii) a relative comparison between agents' behavior. For instance, information that allows agents to compare their behavior with the average of all other agents' behavior can influence the agents' behavior and encourage adherence to a social norm.[26]

5 | CONCLUSIONS

This study offers an analytical framework for studying the influence that social networks and the state of a common property resource have on cooperation. It uses the concept of moral ties and generalizes the concept of social tipping points by taking account of the topological characteristics of social networks, the scarcity of the resource, and the agents' behavior. This combination allows determining the set of frontier lines of a bioeconomic system, that is, the conditions that separate compliance from non-compliance. The location of different frontier lines defines the minimum and maximum share of compliers at which social networks start (stop) having influence on cooperation. The analysis further shows that stable interior and boundary equilibria exist. Depending on the size of their basin of attraction, interior equilibria might be of interest if the socially optimal equilibrium cannot be reached, as they represent socially second-best solutions. For the case of the Western La Mancha Aquifer, we illustrate that a large basin of attraction of an interior equilibrium exists if the costs of social pressure are sufficiently high.

Public awareness of the social dilemma is the prerequisite for farmers to exercise social pressure. Awareness can be raised, for example, by public campaigns, public announcement of distinguished compliers, or legislation. However, even a high share of compliers may be insufficient for achieving the socially optimal equilibrium when agents are not fully informed about the state of the resource or do not perceive the current state as posing a threat for the future. To redress this misperception about scarcity, regulators may strengthen extension services and educational efforts.

Policies to increase social cohesiveness may include creating an association whose membership is open only to norm-complying agents and whose members receiving privileges or benefits. Such policies may consist of the formation of a compliers' association, a nongovernmental support organization, or the organization of seminars, workshops, or field days (Cumming, 2018).

The number of agents targeted by legal enforcement can be reduced because it is only necessary to fine the minimum number of defectors that reaches the basin of the all-complier equilibrium. However, subsidizing social pressure costs may be counterproductive because this substantially reduces the basin of attraction. Policies that aim to raise the compliers' responsiveness threshold and policies that aim to increase cohesiveness are not fully compatible. The former reduces the effectiveness of the latter.

The study provides a framework for comparison of the effectiveness of different enforcement policies for different initial values of the stock, share of compliers, and local cohesiveness of compliers. In the presence of social networks, legal and informal enforcement policies can be less stringent than in the absence of social networks. If the initial conditions form part of the informal enforcement corridor, policymakers can employ any combination of legal and informal enforcement policies.

Depending on the type of network and the scarcity of the resource, network-oriented policies can reduce the critical number of compliers needed for cooperation. However, for the case study of the Western La Mancha aquifer, we find that social networks never reduce the critical number of compliers by more than 26%.

If policymakers are not fully informed about the underlying social network and the agents' choices, the analysis suggests, as a rule of thumb, to focus enforcement policies on geographical zones/neighborhoods where the numbers of defectors and compliers are equal.

With respect to future work, the proposed model offers insights for guiding an empirical evaluation of the effect of social networks on the use of common property resources—for example, it allows estimation of the probability of compliance with a social norm depending on the stock of the resource, share of compliers, local cohesiveness, socioeconomic factors, and fixed effects.

ACKNOWLEDGMENTS

We would like to thank the handling editor Amy Ando and two anonymous reviewers for their helpful comments and suggestions. Likewise, we like to thank Santiago Rubio, Tomás Rodríguez Barraquer, Matthew Jackson, and the participants of the 4th Annual Conference on Network Science and Economics, the 6th World Congress of Environmental and Resource Economists, the 26th

Annual Conference of the European Association of Environmental and Resource Economists, and the 3rd AERNA workshop on Game Theory and Environment for their insightful comments. The authors gratefully acknowledge the support from the Spanish Government, Ministerio de Ciencia e Innovación (MCIN)/Agencia Española de Investigación(AEI), grant PID2020-118268RB, by MCIN/AEI/10.13039/501100011033 and Jorge Marco from the SDGnexus Network (grant number 57526248), Program "Exceed -Hochschulexzellenz in der Entwicklungszusammenarbeit," funded by the DAAD financed by the German Federal Ministry for Economic Cooperation (BMZ). Open Access funding provided thanks to Conferencia de los Rectores de las Universidades Españolas - Consejo Superior de Investigaciones Científicas Agreement with Wiley.

ENDNOTES

[1] As an alternative to the combination of social network characteristics and evolutionary game theory that we employ, one could think of modeling social interaction directly (Cont and Löwe, 2010; Garrod and Jones, 2021). This approach would take account of the agents' heterogeneity with respect to individual attributes and attitudes, but it has the disadvantage that the underlying network structure is homogeneous. Thus, it does not reflect segregation patterns of social networks that are highly relevant for modeling small-world phenomena (Jackson, 2010), which in turn are fundamental for the emergence of social pressure. The modeling approach employed here does not consider individual attributes and attitudes directly but does so indirectly, by considering non homogeneous networks where each agent has a unique position within the network.

[2] The term "neighbor" expresses the fact that two agents are connected.

[3] See Online Appendix F for more details about the rationale for setting the agent's discount factor equal to one.

[4] The non-existence of noncontributing compliers can be justified by the observation that agents tend to adhere strictly to social norms within their circle of trust (neighborhood) but far less outside this circle (Banfield, 1958; Platteu, 2000). This line of argument has been employed by Duernecker and Vega-Redondo (2017). to justify the existence of intrinsically motivated compliers who pressure defectors even when they are not affected by the defectors' behavior.

[5] We interpret the social norm as a recommendation similar to recommendation of "best management practices".

[6] For notational convenience, we generally omit the argument t of the stock and of the share of norm-complying agents (to be introduced below) unless required for an unambiguous notation.

[7] For the theoretical analysis, a cardinal ranking of the compliers' and defectors' water demand functions is completely sufficient. However, for the empirical part of the study, a complete specification of the water resource demand functions is required; it can be found in the Online Appendix F.

[8] Instead of the male and female pronoun, we use the plural form to facilitate reading.

[9] Throughout the paper, we indicate a partial derivative by a subscript of the corresponding variable.

[10] Because it is possible that not all compliers take part in collective actions, the effective strength of local cohesiveness may be less than τ_{c_i}. However, we do not distinguish between effective and nominal local cohesiveness because we approximate τ_{c_i} by τ_i and c_i^2 at a later stage of the study. Thus, τ_i becomes a parameter that reflects either a change in the structure of the network (nominal local cohesiveness) or a change in the willingness to coordinate social pressure on defectors (effective local cohesiveness).

[11] To the best of our knowledge, this relationship, despite its intuitive appeal, is not supported by empirical evidence or theoretical reasoning. For a literature review, see Farrow et al. (2017); Ushchev and Zenou (2020). For this reason, we also analyze the case where social pressure is not affected by the stock, that is $\omega_{s_i} = 0$, and report our findings whenever it offers qualitatively different results than the previous relationship.

[12] Because the agents' rationality is bounded (Assumption A3), they are not in a position to calculate the trajectory of the social network and thus cannot determine the benefits of social pressure.

[13] We assume that the coordination costs are perfectly divisible among agents.

[14] Given the complexity of the relationship between the micro- and macro-scale, one could be tempted to analyze the game at the macro-scale independent of the game at the micro-scale, that is, to start the analysis directly at the macro-scale. However, it is important to consider both scales for three reasons. First, the micro-scale constitutes the basis of the agents' behavior. Second, it provides a benchmark for the accuracy of the macro-scale analysis. Without the micro-scale, the description of the agent's behavior would have to be based on ad-hoc assumptions and the accuracy of the modeling approach could not be evaluated. Third, the macro-scale lends itself to a qualitative analysis that cannot be accomplished at the micro-scale.

[15] As before, we define $\widehat{\omega}_c = \partial\widehat{\omega}/\partial c > 0, \widehat{\omega}_{\tau_c} = \partial\widehat{\omega}/\partial\tau_c > 0, \widehat{\omega}_s = \partial\widehat{\omega}/\partial s < 0$.

[16] The border line is downward sloping if resource growth $R(s)$ is very responsive to changes in the stock, but $w^D(s)$ and $w^C(s)$ are not. For instance, this would be the case if the extraction costs were completely independent of the remaining

level of the stock. The economic context that corresponds to either an increasing or decreasing frontier line or border line are analyzed in detail in Appendix B.

[17] Finally, we analyze the stability of the point $(c^* = \widetilde{c}, s^*)$ in Appendix B when social pressure is not affected by the stock, $\widehat{\omega}_s = 0$. In this case, a second-best steady state exists only if sanctioning costs increase more than social pressure with an increase of cooperation.

[18] The points $c = 0$ and $c = 1$ are excluded because they correspond to the all-defector and all-complier equilibria respectively.

[19] A similar proposition can be formulated for the case where $(s=0) \notin \mathscr{F}_\tau$ and $\mathscr{F}_\tau$ is downward sloping. However, because it does not offer qualitatively new results, we refrain from doing so.

[20] The small arrows in Figures 2 and 3 illustrate the vector field where the arrow indicates the direction of the vectors and the color their magnitude. Colder colors correspond to lower magnitudes.

[21] The Mathematica® code and a documentation (READ ME file) of the bioeconomic model together with an image of the graphic interface are presented in Online Appendix H. The program allows a user to replicate the results of Table 1 by analyzing the effects of changes in the different parameters on the phase diagram, because the results of the sensitivity analysis with respect to parameter values can be visualized by moving the corresponding sliders of the graphic that presents the values of the parameters.

[22] For a single owner/user of an aquifer, all benefits and costs are private. However, as the number of users grows, benefits remain private, but mid- or long-term externality costs are socialized. Because defectors maximize the difference between private benefits and costs, they do not take account of externality costs. Also, they determine their water demand from a short-sighted perspective.

[23] For the interpretation of this result, one has to keep in mind that cooperation depends on the difference in utilities from being a complier or defector. Water saving technologies, crop choice, and so forth are available to compliers and defectors. Thus, they have a clear impact on water consumption, but they do not necessarily affect the difference of the agents' utilities.

[24] The literature review by Bursztyn and Jensen (2017) shows that social pressure motivates behavioral changes in a wide range of settings. However, beyond establishing that such effects exist, important questions remain unanswered. Ibid. propose to work in the future on understanding the underlying determinants of social pressure and whether and how social pressure can be shaped. We are not aware of agricultural/environmental policies that specifically aim to shape social pressure, for instance, by targeting individuals or specific groups of farmers. In contrast, individual targeting is an important element of political campaigns and product marketing to mobilize and persuade voters/consumers. Likewise, it has been applied in relation to the promotion of new agricultural technologies by organizing workshops or field days for specific farmers. One can imagine that the future availability of agent-specific data favors the incorporation of individual- or group-specific targeting. Thus, our approach offers some guidance for the design of better targeted agricultural/environmental policies.

[25] Placing more weight on α_1 compared to α_0 increases the influence of the agents' degree.

[26] To see how voluntary approaches relate to the formation and perseverance of a social norm, one needs to go back to the building elements of a social norm. As defined by Bicchieri (2006) and Bicchieri and Muldoon (2014), a social norm is a rule of behavior in which an agent prefers to comply if the agent (a) observes that most of their friends or acquaintances comply with it (empirical expectations), (b) believes that all other agents should do so as well (normative expectations), and (c) acts dependently on what others do and expect (conditional preferences). Based on this definition, one can see that the three basic elements of voluntary approaches, (i) – (iii), directly influence the empirical and normative expectations and the conditional preferences.

REFERENCES

Acemoglu, Daron, and Matthew O. Jackson. 2017. "Social Norms and the Enforcement of Laws." *Journal of the European Economic Association* 15(2): 245–95.

Ali, S. Nageeb, and David A. Miller. 2016. "Ostracism and Forgiveness." *American Economic Review* 106(8): 2329–48.

Banfield, Edward. 1958. *The Moral Basis of a Backward Society*. New York: Free Press.

Barrett, Scott, and Astrid Dannenberg. 2017. "Tipping Versus Cooperating to Supply a Public Good." *Journal of the European Economic Association* 15(4): 910–41.

Besley, Timothy 2020. "State Capacity, Reciprocity, and the Social Contract." *Econometrica* 88(4): 1307–35.

Bicchieri, Cristina 2006. *The Grammar of Society: The Nature and Dynamics of Social Norms*. Cambridge: Cambridge University Press.

Bicchieri, Cristina, and Ryan Muldoon. 2014. "Social Norms." In *the Stanford Encyclopedia of Philosophy*, edited by Edwin N. Zalta. Redwood City, CA: Stanford. https://plato.stanford.edu/archives/win2018/entries/social-norms/.

Biel, Anders, and Tommy Gärling. 1995. "The Role of Uncertainty in Resource Dilemmas." *Journal of Environmental Psychology* 15(3): 221–33.

Blanco-Gutiérrez, Irene, Consuelo Varela-Ortega, and Guillermo Flichman. 2011. “Cost-Effectiveness of Groundwater Conservation Measures: A Multi-Level Analysis with Policy Implications.” *Agricultural Water Management* 98(4): 639–52.

Bowles, Samuel, and Herbert Gintis. 2011. *A Cooperative Species: Human Reciprocity and its Evolution*. Princeton: Princeton University Press.

Bramoullé, Yann, and Rachel Kranton. 2007. “Public Goods in Networks.” *Journal of Economic Theory* 135(1): 478–94.

Bursztyn, Leonardo, and Robert Jensen. 2017. “ Social Image and Economic Behavior in the Field: Identifying, Understanding, and Shaping Social Pressure.” *Annual Review of Economics* 9(1): 131–53.

Calvó-Armengol, Antoni, and Matthew O. Jackson. 2010. “Peer Pressure.” *Journal of the European Economic Association* 8(1): 62–89.

Coleman, James 1988. “Social Capital in the Creation of Human Capital.” *American Journal of Sociology* 94: S95–S120.

Cont, R, and Matthias Löwe. 2010. “Social Distance, Heterogeneity and Social Interactions.” *Journal of Mathematical Economics* 46(4): 572–90.

Cumming, Graeme S. 2018. “A Review of Social Dilemmas and Social-Ecological Traps in Conservation and Natural Resource Management.” *Conservation Letters* 11(1): e12376.

Dohmen, Thomas, Armin Falk, D. Huffman, and Uwe Sunde. 2009. “Homo Reciprocans: Survey Evidence on Behavioural Outcomes*.” *Economic Journal* 119(536): 592–612.

Duernecker, Georg, and Fernando Vega-Redondo. 2017. “Social Networks and the Process of Globalization.” *Review of Economic Studies* 85(3): 1716–51.

Elster, Jon 1989. *The Cement of Society*. Cambridge: Cambridge University Press.

Esteban, Encarna, and Jose Albiac. 2010. "Groundwater and ecosytem management: empirical findings from La Mancha Aquifers, Document: 10/03." Available from http://www.unizar.es/econatura/documentos/recursoshidricos/wd1003.pdf

Esteban, Encarna, and José Albiac. 2011. “Groundwater and Ecosystems Damages: Questioning the Gisser–Sánchez Effect.” *Ecological Economics* 70(11): 2062–9.

European Comission. 2000. *Water Framework Directive*. 2000/60/EC European Parlament and Council, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:327:0001:0072:EN:PDF.

Farrow, Katherine, Gilles Grolleau, and Lisette Ibanez. 2017. “Social Norms and pro-Environmental Behavior: A Review of the Evidence.” *Ecological Economics* 140: 1–13.

Fehr, Ernst, and Urs Fischbacher. 2003. “The Nature of Human Altruism.” *Nature* 425(6960): 785–91.

Fehr, Ernst, Urs Fischbacher, and Simon Gächter. 2002. “Strong Reciprocity, Human Cooperation, and the Enforcement of Social Norms.” *Human Nature: An Interdisciplinary Biosocial Perspective* 13(1): 1–25.

Fehr, Ernst, and Simon Gächter. 2000. “Cooperation and Punishment in Public Goods Experiments.” *American Economic Review* 90(4): 980–94.

Fehr, Ernst, and Simon Gächter. 2002. “Altruistic Punishment in Humans.” *Nature* 415: 137–40.

Fehr, Ernst, and Herbert Gintis. 2007. “Human Motivation and Social Cooperation: Experimental and Analytical Foundations.” *Annual Review of Sociology* 33(1): 43–64.

Gächter, Simon, Felix Kölle, and S. Quercia. 2017. “Reciprocity and the Tragedies of Maintaining and Providing the Commons.” *Nature Human Behaviour* 1(9): 650–6.

Gale, Douglas, and Shachar Kariv. 2003. “Bayesian Learning in Social Networks.” *Games and Economic Behavior* 45(2): 329–46.

García, Julián, and Matthijs van Veelen. 2016. “In and Out of Equilibrium I: Evolution of Strategies in Repeated Games with Discounting.” *Journal of Economic Theory* 161: 161–89.

Garrod, Matthew, and Nick Jones. 2021. “Influencing Dynamics on Social Networks without Knowledge of Network Microstructure.” *Journal of the Royal Society Interface* 18: 1–12.

Goetz, Renan, and Jorge Marco. 2022 "The Strength of Moral Ties." *Social Science Research Network*, DOI: https://doi.org/10.2139/ssrn.3814048.

Gomes, Diogo, Roberto M. Velho, and Marie-Therese Wolfram. 2014. “Socio-Economic Applications of Finite State Mean Field Games.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 372(2028): 20130405.

Grujic, Jelena, José A. Cuesta, and Angel Sanchez. 2012. “On the Coexistence of Cooperators, Defectors and Conditional Cooperators in the Multiplayer Iterated Prisoner’s Dilemma.” *Journal of Theoretical Biology* 300: 299–308.

Guéant, Olivier 2015. “Existence and Uniqueness Result for Mean Field Games with Congestion Effect on Graphs.” *Applied Mathematics & Optimization* 72(2): 291–303.

Hilbe, Christian, K Chatterjee, and Martin A. Nowak. 2018. “Partners and Rivals in Direct Reciprocity.” *Nature Human Behaviour* 2(7): 469–77.

Hilbe, Christian, Štepa Šimsa, Krishnendu Chatterjee, and Martin A. Nowak. 2018. “Evolution of Cooperation in Stochastic Games.” *Nature* 559(7713): 246–9.

Jackson, Matthew O. 2010. *Social and Economic Networks*. Princeton: Princeton University Press.

Jackson, Matthew O., Brian Rogers, and Yves Zenou. 2017. “The Economic Consequences of Social Network Structure.” *Journal of Economic Literature* 55(1): 49–95.

Jackson, M O. 2014. “Networks in the Understanding of Economic Behaviors.” *Journal of Economic Perspectives* 28(4): 3–22.

Jackson, Matthew O. 2016. "The Past and Future of Network Analysis in Economics." In *Oxford Handbook of the Economics of Networks*, edited by Y. Bramoulle, A. Galeotti, and B. Rogers, 71–9. New York: Oxford Publisher.

Jackson, Matthew O., Tomas Rodriguez-Barraquer, and Xu Tan. 2012. "Social Capital and Social Quilts: Network Patterns of Favor Exchange." *American Economic Review* 102(5): 1857–97.

Karlan, Dean, Markus Mobius, Tanya Rosenblat, and Adam Szeidl. 2009. "Trust and Social Collateral*." *Quarterly Journal of Economics* 124(3): 1307–61.

Kyriakopoulou, Efthymia, and Anastasios Xepapadeas. 2021. "Natural Resource Management: A Network Perspective." *Environmental and Resource Economics* 80(2): 221–56.

Lade, Steve J., Alessandro Tavoni, Simon A. Levin, and Maja Schlüter. 2013. "Regime Shifts in a Social-Ecological System." *Theoretical Ecology* 6(3): 359–72.

Nyborg, Karine 2020. "No Man Is an Island: Social Coordination and the Environment." *Environmental and Resource Economics* 76(1): 177–93.

Palm-Forster, Leah H., Mark Griesinger, Julianna M. Butler, Jacob R. Fooks, and Kent D. Messer. 2022. "Stewardship Signaling and Use of Social Pressure to Reduce Nonpoint Source Pollution." *Land Economics*, 98(4): 618–638.

Palm-Forster, Leah H., Jordan F. Suter, and Kent D. Messer. 2019. "Experimental Evidence on Policy Approaches that Link Agricultural Subsidies to Water Quality Outcomes." *American Journal of Agricultural Economics* 101(1): 109–33.

Platteu, Jean P. 2000. *Institutions, Social Norms and Economic Development*. Amsterdam: Hardwood Academic Publishers and Routledge.

Ravenscroft, Peter, and Lucy Lytton. 2022. Seeing the Invisible: A Strategic Report on Groundwater Quality. Washington, DC:. WorldBank. http://hdl.handle.net/10986/37197

Sethi, Rajiv, and Eswaran Somanathan. 1996. "The Evolution of Social Norms in Common Property Resource Use." *American Economic Review* 86(4): 766–88.

Smith, J. Mynard, and George R. Price. 1973. "The Logic of Animal Conflict." *Nature* 246(5427): 15–8.

Tabellini, Guido 2008. "The Scope of Cooperation: Values and Incentives*." *Quarterly Journal of Economics* 123(3): 905–50.

Tavoni, Alessandro, Maja Schlüter, and Simon Levin. 2012. "The Survival of the Conformist: Social Pressure and Renewable Resource Management." *Journal of Theoretical Biology* 299: 152–61.

Ushchev, Philip, and Yves Zenou. 2020. "Social Norms in Networks." *Journal of Economic Theory* 185: 104969.

Wolitzky, Alexander 2013. "Cooperation with Network Monitoring." *Review of Economic Studies* 80(1): 395–427.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Marco, Jorge, and Renan Goetz. 2024. "Public Policy Design and Common Property Resources: A Social Network Approach." *American Journal of Agricultural Economics* 106(1): 252–285. https://doi.org/10.1111/ajae.12372

APPENDIX A: PROOF OF PROPOSITION 1

Following Definition 1, an equilibrium exists if and only if $\dot{c}=0$. According to Definition 3, the set $\mathcal{F}$ contains all cases where interior stationary values of the share of compliers exist, that is, $c^*=\widetilde{c}\in(0,1)$. Hence, any interior equilibrium of the bioeconomic system where compliers and defectors coexist has to be part of set $\mathcal{F}$.

APPENDIX B: PROOF OF PROPOSITION 2

We have the following dynamic system

$$\dot{c}=c(1-c)\left(\widehat{\omega}\left(c,\tau c^2,s\right)-1+\widehat{\theta}-\widehat{\gamma}(k,c)\right) \tag{B1}$$

$$\dot{s}=R(s(t))-(1-\psi)\left(cnw_i^C(s(t))+(1-c)nw_j^D(s(t))\right) \tag{B2}$$

According to Definition 1, the intersection of the frontier line and the border line in the c,s-plane yields a steady state (c^*,s^*) of the bioeconomic system. To reduce the notational burden, we assume, without any loss of generality, that the percolation rate is equal to zero. The following observation derives the slope of the nullclines in the c,s-plane.

Observation B1. (Slope of the nullclines): The slope of the border line and the frontier line in the c,s-plane are respectively given by

$$\frac{\partial s}{\partial c}\Big|_{\dot{s}=0}=\frac{-\left[n\left(w_j^D(s)-w_i^C(s)\right)\right]}{\frac{\partial R(s)}{\partial s}-cn\frac{\partial w_i^C(s)}{\partial s}-(1-c)n\frac{\partial w_j^D(s)}{\partial s}}=\begin{cases}>0,\text{if } \dfrac{\partial R(s)}{\partial s}-cn\dfrac{\partial w_i^C(s)}{\partial s}-(1-c)n\dfrac{\partial w_j^D(s)}{\partial s}<0\\ <0,\text{if } \dfrac{\partial R(s)}{\partial s}-cn\dfrac{\partial w_i^C(s)}{\partial s}-(1-c)n\dfrac{\partial w_j^D(s)}{\partial s}>0\end{cases} \tag{B3}$$

$$\frac{\partial s}{\partial c}\Big|_{\dot{c}=0}=\frac{-[\widehat{\omega}_c+\widehat{\omega}_{\tau_c}2\tau c-\widehat{\gamma}_c]}{\widehat{\omega}_s}\gtreqless 0. \tag{B4}$$

Proof: Applying the implicit function theorem to Equations (B1) and (B2) respectively yields the results of Observation B1.

Equation (B3) shows that the border line is upward sloping if changes in resource growth are less than the increase in extractions as a result of an increase in the remaining stock. This is the case if the growth rate of the resource (e.g., the natural recharge rate of an aquifer) is independent of the stock. Similarly, the border line is downward sloping if resource growth is very responsive to changes in the stock, but extraction is not, for example, extraction costs are completely independent of the remaining level of the stock. However, as defined in the main text, we concentrate on the case where the border line is upward sloping. Equation (B4) shows that the frontier line is upward sloping if the social pressure function is more responsive to an increase in the share of compliers than to sanctioning costs. This is always the case if sanctioning costs are either fixed or barely responsive to an increase in the share of compliers.

From Equation (B1), we can immediately identify the two boundary equilibria $\underline{c}=0$ and $\overline{c}=1$. Thus, in the following, we concentrate on the case of the equilibria where compliers and defectors coexist, that is, $\dot{c}=\widehat{\omega}(c,\tau c^2,s)-1+\widehat{\theta}-\widehat{\gamma}(k,c)=0$. The Jacobian matrix J of the system (B1) and (B2) is given by

$$J=\begin{pmatrix}\frac{\partial\dot{c}}{\partial c} & \frac{\partial\dot{c}}{\partial s}\\ \frac{\partial\dot{s}}{\partial c} & \frac{\partial\dot{s}}{\partial s}\end{pmatrix}=\begin{pmatrix}\widehat{\omega}_c+\widehat{\omega}_{\tau_c}2\tau c-\widehat{\gamma}_c & \widehat{\omega}_s\\ n(w^D(s)-w^C(s)) & \frac{\partial R(s)}{\partial s}-cn\frac{\partial w_i^C(s)}{\partial s}-(1-c)n\frac{\partial w_j^D(s)}{\partial s}\end{pmatrix}.$$

For the eigenvalues λ_1,λ_2 of the dynamic system, it holds that $\lambda_1\times\lambda_2=\det\ J$, and $\lambda_1+\lambda_2=\text{Trace}\,J$. Based on the previous structure of the functions $\widehat{\omega},w_i^C,w_j^D,\widehat{\gamma}$ and R, the evaluation of the sign of the determinant of J shows that $\det\ J=(\pm)(-)-(+)(-)\gtreqless 0$. Given the mathematical structure of the functions employed, a stable equilibrium in the form of a sink can be identified. For this case, it is required that $\det J>0$ and $\text{Trace}\,J<0$.

The evaluation of the determinant shows that $\det J=(\widehat{\omega}_c+\widehat{\omega}_{\tau_c}2\tau c-\widehat{\gamma}_c)\left(R_s-cnw_{i_S}^C-(1-c)nw_{j_S}^D\right)-n\left(w_j^D(s)-w_i^C(s)\right)\widehat{\omega}_s$, which implies for $\det J>0$ and, taking into account the negative sign of $\widehat{\omega}_s$, that

$$\det J=\frac{(\widehat{\omega}_c+\widehat{\omega}_{\tau_c}2\tau c-\widehat{\gamma}_c)}{\widehat{\omega}_s}>\frac{n\left(w_j^D(s)-w_i^C(s)\right)}{R_s-cnw_{i_S}^C-(1-c)nw_{j_S}^D}. \tag{B5}$$

Multiplying this inequality by -1 yields

$$\frac{-(\widehat{\omega}_c+\widehat{\omega}_{\tau_c}2\tau c-\gamma_c)}{\widehat{\omega}_s}<\frac{-n(w^D(s)-w^C(s))}{R_s-cnw_s^C-(1-c)nw_s^D}. \tag{B6}$$

Thus, according to Equations (B3) and (B4), the left and right sides of the inequality can be related to the signs of the slopes of the frontier line and border line, respectively. Hence, the existence of a sink requires that $\frac{\partial s}{\partial c}|_{\dot{c}=0}<\frac{\partial s}{\partial c}|_{\dot{s}=0}$, which is satisfied if $\frac{\partial s}{\partial c}|_{\dot{c}=0}<0$ because $\frac{\partial s}{\partial c}|_{\dot{s}=0}>0$. We can relate this inequality directly to the elements of the matrix J. This implies that $\frac{\partial\dot{c}}{\partial c}<0$. Moreover, the last inequality guarantees that $\frac{\partial\dot{c}}{\partial c}+\frac{\partial\dot{s}}{\partial s}=\lambda_1+\lambda_2=\text{Trace}\,J<0$. Alternatively, we can consider the case where $0<\frac{\partial s}{\partial c}|_{\dot{c}=0}<\frac{\partial s}{\partial c}|_{\dot{s}=0}$. However, in this case, it cannot be guaranteed that $\frac{\partial\dot{c}}{\partial c}+\frac{\partial\dot{s}}{\partial s}=\lambda_1+\lambda_2=\text{Trace}\,J<0$, and this has to be imposed as an additional condition.

Thus, we have proven Part (a) of Proposition 2, which states that an interior equilibrium $(c^*=\widetilde{c},s^*)$ of the bioeconomic system is characterized by a sink (attractor) if the frontier line is downward sloping and the border line at this point is upward sloping.

Similarly, we can analyze the conditions for an equilibrium in the form of a saddle, where it is required that $\det J<0$. We can derive the necessary condition from Equation (B6) by reversing the inequality sign. To guarantee the existence of a saddle point, it has to hold that $\frac{-\left(\widehat{\omega}_c+\widehat{\omega}_{\tau_c}2\tau c-\gamma_c\right)}{\widehat{\omega}_s}>\frac{-n\left(w_j^D(s)-w_i^C(s)\right)}{R_s-cnw_{i_S}^C-(1-c)nw_{j_S}^D}$. Thus, an equilibrium in the form of a saddle exists if the positive slope of the $\dot{c}=0$ nullcline is greater than the positive slope of the $\dot{s}$-nullcline.

In other words, we can confirm Part (b) of Proposition 2, which states that an interior steady state $(c^*=\widetilde{c},s^*)$ of the bioeconomic system is characterized by a saddle if the frontier line and border line at this point are upward sloping but the slope of the frontier line is greater than the slope of the border line.

If social pressure is independent of the level of the remaining stock, that is, if $\widehat{\omega}_s = 0$, an equilibrium is in the form of a sink if $\det J = \lambda_1 \times \lambda_2 = (\widehat{\omega}_c + \widehat{\omega}_{\tau_c} 2\tau c - \widehat{\gamma}_c)\left(R_s - cnw_{i_S}^C - (1-c)nw_{j_S}^D\right) > 0$ and $\text{Trace}\, J = \lambda_1 + \lambda_2 < 0$. Because $\left(R_s - cnw_{i_S}^C - (1-c)nw_{j_S}^D\right) < 0$, an equilibrium is in the form of a sink if $(\widehat{\omega}_c + \widehat{\omega}_{\tau_c} 2\tau c - \widehat{\gamma}_c) < 0$. Likewise, we may find an equilibrium in the form of a saddle if $\det J = \lambda_1 \times \lambda_2 = (\widehat{\omega}_c + \widehat{\omega}_{\tau_c} 2\tau c - \widehat{\gamma}_c)\left(R_s - cnw_{i_S}^C - (1-c)nw_{j_S}^D\right) < 0$, which requires that $(\widehat{\omega}_c + \widehat{\omega}_{\tau_c} 2\tau c - \widehat{\gamma}_c) > 0$. We can summarize this result in the following proposition.

> **Proposition B1.** ***(Sink and saddle in the absence of stock effects):*** *An interior steady state $(c^* = \widetilde{c}, s^*)$ of a bioeconomic system where social pressure is independent of the remaining stock is characterized by a sink (saddle) if the costs of social pressure increase more (less) than social pressure with an increase in compliers.*

APPENDIX C: PROOF OF PROPOSITION 3

Let $(\mathscr{R}, \leq)$ be a set where elements are totally ordered by the relation $\leq$. Because the definition of set $\mathscr{R}$ is given by $\mathscr{R} = \bigcup_{\tau \in [0,1]} \mathscr{R}_\tau = \left\{c, s \in \mathbb{R}^2_{\geq 0} \,|\, \widehat{\omega}(c, \tau c^2, s) - 1 + \widehat{\theta} - \widehat{\gamma}(k, c) < 0 \wedge c < 1\right\}$, we can define for a given stock a lowest upper bound (supremum) of c in $\mathscr{R}$ but not a maximum. The supremum of c is denoted by $c^{\sup}|_s \in [0,1]$, with $s \in [0, s_{\max}]$, and is given by

$$c^{\sup}|_{s \in [0, s_{\max}]} = \begin{cases} 1 \quad , & (s, c=1) \notin \mathscr{R}_{\tau=1} \\ c \in \mathscr{F}_{\tau=1} \,, & \text{if } s \in \mathscr{F}_{\tau=1} \text{ and } (c > c \in \mathscr{F}_{\tau=1}) \notin \mathscr{R}. \\ \nexists \quad , & \text{if } s \notin \mathscr{R}_{\tau=1} \end{cases} \tag{C1}$$

Equation (C1) defines the supremum of c for the cases where the frontier line $\mathscr{F}$ is defined for the upper part, $c^{\sup} = 1$, or for the lower part, $c^{\sup} = 0$, and when it is defined for the intermediate part, $c^{\sup} \in (0,1)$, of the c,s-plane. Within the c,s-plane, cooperation may not emerge when the following three conditions hold: (a) none of the three sets $\mathscr{R}$, $\mathscr{F}$, and $\mathcal{G}$ is empty; (b) for a given stock $s \in [0, s_{\max}]$, the supremum $c^{\sup}|_s$ exists and $\mathscr{R}$ is continuous in c, such that $\left(c \leq c^{\sup}|_s, s\right) \in \mathscr{R}$; and (c) the set $\mathscr{R}$ includes the point $c = 0$, such that $(0, s) \in \mathscr{R}$. In the case where all three conditions hold, there exists a path in the c,s-plane that lies entirely within the set $\mathscr{R}$ and connects a possible high but insufficient level of cooperation, $0 < c < c^{\sup}|_s \leq 1$, with no cooperation at all, $c = 0$. This path represents all the cases where the agents do not perceive the state of the social dilemma as severe. Following this path, it can be observed that, even when the bioeconomic system departs from high levels of cooperation, defection or resource depletion may occur. If the three conditions hold, the higher the values of s that belong to set $\mathscr{R}$, the higher the value of $c^{\sup}|_s$, which cannot prevent the emergence of the all-defector equilibrium.

APPENDIX D: PROOF OF PROPOSITION 4

For the case of $\widehat{\gamma}(k,c) = 0$, we observe from Definition 1 that a second-best solution can exist only if $\max\{\widehat{\omega}\} \geq 1$, that is, social pressure has to be greater than or equal to the defectors' extra benefits, which are normalized to one. We have verified numerically that there exists at most one interior steady state for any value of τ. For Figure 2, the expected cohesiveness of $\tau = 0.6$ falls within the range of possible values of τ values in real-world social networks (Goetz & Marco, 2022), so that the interior steady state $\widetilde{c} = (c^* = 0.4, s^* = 22)$ can be achieved through network-oriented policies.

Verifying the conditions of Proposition 2 Part b demonstrates that the interior steady state is in the form of a saddle. Evaluating the determinant of the Jacobian matrix det$J$ at $\widetilde{c}$ confirms this result because it is negative det$J = -0.09$. See also Appendix B (Proof of Proposition 2).

Taking account of the bell shape of the sanctioning costs, we illustrate the case where legal enforcement is absent, $\widehat{\theta} = 0$, and the sanctioning costs are given by $\widehat{\gamma}(k,c) = 0.62(1 - c + 4.25c(1-c))$, that is, $\upsilon(k) = 0.62$, $\alpha_0 = \alpha_1 = 1, \alpha_2 = 4.25$. Verifying the results of Propositions 2 [part (a) and (b)] demonstrates that the two interior steady-state points $\widetilde{c}_1 = (c^* = 0.21, s^* = 16.73)$ and $\widetilde{c}_3 = (c^* = 0.42, s^* = 29.70)$ are saddle points, whereas $\widetilde{c}_2 = (c^* = 0.33, s^* = 20.79)$ is a sink. Evaluating the determinants of the Jacobian matrix at the points $\widetilde{c}_1, \widetilde{c}_2, \widetilde{c}_3$ yields det$J = -0.005452$, det$J = 0.000487$ and det$J = -0.000577$, respectively. Hence, the numerical analysis confirms that the points $\widetilde{c}_1$ and $\widetilde{c}_3$ are saddle points, and $\widetilde{c}_2$ is a sink, because the trace of the Jacobian matrix evaluated at point $\widetilde{c}_2$ is -0.061682. The emergence of three interior steady states requires that the interior equilibrium condition $\widehat{\omega}(c, \tau^* c^2, s_t) - 1 - \widehat{\gamma}(k,c) = 0$ changes sign at least twice, that is, it has at least three different roots and $+1 + \widehat{\gamma}(k,c) > \max_c \widehat{\omega}(c, \tau^* c^2, s_t) \equiv 2$ for the set Z with $Z \subset \{0,1\}$. In other words, for some values of c, the sum of extra benefits and sanctioning costs has to be greater than the maximal value of social pressure.