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Pauline Pedehour, Lionel Richefort

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By Pauline Pedehour, Université de Nantes
Lionel Richefort, Université de Nantes

Summary

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Keywords: Comparative statics, Conformism, Nash equilibrium, Network, Social norms, Water extraction

JEL Classification: D04, D80, Q01, Q25

Address for correspondence:
Pauline Pedehour
LEMNA – Laboratoire d'Economie et de Management de Nantes-Atlantique
Université de Nantes
Chemin de la censive du Tertre - Batiment Erdre, BP 52231
44322 Nantes
France
E-mail: pauline.pedehour@univ-nantes.fr

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Corso Magenta, 63, 20123 Milano (I), web site: www.feem.it, e-mail: working.papers@feem.it

Empowerment of social norms on water consumption

Pauline Pedehour*, Lionel Richefort†

Abstract

This study develops a model of water extraction with endogenous social norms. Many users are connected by a unique shared resource that can become scarce in case of over-exploitation. Preferences of individuals are guided by their extraction values and their taste for conformity to social norms which provide incentives to follow others. As the main result of this study, the uniqueness of the Nash equilibrium is established under a sufficient condition. Afterward, some comparative statics analysis shows the effects of change in individual heterogeneous parameters, conformism, and density of the network on the global quantity extracted. Welfare and social optimum properties are established to avoid the tragedy of the commons and sub-optimal consumptions of water. Lastly, this theoretical framework is completed by extensions to highlight levers of water preservation, including the calibration of social norm incentives.

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*LEMNA, Université de Nantes. Adress: Chemin de la censive du Tertre - Bâtiment Erdre, BP 52231, 44322 Nantes Cedex 3, France. Email: pauline.pedehour@univ-nantes.fr (corresponding author)

†LEMNA, Université de Nantes. Email: lionel.richefort@univ-nantes.fr

1 Introduction

In our daily lives, behaviours are oriented by social norms[1] in diverse situations through consumption norms, regulation of the use of money, reciprocity or cooperation, and even work norms (Elster, 1989). To cite only a few examples, conformism[2] and normative effects appear in working hours, dress code, courtesy rules, waste sorting but also meal-times. According to Kreps (1997), the fundamentals of these norms are multiple; they include peer-pressure effects, coordination between agents and lack of costs. Azar (2004) suggests norms avoiding over-exploitation of the commons.

Avoiding over-exploitation of the commons is of interest, especially for scarce resources such as water because norms can sustain vicious or virtuous cycles on environmental issues (Nyborg, 2020). Heterogeneous spatio-temporal repartition of water and conflicts of use, escalating with climate change (Ambec and Dinar, 2010), concern the actual use of water and generate new challenges. Therefore, to avoid transboundary conflicts or more local distortions, optimisation of water sharing is needed. Game theory researchers have been exploring the issue by focusing on various types of consumers (farmers, industries, and households) and territories (Madani, 2010). On cross-border flowing rivers (Ambec and Sprumont, 2002; Ambec and Ehlers, 2008; Ambec et al., 2013) and on sources (İlkılıç, 2011), the main objective of this theoretical framework is to limit sub-optimal extraction by reducing the deviations between consumptions and real needs.

Many instruments such as taxes, quotas, or even laws have been implemented to preserve water, but they are often not efficient enough to prevent overconsumption and the tragedy of the commons. Barnes et al. (2013) show that sometimes people subject to regulatory instruments suffer not only from an aversion of responsibility and lack of knowledge on regulative goals but also high resistance to enforced regulation. To correct these market failures, some authors (Barnes et al., 2013; Schubert, 2017) focus on the flourishing concept of nudge that can appeal to other-regarding preferences and

[1] Many definitions of social norms exist in the literature (see, for example, Elster (1989) and Kreps (1997)). In our study, we consider the social norm as the average action of neighbours as in the approach of Ushchev and Zenou (2020). The last part of this study with extensions of the model raises additional intuitions on the characterisation of this term.

[2] Conformism in this study follows the definition of Azar (2004), who states that *'conformist transmission is a tendency to copy the most frequent behaviour in the population, using the popularity of a choice as an indirect measure of its worth'* (page 50).

people's inclination to follow the crowd. Both empirical and theoretical studies have already emphasised the effects of informational social norm imposed by a regulator on water consumption (see, for example, Datta et al. (2015)'s study on the influence of neighbours consumption's information on domestic water, Chabe-Ferret et al. (2019)'s study on farmers with social comparison through smart grid consumption, Earnhart et al. (2020)'s study on social comparison in wastewater treatment facilities and Ouvrard and Stenger (2020)'s study on a formalisation of informational social norm incentives). In addition, Bénabou and Tirole (2006) point out that behaviours can be guided by not only intrinsic and extrinsic but also reputational motivations, which can backfire. For example, rewards can be low or even negative reinforcers when they exert hidden social costs (Bénabou and Tirole, 2006). Moreover, economic incentives can reduce effects of normative messages (Pellerano et al., 2017). As an example, Chabe-Ferret et al. (2019) observe a "boomerang" effect with an increase of consumption in low-water consumers. That is undesirable to preserve the resource.

To avoid the limitations of the regulative approach raised in the previous paragraph, this study aims to offer a theoretical framework on endogenous social norms in water extraction games. Let us start with a realistic example to get the intuition. Internalised norms can play a strong role in refining the preferences of water users. Imagine a group of farmers whose farms are near to each other, who endure the same periods of drought or abundance of the resource, who know each other, and who discuss their crops and irrigation practices. A farmer who waters without measurements during a drought will be singled out by others. Such a farmer will be exposed to shame, low self-esteem, embarrassment, and guilt, characteristics of the disapproval of others defined by Elster (1989). Thus, preferences of water extractors consider the way people look at each other, coordination between agents, wish to make an effort if others do likewise and so on. This echoed the quote by Gintis (2003) when the author said, *'internalized norms are accepted not as instruments towards and constraints upon achieving other ends, but rather as arguments in the preference function that the individual maximises'* (page 156).

To our knowledge, endogenous social norms' effect on water extraction is inadequately discussed theoretically in the literature. To address this research gap, we bridge three academic frameworks: social norms, water extraction games, and network theory. While we already introduced the first two, we now add a few comments on the last one. Network theory has been widely used in the contribution and the provision of public goods (Allouch, 2015; Bramoullé et al., 2007). As shown by Ballester et al. (2006), some agents can play a crucial role in behaviours of others and can, in our case, significantly influence the water extraction in the network of water users. Second, this literature can consider linear complementarity problems with games, including cross-influences (Ballester and Calvó-Armengol, 2010). That is, both substitutabilities and complementarities that appear in water extraction with social norms can be considered.

More formally, we consider a group of heterogeneous agents in a connected network with no self-loop links, sharing one common water resource. As in İlkılıç (2011), agents receive a concave benefit from their extraction such that the first units of water are essential, but as in Ambec and Ehlers (2008), they are also satiable. Additionally, we rely on İlkılıç (2011) who assumes that agents endorse a convex cost from extraction. This cost varies with the consumption of others. It introduces substitutabilities between agents because when one user extracts more, water becomes scarcer and less affordable for the others, who consequently consume less. The converse is true. Substitutabilities are sometimes balanced by complementarities coming from normative effects. When an agent increases (decreases) his or her consumption of water, neighbours will follow this trend by conformist transmission and also increase (decrease) their extractions. Note that we consider a descriptive type of norm[3] because, as in the work of Ushchev and Zenou (2020), norms are induced by the network of relations in itself and generate externalities on agents who deviate from it.

The rest of the paper is as follows. The next section introduces the model of water extraction with endogenous social norms. The main result of this study, presented in section 3, is to establish the uniqueness of the Nash equilibrium in a model of water extraction that considers endogenous social norms under a sufficient condition. This section also characterises the equilibrium. Afterward, comparative statics is provided on the relationship between individual parameters and global quantity extracted, and the network's

[3]In 1990, Cialdini et al. introduced the distinction between injunctive (what ought to be done) and descriptive norms (what is done); our study considers the second ones.

density. When water users are under moral constraint conditions, we obtain apparent results such as direct positive effects of the amplitude of the benefit and direct negative effects of cost and density of the network on total consumption. Section 5 discusses social optimum properties such that water users consider the diffusion of their actions in the whole network. Thus, we consider the social welfare[4] and provide a condition for the Nash equilibrium to be socially optimal. To avoid sub-optimal water extractions, we discuss the tragedy of the commons when individual extractions at equilibrium exceed the social optimum ones. Section 6 extends this model by discussing anti-conformism, formalising the social norm related to the notion of centrality[5], public implications and regulatory intervention. We conclude with the main contributions and limitations of the study. The proofs are provided in the appendix.

2 A model of water extraction

Consider a territory composed of n agents located around a unique common water pool. The set of agents, denoted by $N = \{1, \dots, n\}$, shares Q units of water that is the total amount of water extracted from this source (lake, river, ...). Each agent i extracts q_i such that the total quantity of retrieved water is the aggregate of individual consumptions, that is,

$$Q = \sum_{i \in N} q_i.$$

We denote Q_{-i} as the total consumption of all agents except i. Following the work of Ambec and Ehlers (2008), all agents need at least a minimum subsistence amount of water; therefore, individual extractions follow a non-negativity constraint. Hence, we have an interior equilibrium and for all i in N: $q_i > 0$.

As agents are sharing a common pool, they can interact and influence each other on water allocation. These interactions comprise the set of links between agents (with no self-loops links) denoted by L. Agent i and agent j are connected if $ij \in L$ exists. More formally, the undirected and unweighted graph $g = \{N, L\}$ represents social interactions

[4]This definition is commonly accepted in the literature (Lange, 1942) and has been widely used in water extraction processes (Ambec and Sprumont, 2002)

[5]According to Bloch et al. (2019), a centrality measure is a function $c : G(n) \to \mathbb{R}^n_+$ where $c_i(g)$ is the centrality of node i in the social network g

between agents during the water extraction process. The graph includes both a disjoint set of nodes formed by N agents and a set of links L between them.

Realistically, an agent does not necessarily interact with all others. However, because they share a common resource, the network is connected and there is no isolated individual. Given the interaction structure, let N_i be the set of neighbours of agent i, that is,

$$N_i = \{j \in N \text{ such that } ij \in L\}.$$

We denote n_i as the cardinal of N_i; that is the number of agents that i interacts with, such that $n_i \geq 1$ for all $i \in N$. Moreover, we write $\bar{Q}_i$, the social norm associated to the quantity extracted by i's neighbours, such that

$$\bar{Q}_i = \sum_{j \in N_i} \frac{q_j}{n_i} = \frac{Q_{N_i}}{n_i}.$$

Each agent i has a utility function $U_i : \mathbb{R}^n_+ \to \mathbb{R}$ given by

$$U_i = \alpha_i q_i - \frac{\beta_i}{2} q_i^2 - \gamma_i q_i Q - \frac{\delta_i}{2}(q_i - \bar{Q}_i)^2,$$

where α_i, β_i, γ_i and δ_i are strictly positive parameters. Note that agent's preferences are heterogeneous because water users do not necessarily have the same needs for the resource. This function is composed of three parts where the first two follow the water extraction game of İlkılıç (2011) but on a single source. This characterisation follows standard convex cost and concave benefit functions, widely used in natural resources (Smith, 1968). The third is a social norm, inspired by the work of Ushchev and Zenou (2020).

First, $\alpha_i q_i - \frac{\beta_i}{2} q_i^2 : \mathbb{R}_+ \to \mathbb{R}$ represents i 's concave benefit associated with the value of water extraction. The marginal value of extraction is defined by the amplitude of benefit α_i and its depreciating slope β_i. Per the incompressible consumption of first units of water, the marginal value for water extraction, which is linear and strictly decreasing with respect to individual consumption, is high enough to avoid no water consumption and corner solutions. This specification is also consistent with the work of Ambec and Ehlers (2008), which considers satiable agents, such that after an amount of consumed water, users suffer disutility from additional consumption.

Second, $\gamma_i q_i Q : \mathbb{R}_+ \to \mathbb{R}_+$ is a strictly convex cost function of extraction that relies on the total amount of consumed water. The marginal cost γ_i is defined such that the price of extraction for an additional unit of water is always more costly than the previous one. This parameter is sufficiently low to maintain the cost of water affordable for agents. Realistically, first water units extracted benefit from direct accessibility, better quality, the abundance of resources, and proximity. Conversely, the more consumption increases, the more scarce and expensive the resource is due to the lack of accessibility and proximity, transportation costs, leaks of conveyance, and bad quality. Thus, the convex cost function is dissuasive and limits the global extraction of water.

Third, the term $\frac{\delta_i}{2}(q_i - \bar{Q}_i)^2$ represents the endogenised social norm and consequently the influence of neighbourhood's water consumption on the extraction of agent i. Because water users assume a disutility induced by moral cost to deviate from the norm, they are influenced by other-regarding preferences. Parameter δ_i represents the taste for conformity of agent i such that $\delta_i > 0$ and $\bar{Q}_i$ is the endogenous social norm that varies according to the structure of the network. The higher δ_i is, the more agent i is a conformist and has a moral constraint to follow the others.

3 Equilibrium properties

In the following section, we introduce the equilibrium properties of the water extraction game presented in the previous model.

3.1 Existence and uniqueness of Nash equilibrium

Each water user chooses to maximise U_i by taking the network structure of relations and extractions of other agents on the common water source. All of them face the following optimisation problem:

$$\max_{q_i} \alpha_i q_i - \frac{\beta_i}{2} q_i^2 - \gamma_i q_i Q - \frac{\delta_i}{2}(q_i - \bar{Q}_i)^2$$

under constraint

$$q_i \geq 0, \forall i \in N.$$

Under Nash assumptions, agent i makes his or her own decisions. In contrast, Q_{-i} (quantity of water consumed by all agents except i) and $\bar{Q}_i$ are exogenously treated as they rely on the decisions of other agents. Note that the available extracted amount of water Q is implicitly limited by the convex cost function, which avoids an infinite quantity.

In this study, matrices are written in upper case and boldface, while vectors in lower case and boldface. A matrix to the power $\intercal$ denotes its transpose, and $\mathbf{I}$ is the notation for the identity matrix. The maximisation programme of water extractor is associated with the linear complementarity problem $LCP(-\boldsymbol{\alpha}, \mathbf{M})$, given in the appendix. As shown in the appendix, if $\frac{\beta_i}{\gamma_i} > n-3$, the interaction matrix $\mathbf{M}$ is strictly diagonally dominant and consequently ensures the uniqueness of the equilibrium with $\mathbf{q}$ as the vector of individual water extractions.

Theorem 1. *Assume that the following condition holds:*

$$\frac{\beta_i}{\gamma_i} > n - 3 \quad \textit{for all } i \in N. \tag{1}$$

Then, the water extraction game admits a unique Nash equilibrium.

Several comments on Theorem 1 are in order. First, we do not generalise the results of İlkılıç (2011), but we consider both positive and negative externalities (complementarities and substitutabilities, respectively) between agents following the work of Ballester and Calvó-Armengol (2010).

Second, note that $\frac{\beta_i}{\gamma_i}$ is an inverse ratio of second derivatives of the costs and benefits associated with water extraction. The second derivative of benefits represents the marginal will to consume more. The marginal benefit is expected to grow slowly when the extracted quantity increases. Conversely, the marginal cost is expected to increase rapidly when the extracted water quantity increases. If the evolution of marginal benefits is higher than the evolution of marginal costs, consumers extract increasingly more water. On the contrary, if marginal cost variation is really high, this ratio tends to be low, and agents extract increasingly less water. The variations of this ratio reflect the evolution of the marginal propensity to consume when the quantity of water extracted varies.

Third, to obtain the unicity of the Nash equilibrium, the agent's willingness to consume has to be high compared to the number of agents. Thus, parameter β for all agents should balance the number of water extractors included in the network to ensure a sufficient condition. However, this condition is less restrictive than it seems to be because parameter γ_i is low. It has to be little enough to avoid the unaffordable cost of water. Thus, if this parameter of cost is low enough, the limits of the ratio tend towards a high value

$$\lim_{\gamma_i \to 0} \frac{\beta_i}{\gamma_i} = \infty.$$

The condition of uniqueness is thus easily satisfied because the ratio of propensity to consume is high and easily exceeds $n-3$. It can even happen in really huge networks of many agents.

Fourth, this condition is sufficient but not necessary so that the uniqueness of Nash equilibrium is not guaranteed only under it. It can also be established in other cases without this sufficient condition. Further, it can open the diversity of possibilities for other examples of networks. This equilibrium is characterised in the following words.

3.2 Characterisation of Nash equilibrium

We investigate the characterisation of interior pure strategy Nash equilibrium, when all agents consume at least a minimum vital level of water[6], as in Ambec and Ehlers (2008). In case of interior solution, the quantity vector of water extractions is given by

$$\mathbf{q} = \mathbf{M}^{-1}\boldsymbol{\alpha}.$$

However, it is interesting to decompose $\mathbf{M}$ to understand all interactions between agents.

The first-order condition of utility maximisation for agent i with respect to q_i is given by

$$\frac{\partial U_i}{\partial q_i} = \alpha_i - \beta_i q_i - \gamma_i(q_i + Q) - \delta_i(q_i - \bar{Q}_i) + \mu_i = 0$$

$$\text{with } \mu_i \geq 0 \text{ and } \mu_i q_i = 0$$

where μ_i is the Karush-Kuhn-Tucker multiplier associated with the positivity constraint

[6] A relative condition on parameters such that $\alpha_i > \gamma_i Q_{-i} - \delta_i \bar{Q}_i$

on water extraction quantities. Note that the implications induced by social norms in the model are reflected in the first-order conditions such that

$$-\delta_i(q_i - \bar{Q}_i) \lesseqgtr 0 \Longleftrightarrow \bar{Q}_i \lesseqgtr q_i.$$

Thus, in maximising utility, an agent can be in three diverse situations. If $(q_i - \bar{Q}_i) = 0$, it is similar to a standard maximisation programme without social norm and marginal cost equalling marginal benefit. If $(q_i - \bar{Q}_i) > 0$ then the benefit has to compensate both the cost and the disutility of the social norm induced by overconsumption of water. When $(q_i - \bar{Q}_i) < 0$, then the benefit and social norm externality have to compensate the cost following a trend of not consuming a lot.

By computing the first-order condition of agent i with respect to q_i, we express the best-reply function for each water user as follows:

$$q_i = \frac{\alpha_i - \gamma_i Q_{-i} + \delta_i \bar{Q}_i}{\beta_i + 2\gamma_i + \delta_i}$$

or equivalently written in matrix form:

$$\mathbf{q} = \mathbf{a} - \mathbf{B}\mathbf{q} + \mathbf{C}\mathbf{q}$$

where the matrix $\mathbf{B}$ represents substitutabilities and $\mathbf{C}$ represents neighbourhood's complementarities. A substitutability effect is induced by the cost of water extraction, which increases for agent j when i consumes more and vice versa. Conversely, when individuals influence each other through peer effects, the social norm acts as a complementarity effect. By conformity, if individual i increases (or decreases) his or her consumption, his or her neighbour j will be encouraged to do likewise. Thus, the vector of individual extracted quantities $\mathbf{q}$ is given by the following fact.

Fact 1. *Assume condition (1) holds and let $q_i^* > 0$ for all $i = 1, \ldots, n$. Then, the unique Nash Equilibrium is given by*

$$\mathbf{q}^* = [\mathbf{I} - (\mathbf{C} - \mathbf{B})]^{-1}\mathbf{a}.$$

In the following proposition, $\mathbf{C} > \mathbf{B}$ implies that there exists at least one entry of matrix $\mathbf{C}$ superior to its equivalent entry in $\mathbf{B}$ and that all other entries are at least equal. Let ρ be the spectral radius[7] of a matrix.

Proposition 1. *Assume condition (1) holds and let $q_i^* > 0$ for all $i = 1, \ldots, n$. Then,*

1. *If $\mathbf{C} > \mathbf{B}$ and $\rho(\mathbf{C} - \mathbf{B}) < 1$, the unique Nash equilibrium is given by*

$$\mathbf{q}^* = \sum_{k=0}^{\infty} (\mathbf{C} - \mathbf{B})^k \mathbf{a}.$$

2. *If $\mathbf{C} < \mathbf{B}$ and $\rho(\mathbf{B} - \mathbf{C}) < 1$, the unique Nash equilibrium is given by*

$$\mathbf{q}^* = \left[\sum_{k=0}^{\infty} (\mathbf{B} - \mathbf{C})^{2k} - \sum_{k=0}^{\infty} (\mathbf{B} - \mathbf{C})^{2k+1} \right] \mathbf{a}.$$

A few comments on Proposition 1 are in order. The first case is a specific one as long as it concerns only complete graphs such that all of the out-of-diagonal terms in the matrix are composed of social norms and costs. It happens when the society is composed of strongly conformist agents and when social norms take the lead on cost effects. For both even and odd paths between agents, the effects on water extraction are positive, and complementarities introduced by norms exceed the costs. This situation is more plausible in small networks when everybody knows and talks to each other. In this case, water users are more likely to influence their neighbours' consumption and create spill-over effects.

The second case corresponds to a weak conformist society where the costs assumed by agents are predominant compared to social norms. Because $\mathbf{C} < \mathbf{B}$, the positive sign associated with the first sum implies that the equilibrium extraction from a link is negatively related to the even links that start from it. These strategic substitutabilities are coming from costs. Conversely, the negative sign behind the second sum for odd links induces complementarity effects between nodes that come from the normative conformism effects. Thus, complementarities are overtaken by substitutabilities induced by costs. This characterisation of norms highlights an alternance, depending on the degree and number of walks between the agents. Neighbours connected by an even number of links are influenced

[7] Let us consider an arbitrary matrix $\mathbf{M}$; the spectral radius of this matrix denoted by $\rho(\mathbf{M})$ is given by the largest modulus of its eigenvalues.

by strategic substitutabilities, while odd links between agents are more influenced by the social norm, which implies strong complementarities. This result highlights the role of intermediary agents who can balance the effects between non-neighbours.

Remark 1. If we cannot conclude on the predominant effect between substitutabilities and complementarities for all agents, then we cannot give a global characterisation of $\mathbf{q}$. Some elements of the matrix alone are non-negative.

Thus, in that case, it depends on the individual but not general conclusions. If an individual is characterised by a very strong social norm influence, it will outweigh the cost. $\mathbf{q}$ depends on individual heterogeneous parameters and the positioning within the network behind the construction of the interaction matrix.

Conditions required in the previous proposition state that spectral radius of matrices $(\mathbf{C} - \mathbf{B})$ and $(\mathbf{B} - \mathbf{C})$ (respectively for cases 1 and 2) have to be lower than 1 to follow the Perron-Frobenius theorem since matrices are non-negative. The highest eigenvalue increases if the network expands. However, following the Gershgorin theorem, all eigenvalues of the matrix are contained in a circle of radius. This implies that, in the first case, when $\mathbf{C} > \mathbf{B}$, the differential values between complementarities and substitutabilities are sufficiently low and complementarities over-compensate the cost. In the second case, when $\mathbf{C} < \mathbf{B}$, the values of substitutabilities are not sufficiently low to be compensated by complementarities, but the difference between the two stays small. Following the work of Ballester and Calvó-Armengol (2010), the spectral radius is an increasing function of networks links' intensity. In the first case, all out-of-diagonal terms are composed of both complementarities and substitutabilities. Each agent is connected to others to make the network dense and regular. On the contrary, in the second case, the complete network is a particular case, such that the network is most likely to be less dense and regular and to have a lower spectral radius.

In conclusion, the effects of norms on water extraction have complex implications. To avoid sub-optimal consumptions and over-exploitation of the resource, it is necessary to avoid destructive effects of norms, which lead to an increase in water consumption and tragedy of the commons. The following section determines the effects of individual parameters and network's influence on the global quantity extracted.

4 Comparative statics analysis

Relying on comparative statics analysis of the Nash equilibrium, this section aims to understand the properties of the model through the effects of heterogeneous individual parameters, conformism, and density of the network on global water extraction.

In the following results, we consider $e_i = \dfrac{\delta_i}{\beta_i + \gamma_i + \delta_i}$, which is the moral motivation of agent i to extract water. This parameter pertains to $]0,1[$ and relies on taste for conformity. A value close to one indicates a highly conformist behaviour under strong moral constraint. On the contrary, a value close to zero indicates a weak moral constraint induced by other-regarding preferences such that conformism is not prioritised in individual decisions. In this case, we observe individualist behaviours. Note that as γ_i is necessarily low, the value of this moral motivation depends on the relative values of δ_i and β_i. If the slope of marginal benefit is high, it implies a low moral motivation regarding the others because individual interests increase and conversely so.

4.1 How individual parameters influence water extraction

Let us start with the amplitude of benefit α_i from water extraction.

Proposition 2. *Assume condition (1) holds and let $q_i^* > 0$ for all $i = 1, \dots, n$. Suppose the following condition also holds:*

$$\sum_{i \in N_1} \frac{e_i}{n_i} = \dots = \sum_{i \in N_n} \frac{e_i}{n_i}. \tag{2}$$

Then, the change in total water consumption resulting from a change in amplitude of benefit for any agent i is given by

$$dQ = \sigma_i d\alpha_i$$

where $\sigma_i > 0$.

Before studying the effects of the amplitude of benefit directly, let us discuss the second condition required for all static comparative results. Condition (2) refers to ponderated moral motivation that relies on the number of neighbours. For instance, equality between sums can appear when an individual has more neighbours with a huge moral motivation, and another only a few neighbours with a small moral motivation. This equality can also occur if the moral motivation of agents match and they have the same number of neighbours (cardinal number of neighbours). Thus, this ratio highlights the moral motivation with respect to the structure of the neighbourhood in the network of relations. If this condition does not hold, we cannot conclude. The effect of variations of a parameter on the total water extraction can be positive, negative, or null.

Remark 2. Suppose that for all agents i in N, the parameter of taste for conformity δ_i is null. Then condition (2) always holds because the moral motivation e_i for all agents i in N turns out to be equal to zero.

This remark applies to all propositions of comparative statics. When agents do not care about the social norm, only condition (1) is required for the following propositions.

Considering the individual amplitude of benefit, we observe a direct positive effect of a change in this parameter (α_i) on the change in total water consumption. This result is apparent and intuitive. An increase in the benefit amplitude for an agent will induce an increase in water consumption and consequently raise the total water extraction.

We now focus on the effect of the slope of marginal benefit β_i on extraction outcomes.

Proposition 3. *Assume condition (1) and (2) hold, and let $q_i^* > 0$ for all $i = 1, \ldots, n$. Then, the change in total water consumption resulting from a change of the slope of the marginal benefit for any agent i is given by*

$$dQ = -\sigma_i q_i^* d\beta_i$$

where $\sigma_i > 0$.

The direct effect of a change in the slope of marginal benefit (β_i) negatively impacts the change in total water consumption. In the individual utility function, the higher this slope, the more the value of an additional unit of water is depreciated. Thus, it is intuitive to notice that a change in this slope induces a direct negative effect on the change in total water extraction. In addition, note that this negative effect increases with the value of extracted water at equilibrium for an agent i. The more agent i extracts at equilibrium, the more a change in the slope of marginal benefit will impact the total water extraction.

An agent i with a high level of consumption can significantly impact the total water extracted.

Now we look at the impact of the cost effect on individual and global water extraction.

Proposition 4. *Assume condition (1) and (2) hold, and let* $q_i^* > 0$ *for all* $i = 1, \ldots, n$. *Then, the change in total water consumption resulting from a change of the slope of marginal cost for any agent* i *is given by*

$$dQ = -\sigma_i \left(Q^* + q_i^*\right) d\gamma_i$$

where $\sigma_i > 0$.

Under linear mapping simplification of moral constraints, the direct price effect of a small change in the slope of marginal cost (γ_i) negatively impacts the total water consumption. This result seems logical insofar as a variation in the slope of the marginal cost will have an impact on the direct benefit derived by agent i from water consumption. The higher the cost of an additional unit of water, the less incentive an individual will have to extract water. Furthermore, this change in total water extraction is positively impacted by the quantity extracted at equilibrium by agent i and the entire structure of the network of water users. The cost of first water units is lower because it benefits from direct accessibility, proximity, and availability of the resource. Thus, if the individual quantity of any agent i and the general quantity extracted at equilibrium increase, it amplifies the negative direct effect of a variation of the slope of marginal benefit on the total water extraction, leading to a direct negative impact of a change in the slope of the marginal cost on the change in the total water extraction.

This expected negative direct price effect on global quantity should, however, be discussed more extensively. If moral constraints do not follow condition (2), a more complex mechanism of interactions can arise and can be decomposed in the following steps:

- A direct negative impact of an increase in the price for one agent decreases his or her consumption and, consequently, the global quantity.
- Neighbours of this agent have an incentive to follow this line and also decrease their water consumption because of conformity to the norm.

- However, if many agents decrease their consumption, water will be more accessible and cost less.
- This reduction of cost and water accessibility encourages agents, even the first agent previously impacted by the cost effect, to increase their consumption.

Thus, depending on the predominant effect, a price increase can also lead to more consumption. This effect of cost should be treated cautiously.

4.2 Does a conformist society extract more water?

This subsection focuses on the eagerness of taste for conformity δ_i on individual and global outcomes of water extraction.

Proposition 5. *Assume condition (1) and (2) hold, and let* $q_i^* > 0$ *for all* $i = 1, \ldots, n$. *Then, the change in the total water consumption resulting from a change of the taste for conformity for any agent* i *is given by*

$$dQ = \sigma_i \left(\bar{Q}_i^* - q_i^* \right) d\delta_i$$

where $\sigma_i > 0$.

The change in taste for conformity for any agent i impacts the change in the total water consumption in two ways that induce an ambiguous effect. This direct effect is positively related to the value of the social norm of agent i. A change in taste for conformity – for instance, an individual i is more conformist – induces a positive change in the total water extraction that is amplified through the value of his or her social norm. A high social norm, by conformity, will incentivise individual i to increase his or her consumption. With peer effects, it is the total quantity of consumed water that will increase. Conversely, the change in taste for conformity induces a negative direct effect of the total water consumption directly related to individual extraction of agent i at equilibrium. The higher the individual extraction of agent i, the higher the negative impact of a change of his or her taste for conformity on total water extraction. Thus, this ambiguous effect of taste for conformity offers two configurations. The first one occurs if the social norm of agent i exceeds the agent's consumption at equilibrium $(\bar{Q_i}^* - q_i^* > 0)$. A change of taste for conformity induces a positive change in the total water extraction. Agents want to conform more to the norm due to the variation in the taste for conformity and imitate others, thus raising the total consumption. The second configuration occurs if the individual consumption of agent i exceeds his or her social norm at equilibrium $(\bar{Q_i}^* - q_i^* < 0)$ and induces a negative change on the total water extraction. Here, the change in taste for conformity negatively affects the total water extraction because user i is a huge water extractor. If the agent increases his or her taste for conformity, he or she will follow others, thus reducing his or her extraction and consequently the global one.

4.3 Do users extract more water in denser networks?

In this section, we investigate how the creation or the deletion of a link between two network agents influences water extraction.

Proposition 6. *Assume condition (1) and (2) hold, and let $q_i^* > 0$ for all $i = 1, \ldots, n$. Then, the change in total water consumption resulting from the addition or the deletion of a link between any two agents i and j is given by*

$$dQ = -\sigma \left(\frac{e_i}{n_i} \bar{Q}_i^* dn_i + \frac{e_j}{n_j} \bar{Q}_j^* dn_j \right)$$

where $\sigma > 0$.

This proposition shows that in any network, we can observe a negative effect of a change in the network's density on the total water consumption. This negative effect increases with the respective moral motivations of agents i and j denoted by e_i and e_j, but also by their respective social norm values at equilibrium. The more their neighbours extract the resource, and they have a moral motivation to follow them, the more the direct negative effect of a change in density on total water extraction is important. On the contrary, if the cardinal number of neighbours for i and j is high and agents are much more connected, this direct negative effect would be less important. This is understandable because if they are already a lot of links in the network, the creation or the deletion of one link will only have a slight effect on the total water extraction.

We studied the effects of individual parameter variation, conformism strength, and density of the network on the total water consumption. The following section provides more details on how agents can reach a social optimum configuration.

5 Welfare and social optimum properties

We now analyse social optimum properties in the case of interior solutions. In this study, we consider social welfare denoted by W as the sum of individual utilities given by:

$$W = \sum_{i=1,2,\ldots,n} U_i.$$

Here, social welfare represents the aggregated satisfaction of agents coming from their extraction of water. Thus, the maximisation problem of society's welfare from water extraction is given by

$$\max_{q_i} \sum_{i=1}^{n} \left[\alpha_i q_i - \frac{\beta_i}{2} q_i^2 - \gamma_i q_i Q - \frac{\delta_i}{2} (q_i - \bar{Q}_i)^2 \right]$$

$$\text{s.t. } q_i > 0, \text{ for all } i \text{ in } N.$$

The next proposition introduces a characterisation of the first best extraction of water. It also provides a condition for the Nash equilibrium to be the first best.

Proposition 7 (First best)**.** *Let $q_i^o > 0$ for all $i = 1, \ldots, n$. Then,*

1. *For each agent i, the first best extraction of water q_i^o is a solution to*

$$q_i = \frac{\alpha_i - \gamma_i Q_{-i} + \delta_i \bar{Q}_i - \sum_{j \neq i} \gamma_j q_j + \sum_{k \in N_i} \frac{\delta_k}{n_k} (q_k - \bar{Q}_k)}{\beta_i + 2\gamma_i + \delta_i}$$

or, in a matrix form,

$$\mathbf{q} = \mathbf{a} - \mathbf{B}\mathbf{q} + \mathbf{C}\mathbf{q} - \mathbf{N}\mathbf{q}.$$

2. *If condition (1) holds and $q_i^* > 0$ for all $i = \ldots, n$, the unique Nash equilibrium is socially optimal, i.e., $\mathbf{q}^* = \mathbf{q}^o$, if and only if the following condition holds:*

$$\mathbf{N} \left[\mathbf{I} - (\mathbf{C} - \mathbf{B}) \right]^{-1} \mathbf{a} = \mathbf{0}.$$

Part 1 of this proposition highlights the difference between Nash equilibrium and optimum best answer. Compared to the Nash equilibrium, this first best answer has two additional terms, also represented by the addition of the **N** matrix. With social optimum, agents care about the diffusion of their influence in the network on the choices of others. The first additional term, denoted by $\sum_{j \neq i} \gamma_j q_j$ represents the negative impact of cost induced by others' extraction from the common pool. The higher this sum of individual costs assumed by others is, the lesser the amount of water individual i extracts at social optimum. The second additional term, denoted by $\sum_{k \in N_i} \frac{\delta_k}{n_k}(q_k - \bar{Q}_k)$, corresponds to the social norms deviations of all neighbours of agent i. For each agent k that is a neighbour of agent i, it sums the deviation between k's extraction and his or her respective social norm, ponderated by his or her taste for conformity. Thus, two configurations appear. First, if $(q_k - \bar{Q}_k)$ is positive, for instance, agent k extracts more than the mean consumption of his or her neighbours, the quantity extracted by agent i is positively impacted. As k is part of i's neighbourhood, if his or her consumption is high, agent i will have an incentive to do likewise. Secondly, if $(q_k - \bar{Q}_k)$ is negative, for instance, agent k extracts less than the mean consumption of his or her neighbours, it will impact negatively the quantity extracted by i at social optimum. Agent i will get closer to his or her neighbours and thus decrease consumption to follow this line. This last term is a sum of $\frac{\delta_k}{n_k}(q_k - \bar{Q}_k)$ across all neighbours of agent i. Thus, some neighbours can be in the first configuration and others in the second one. One effect of this social norm prevails on the other and influences positively or negatively the first best extraction at optimum. We also observe a snowball effect from the indirect social norm because this effect relies on the social norms of neighbours and thus two degrees connections from i, going by the intermediary of k.

In conclusion, at the Nash equilibrium, when agents decide their best level of water extraction, they do not consider the positive or negative externalities induced by their extraction on others' satisfaction. On the contrary, at social optimum's first best, agents consider costs assumed by others and their influence through direct and indirect social norms. The focus on society's welfare implies that each individual's choice of water consumption depends on his or her impact on the rest of water extractors through consumption costs, and direct and indirect norms of the others. For instance, in a group of domestic consumers or farmers, it implies that people will care about others, show altruism to ensure that everybody can afford some water, and care about other-regarding preferences and self-image.

The second part of proposition 8 provides a condition on the matrix such that the extraction quantities at the Nash equilibrium are identical to those extracted at social optimum. This condition relies on the matrix $\mathbf{N}$, which introduces the consideration of others' utility in the maximisation problem. It needs precise parameters adequation and could thus be uncommon to hold. Still, water extractors can reach the vector of individual extracted quantities at the social optimum $\mathbf{q}$, given by the following Fact 2. It not only relies both complementarities $\mathbf{C}$ and substitutabilities $\mathbf{B}$ but also on $\mathbf{N}$, which represents interactions induced by the consideration of society's welfare.

Fact 2. *Let $q_i^o > 0$ for all $i = 1, \ldots, n$. Then, the social optimum is given by*

$$\mathbf{q}^o = [\mathbf{I} - (\mathbf{C} - \mathbf{B}) + \mathbf{N}]^{-1}\mathbf{a}.$$

To respect individual social welfare and implement a fair division of the resource, over-exploitation by some water users must be avoided. Otherwise, as they all extract on a single shared resource, it can lead to a tragedy of the commons that deteriorates the water resource. The definition of the tragedy of the commons introduced by Hardin (1968) is taken in its strong sense, meaning that all agents over-extract from the common water pool. Thus, for all agents i in N, the individual extraction at equilibrium exceeds the one at social optimum. For instance,

$$\mathbf{q}^* >> \mathbf{q}^o.$$

The following proposition states a condition for the tragedy of the commons to hold.

Proposition 8 (Tragedy of the commons)**.** *Assume condition (1) holds. Let $q_i^* > 0$ and $q_i^o > 0$ for all $i = 1, \ldots, n$. If $\mathbf{C} > \mathbf{B}$, $\rho(\mathbf{C} - \mathbf{B}) < 1$ and the following condition holds:*

$$\sum_{j \in N \setminus \{i\}} \gamma_j q_j^o - \sum_{k \in N_i} \frac{\delta_k}{n_k} \left(q_k^o - \bar{Q}_k^o \right) > 0 \quad \text{for all } i \in N, \tag{3}$$

then, in equilibrium, each agent overconsumes water compared to the first best.

Remark 3. Consider that condition (3), in the previous proposition, is reversed such that the difference between the two sums is negative. Then, in equilibrium, each agent underconsumes water compared to the first best.

This proposal considers all agents that form the extraction network, with positive extractions at (unique) equilibrium and social optimum. We observe a tragedy of the commons when condition 3 applies to all of them. This condition requires that for each agent i, the difference between the sum of costs assumed by all agents except i ponderated by their optimal individual quantity of extraction and the weighted sum of the differences for each of his or her neighbours between their equilibrium quantity and their social norm is positive. In this case, agent i overconsumes. Doing the same for all agents i, we obtain that all of them overconsume at an individual scale, and thus a tragedy of the commons in a strong sense occurs. Tragedy of the commons is an usual outcome of water extraction games and natural resources (Hardin, 1968; İlkılıç, 2011). However, proposition 8 requires that complementarities underpass substitutabilities, which can happen only in complete graphs. In case of $\mathbf{B} > \mathbf{C}$ we cannot generalize the results. Thus, some agents overconsume and some others underconsume water. This under-consumption may be due, for example, to a lack of suitable agricultural infrastructure for farmers, or to hanchored consumption habits for households. It therefore takes time to adapt these consumptions to real needs. Now that we have discussed welfare and consumption optimality, the following section extends our model.

6 Extensions

6.1 Anti-conformism

This extension follows the model settings of Ushchev and Zenou (2020) where the social norm is ponderated by the taste of conformity of agents. We now consider anti-conformists behaviours of water extractors such that $\delta_i < 0$ represents the taste for non-conformity. The amplitude of this parameter indicates the will of an agent to distinguish himself or herself from others. For instance, this can happen when individuals have strong, anchored habits in water consumption or even when keeping a good self-image when they do not consume a lot. Instead of complementarities, the social norm here acts now as substitutabilities. Thus, when a neighbour of agent i increases his or her consumption of water, agent i has an incentive to decrease his or her consumption and deviate from the norm.

Proposition 9. *Assume condition (1) holds and let $\delta_i < 0$ for all $i = 1, \ldots, n$. Suppose that the following condition also holds:*

$$\beta_i + 2\gamma_i > -\delta_i \quad \textit{for all } i \in N.$$

Then, the water extraction game admits a unique Nash equilibrium.

As long as agents are not too anti-conformists, our model with a unique Nash equilibrium can be extended to the case of non-conformity. Thus, we observe higher differences between individual extraction, as homophily is not the rule anymore. The relative value of taste for non-conformity (δ_i) has to be sufficiently low compared to β_i. Otherwise, we cannot prove the uniqueness of the equilibrium. In the case of slightly non-conformist agents, most of the equilibrium analysis still holds, but it implies new interpretations of the results. For instance, equilibrium's best-reply function (given in part 3.2) states that agent i's consumption relies positively on the amplitude of individual benefit, which is now balanced both by cost and social norm. When others extract more, i will extract less to deviate from others and avoid unaffordable costs.

One major concern of this extension compared to the approach of Ushchev and Zenou (2020) is that the complementarities induced by cost effects included in individual decisions are even accentuated with these anti-conformists behaviours. Non-conformity acts as a reinforcer of cost-effectiveness. When an agent i increases his or her consumption, his or her neighbour j will be doubly influenced to decrease his or her consumption: both because the cost of water increases due to scarcity and deviates from the behaviour of i.

More generally, degrees of conformism can have a really strong influence on water consumption. To discuss it further, we can distinguish four main situations and make a parallel with the approach of norms of Schultz et al. (2007) who distinguish constructive, destructive, and reconstructive effects of norms. The first one occurs when an individual i, a less-water-consumer, increases his or her extraction to get closer to others, weakening the water resource. This is defined by Schultz et al. (2007) as the destructive effect of norms. Another situation happens when individual i is a conformist and a high consumer among low ones. In this situation, we observe a constructive effect such that the agent will decrease his or her extraction to get close to the others, preserving more of the resource. A third situation considers an anti-conformist agent i in a high consumer group that will have an incentive to consume less water quantity to deviate from the others. This effect is a reconstructive one. The last situation occurs when a non-conformist agent is among less-water-consumers and is incentivised to increase his or her consumption, as a free rider behaviour. In this situation, i enjoys affordability and disponibility of the resource given that others do not extract a lot on the common resource. This elicitation on various situations and effects of conformism show that it could play a strong role in the preservation of water resources.

6.2 Reference consumption

This extension presents two different situations in which the reference consumption is not the social norm anymore but a ponderated one. In the first situation, agents have an incentive to behave virtuously and tend towards a lower consumption than the norm. The second situation is the opposite of the first. Agents have an incentive to free-ride and benefit from extracting more than the social norm. In our case, adding a ponderation on the social norm will not significantly change the results and demonstration of the Nash equilibrium's uniqueness except that it introduces a parameter behind social norm in the disutility of agents to diverge from the norm.

To address this issue, let us extend the utility function of agents such that $U_i : \mathbb{R}^n_+ \to \mathbb{R}$ is given by

$$U_i = \alpha_i q_i - \frac{\beta_i}{2} q_i^2 - \gamma_i q_i Q - \frac{\delta_i}{2}(q_i - \lambda_i \bar{Q}_i)^2,$$

where $0 < \lambda_i < 1$ is the reference ponderation factor of the norm for agent i in the first situation. The reference consumption is thus lower than his or her social norm consumption. In the second situation, $\lambda_i > 1$ such that the reference consumption is higher than the social norm consumption. Note that in the case of $\lambda_i = 1$, we note no difference from our standard model.

Characterisation of the equilibrium includes a ponderation from the reference consumption. It slightly modifies the results. However, as this ponderation is positive and only ponderates complementarities, the equilibrium consumptions follow the same lines as above. Thus, best-reply-function for each individual i at equilibrium is now given by

$$q_i = \frac{\alpha_i - \gamma_i Q_{-i} + \lambda_i \delta_i \bar{Q}_i}{\beta_i + 2\gamma_i + \delta_i}$$

Equivalently written in matrix form :

$$\mathbf{q} = \mathbf{a} - \mathbf{B}\mathbf{q} + \mathbf{\Lambda}\mathbf{C}\mathbf{q}$$

where $\mathbf{\Lambda}$ is a dimension $n \times n$ matrix such that

$$\lambda_{i,j} = \begin{cases} 0 & \text{for } i = j \text{ or for } (i \neq j \text{ and } j \notin N_i) \\ \lambda_i & \text{for } i \neq j \text{ and } j \in N_i. \end{cases}$$

The matrix $\mathbf{M}$ stays a P-Matrix with a positive ponderation on the norm that can influence up or down the reference consumption. It follows the same line of proof of Theorem 1, but this time with a λ_i parameter before the taste for conformity that still ensures the uniqueness of the equilibrium.

Depending on whether λ_i is lower or higher than one, interpretations of the results are slightly modified as defined for each case in the following words.

6.2.1 When agents follow injunctive norms

Our model focuses on what is done by others (descriptive norm) but not on what must be done (injunctive one). However, the literature shows that it can be interesting to combine both of them (Le Coent et al., 2021). People know that water is an important and scarce resource that has to be preserved. Thus, it seems realistic to assume that agents may be incentivised to diminish their consumption for environmental motivation. To discuss this point, we introduce a reference consumption that people could follow and that is lower than what their neighbours are doing. In this first case, agents are thus incentivised to follow a lower reference than the social norms of neighbours.

This influences the interpretation of the model. In the best-reply function with ponderation of social norm, compared to the standard model, the positive impact of the social norm on individual consumption (given by $\lambda_i \delta_i \bar{Q}_i$) is depreciated. It encourages less i to consume water. More generally, the matrix $\mathbf{\Lambda}$ weights down each of the existing complementarities introduced by social norm. It guides towards a low consumption of water, which is seen as beneficial for the preservation of the resource.

Thus, based on a reference consumption point, this extension details the case when individuals, for ecological reasons, have an incentive to diminish their water consumption and preserve the resource, following an implicit injunctive norm.

6.2.2 When agents free-ride

This part follows the same line as the previous, but it takes the opposite direction and focuses on free-riding behaviours (see Grossman et al. (1993) for an empirical example of such behaviours). It follows the approach of Ushchev and Zenou (2020), who studied the ambition of agents. In our case, as we focus on the water, it corresponds to a situation in which agents may benefit from extracting more water than the average consumption of their neighbours. If all agents extract little, water would still be affordable for an agent i who would have an incentive to consume a lot and even to overexploit the resource without paying exorbitant costs in exchange.

The reference consumption of agents is now amplified and exceeds the mean value of neighbours' consumption. In the best-reply function, with over ponderation of the social norm, the positive impact of the social norm on individual consumption ($\lambda_i \delta_i \bar{Q}_i$) is high and encourages i to consume more water.

More generally, the matrix $\mathbf{\Lambda}$ weighs up individual consumption of water as it incentivises to exceed social norm's consumption of water. It induces over-exploitation and free-riding behaviours, which are problematic for the preservation of the resource. Thus, this second situation details free-riding effects when agents do not fairly exploit the resource and do not bear a cost commensurate with the degradation of the resource.

To conclude on this extension, we show that the uniqueness of the Nash equilibrium persists when we change upwards or downwards the normative reference point. In the first case, people tend to decrease their consumption compared to the norm for environmental reasons. In the second case, agents benefit from the access to water at a low cost. They have an incentive to deviate from the norm to increase their consumption at an affordable price, overexploiting the resource.

6.3 Characterisation of social norms

Until now, we have focused on social norms as the mean value of neighbours. Mean value norms have been widely used in the academic literature (Ushchev and Zenou, 2020) and also in experimental fields (Bernedo et al., 2014; Datta et al., 2015). However, this measurement presents limitations. First, only direct neighbours with one-degree connection reference the social norm. The diffusion process and positioning in the complete architecture of the extraction network is neglected. Secondly, we notice a smoothing of consumptions of neighbours briefly discussed by Ushchev and Zenou (2020) following a study on graduates. The mean value of the norm does not reflect variations between consumers and provides smoothed incentives for agents. For instance, in France, people use approximately 150 litres of tap water each day. However, this mean value could be composed of consumers who extract 130 and 170 litres or 100 and 200 litres. The last two situations will provide the same social norm while the reality of consumption is very different. Thirdly, mean value norm points the finger only on huge consumers while it can be interesting to consider relative performance to target all of them (Brent et al., 2020). To palliate these limitations, this extension offers various suggestions to adapt norm's measurement. For more salience, we discuss the effects of each specification with examples on four agents. Our discussion allows covering a huge diversity of social network structures. Circular (G1), complete (G2), linear (G3), irregular (G4), and star networks (G5) are represented in the following figures.

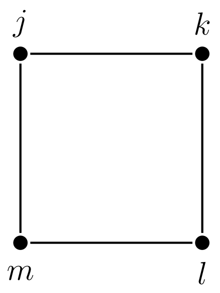

Figure 1: Circular graph

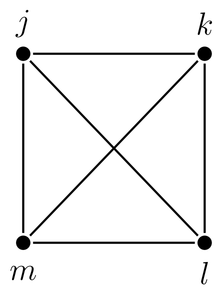

Figure 2: Complete graph

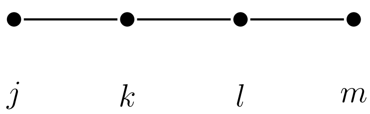

Figure 3: Linear graph

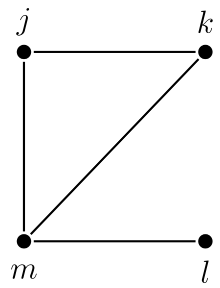

Figure 4: Irregular graph

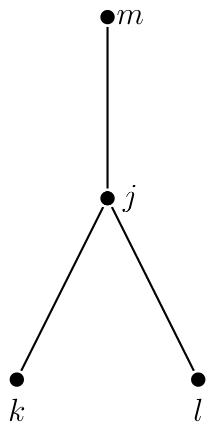

Figure 5: Star graph

6.3.1 Social norm based on variance

We first suggest a representation of social norm based on variance with other water extractors such that

$$\bar{Q}_i = \frac{\sum\limits_{i \neq j} (q_j - q_i)^2}{n_i}.$$

To consider all variations between agent i's consumption and his or her neighbours' consumption, variance catches more variability and does not suffer from the smoothing of consumptions reproached to mean values.

Here, if an agent deviates upwards or downwards from his or her neighbours' quantity, he or she is subject to externalities from non-conformity. Thus the disutility induced by variations (both upwards or downwards) leads to homophily between agents who want to conform to the others.

The application of such a norm on an example with four agents is provided in the appendix. This norm palliates to the smoothing of variability between consumptions of water but still does not consider the global structure of the network. A third measure aims to correct the limit by introducing some weak ties in normative effects.

6.3.2 Strength of weak ties on water consumption

Developed by Granovetter (1973), the concept of strength of weak ties relies on the importance of intermediary agents and central positions of individuals. Torres and Carlsson (2018) show that direct effects of social information on water savings are coupled with spill-over effects on untargeted agents and that there is a strong diffusion of social incentives among people. In their paper, Minato et al. (2010) study the management of lands and natural resources in a changing rural community and highlight that *'key players in the community have many connections and a strong influence to initiate (or resist) change'* (page 399). They discuss the central position of some agents (due to seniority, knowledge, roles,...) in diffusion processes and their strong influence on natural resource management. This approach considers both influential and peripheral stakeholders. There is a trend to get close to popular and central ones. To preserve water, these key agents should adopt virtuous behaviours for the resource, expecting that others will follow them and reduce waste.

Herewith, we develop another measurement of the social norm, which takes roots in the eigenvector centrality defined by Bonacich (1972). The centrality of the node i is proportional to the sum of centralities of neighbours of this node, considering weak ties for each water extractor. Consequently, this measurement of norms depends on indirect neighbours with a degree connection equal to or higher than one. For instance, we can state that

$$\bar{Q}_i = \frac{\sum\limits_{i \neq j} n_j q_j}{\sum\limits_{i \neq j} n_j}, \forall j \in N_i$$

where we divide the quantity ponderated by j's degree centrality for each j by the cardinal of j's neighbours for all agents. This characterisation of the norm allows considering a centrality of two degrees.

The application of such a norm on an example with four agents is given in the appendix. It shows that in regular networks, these norms are equal to the mean value because all agents have an identical degree of centrality $n-1$. In addition, on an irregular network, there is a stronger influence of closely connected neighbours because their centrality and popularity are higher. To complete this measurement, we can suppress the constraint that j is in N_i.

6.3.3 Closeness of social norms in the complete network

Another measurement of a social norm that we would like to discuss relies on the paper of Datta et al. (2015), which shows that city comparison involves fewer effects than the neighbourhood one. These low effects come from the lack of proximity between agents in the first case. A more recent field study based on the reduction of shower time in the context of water scarcity was conducted by Lede (2019). This study shows empirically that ingroup norm appeals are more effective than general ones because social identity to the closest group is stronger. Theoretically, this idea is defined by a social norm where the water extraction process of agent i is guided by the choices of all the agents who compose the connected network but also length of paths between them. It takes roots in the closeness and Katz Bonacich's centrality measurements (Katz, 1953; Bonacich, 1987). The closeness' centrality is based on distances in the network between one node and another such that a high score induces a low centrality. Herewith, we consider that the more the distance between node i and another node is high, the lower is its influence on i's water consumption. This following characterisation of centrality also presents similitudes with the Katz Bonacich (1953, extended in 1987) centrality, which states that centrality relies on the number of walks from node i and their length. We could imagine a calculation of the norm such that

$$\bar{Q_i} = \frac{\sum_{i \neq j} \delta_j q_j}{\sum_{i \neq j} \delta_j}$$

for all j in N so that the higher the length between i and j, the less δ_j is important. We consider all j of N, that is, the complete structure of the network.

The application of this kind of norm on an example with four agents is given in the appendix. Let us reconsider our examples of four agents. In all cases, as the social norm considers the entirety of the network, for all j in N: $\bar{Q_j} = \frac{\delta_k q_k + \delta_l q_l + \delta_m q_m}{\delta_k + \delta_l + \delta_m}$ but what differs is the value of all δ parameters, which would be higher for closer neighbours. Note that when we consider a complete graph, the length between all agents is the same, and thus social norm measurement is equivalent to a simple mean norm over all the graphs.

6.3.4 General comments

If we consider a complete graph, some similarities between kinds of norms appear. Various reasons can explain them. First, the number of connections of each agent is identical and equals to $n-1$, that is, the total number of agents except the one referred to. Thus, it follows that for all i in N, $n_i = n_j = |N_i| = n-1$. Moreover, in a complete graph, all agents are directly connected to each other such that for all i in N , $Q_{N_i} = \sum_{i \neq j} q_j$. In this special case of a complete graph,

$$\frac{Q_{N_i}}{n_i} = \frac{\sum_{i \neq j} n_j q_j}{\sum_{i \neq j} n_j} = \frac{\sum_{i \neq j} \delta_j q_j}{\sum_{i \neq j} \delta_j} = \frac{\sum_{i \neq j} q_j \Delta_j}{n_i}$$

$$\iff \frac{Q_{N_i}}{n-1} = \frac{\sum_{i \neq j} (n-1) q_j}{(n-1)^2}$$

However, a complete graph is scarce in reality except in small networks and towns where all agents know each other. In this case, only peer comparison can apply to everybody in the city on water consumption. To compare the previous norm calculations, the following table offers a summary:

	Implications on water extraction	Main characteristics	Associated centrality measure	Part of the network included	Limits
Mean value	In a group of high consumers, there is a destructive effect (high consumption) and contrarily a constructive effect in a group of low consummers.	$\bar{Q}_i = \frac{Q_{N_i}}{n_i}$	Degree centrality	Direct relations (one degree links)	Incomplete network that do not consider global consumption and smoothing of influences from neighbours
Variance	Homophily between agents to decrease the desutility of non-conformism	$\bar{Q}_i = \frac{\sum_{i \neq j} (q_j - q_i)^2}{n_i}$	Degree centrality	Direct relations (one degree links)	Incomplete network that does not consider global structure of extraction
Strength of weak ties	Importance of intermediary and central agents. If key agents are virtuous, it decreases water consumption, otherwise it results in overconsumption	$\bar{Q}_i = \frac{\sum_{i \neq j} n_j q_j}{\sum_{i \neq j} n_j}$	Eigenvector centrality	Indirect links and intermediary (two degrees links)	Structure of network limited to some indirect links. On regular networks it is as mean value so it smoothes influences.
Closeness social norms	Proximity between agents higher their influences on each other. Individuals follow close neighbours and if they are low consumers, it decreases consumption.	$\bar{Q}_i = \frac{\sum_{i \neq j} \delta_j q_j}{\sum_{i \neq j} \delta_j}$	Closeness and Katz Bonacich centrality measures	Complete network	If close neighbours are high consumers it influences others to follow overconsumption

Table 1: Synthesis of norms

7 Concluding comments

This study analyses impacts of social norms in a model of water extraction where heterogeneous agents share a single common resource. As proposed by İlkılıç (2011), individual utility functions are composed of a concave benefit of extraction and a convex cost, which relies on others' consumption. To refine these preferences, we add social norms and other-regarding considerations using the term of taste for conformity inspired by Ushchev and Zenou (2020). The main result of this study is to establish the uniqueness of the Nash equilibrium under a sufficient condition. As in Ushchev and Zenou (2020), this result holds when agents are slightly anti-conformist. The result allows considering various situations. Conformism occurs when agents care about peer-pressure effects, fairness of water sharing, homophily, and trends effect. It also allows considering small deviations from the norm because of anchored habits of consumption, self-image, or even free-riding behaviours. Thus, this model offers an operational framework to study equilibrium water consumption.

Afterward, the study provides comparative statics analysis to understand the effects of individual parameters and global consumption of water. Some intuitive conclusions include the positive direct effect of an increase in amplitude extraction value on the global extraction or a direct negative effect from an increase in the price. However, some effects concerning the taste for conformity are more ambiguous. This echoes the literature on social norms, which highlights constructive, reconstructive, or destructive effects (Schultz et al., 2007). More specifically, in the case of water, ambiguity can also come from geographical delimitation where proximity often encourages the collective reduction of water consumption (Datta et al., 2015).

As water is a scarce but necessary good, this study also offers insights into social welfare and optimal water consumption. Water users consider the impacts of their consumptions on others' satisfaction and spill-over effects of norms. Additionally, we provide a condition for the Nash equilibrium to be socially optimal and avoid the tragedy of the commons. Investigation is crucial to preserve the resource.

As the effects of the norm and peer pressure can strongly impact people's behaviour, the last part offers extensions of this model to discuss any situations, such as, when some individuals turn to be anti-conformists or free riders. In addition, norm incentives have been widely seen as mean values of neighbours' consumption in the academic literature (Ushchev and Zenou, 2020) and also in experimental fields (Bernedo et al., 2014; Datta et al., 2015). However, these norms based on mean value have limitations. Hence, this study also discusses formalising these standards and shows how they can influence water consumption, and discusses other types of norm measurements. Here, we deliberately focus on endogenous social norms as they are inadequately studied elsewhere in water theoretical frameworks. However, this discussion on formalising norms also offers interesting patterns for exogenous norms (for instance, the information provided by a regulator). Some types of social norms are more appropriate to target other types of consumers.

This study also raises other research questions. First, the endogenous structure of the graph stems from the consideration of water resources and the domestic extraction process. In real life, people do not choose their living place or farming area depending on the water extraction of their neighbours but mainly on other criteria. Thus, the network in itself is already imposed on people and consequently, at least partly, on the social norm. However, an external regulation from public authorities or water firms can play a crucial role and generate links to raise collective awareness among water users. An additional regulatory intervention could influence the network structure with incentives, taxes, and connections to avoid sub-optimal consumptions. The second perspective of research is open on the formalisation of norms. This study focuses on descriptive norms, but injunctive ones could also be appropriate. There is a common awareness regarding the need to preserve the resource and consume sustainably. This goes hand-in-hand with further research on complementarity between normative incentives and other regulative tools. A third limitation to the study is that it focuses on theoretical aspects of the model. It could be interesting to also try applying the model with empirical simulations and agent based models to provide new insights into endogenous norms in networks.

8 Appendix

The first order conditions define the following linear complementarity problem (Cottle et al., 2009). For all $i = 1, \dots, n$, the problem is to find an extraction $q_i \geq 0$ which satisfies the system

$$\begin{cases} q_i \geq 0 \\ \alpha_i - \beta_i q_i - \gamma_i (q_i + Q) - \delta_i (q_i - \bar{Q}_i) \leq 0 \\ \left[\alpha_i - \beta_i q_i - \gamma_i (q_i + Q) - \delta_i (q_i - \bar{Q}_i)\right] q_i = 0 \end{cases}$$

or equivalently, find a vector $\mathbf{q} \in \mathbb{R}^n_+$ which satisfies the system

$$\begin{cases} \mathbf{q} \geq \mathbf{0} \\ -\boldsymbol{\alpha} + \mathbf{M}\mathbf{q} \geq \mathbf{0} \\ \mathbf{q}^\mathsf{T}(-\boldsymbol{\alpha} + \mathbf{M}\mathbf{q}) = 0 \end{cases}$$

where $\boldsymbol{\alpha} = [\alpha_i]_{n \times 1} \in \mathbb{R}^n_+$ and $\mathbf{M} = [m_{i,j}]_{n \times n}$ is such that

$$m_{i,j} = -\frac{\partial U_i}{\partial q_i \partial q_j} = \begin{cases} \beta_i + 2\gamma_i + \delta_i & \text{for } i = j \\ \gamma_i - \dfrac{\delta_i}{n_i} & \text{for } i \neq j \text{ and } j \in N_i \\ \gamma_i & \text{for } j \neq i \text{ and } j \notin N_i. \end{cases}$$

Let LCP$(-\boldsymbol{\alpha}, \mathbf{M})$ denote the above linear complementarity problem.

Proof of Theorem 1. Following Cottle et al. (2009, Theorem 3.3.7), the LCP$(-\boldsymbol{\alpha}, \mathbf{M})$ admits a unique solution if $\mathbf{M}$ is a P-matrix. A sufficient condition is that $\mathbf{M}$ be a strictly diagonally dominant matrix with positive diagonal entries (Berman and Plemmons, 1994, Theorem 2.3, p.134). The matrix $\mathbf{M}$ is said to be strictly diagonally dominant if

$$m_{i,i} > \sum_{j \in N \setminus \{i\}}^{n} |m_{i,j}| \quad \text{for all } i \in N.$$

Since $\beta_i / \gamma_i > n - 3$, it holds that

$$\beta_i + 2\gamma_i + \delta_i > (n-1)\,|\gamma_i| + n_i \left| -\frac{\delta_i}{n_i} \right| \quad \text{for all } i \in N.$$

By the triangle inequality property of the absolute value, it holds that

$$\begin{aligned} & |\gamma_i| + \left|-\frac{\delta_i}{n_i}\right| \geq \left|\gamma_i - \frac{\delta_i}{n_i}\right| \\ \iff\ & n_i\,|\gamma_i| + n_i\left|-\frac{\delta_i}{n_i}\right| \geq n_i\left|\gamma_i - \frac{\delta_i}{n_i}\right| \\ \iff\ & n_i\left|-\frac{\delta_i}{n_i}\right| \geq n_i\left|\gamma_i - \frac{\delta_i}{n_i}\right| - n_i\,|\gamma_i| \quad \text{for all } i \in N. \end{aligned}$$

It follows that

$$\begin{aligned} \beta_i + 2\gamma_i + \delta_i &> (n-1)\,|\gamma_i| + n_i\left|\gamma_i - \frac{\delta_i}{n_i}\right| - n_i\,|\gamma_i| \\ &= (n - n_i - 1)\,|\gamma_i| + n_i\left|\gamma_i - \frac{\delta_i}{n_i}\right| \quad \text{for all } i \in N. \end{aligned}$$

Thus, $\mathbf{M}$ is a strictly diagonally dominant matrix with positive diagonal entries, and uniqueness is established.

□

Proof of Fact 1. Since $q_i^* > 0$ for all $i = 1, \ldots, n$, the $LCP(-\boldsymbol{\alpha}, \mathbf{M})$ reduces to

$$-\boldsymbol{\alpha} + \mathbf{Mq} = \mathbf{0} \iff \mathbf{q} = \mathbf{M}^{-1}\boldsymbol{\alpha}$$

where $\mathbf{M}^{-1}$ exists since $\mathbf{M}$ is a P-matrix. Hence, the first order conditions yield

$$q_i = \frac{\alpha_i - \gamma_i Q_{-i} + \delta_i \bar{Q}_i}{\beta_i + 2\gamma_i + \delta_i} \quad \text{for all } i \in N,$$

or equivalently,

$$\mathbf{q} = \mathbf{a} - \mathbf{Bq} + \mathbf{Cq} \iff \mathbf{q}^* = [\mathbf{I} - (\mathbf{C} - \mathbf{B})]^{-1}\mathbf{a}$$

where $\mathbf{a} = [\alpha_i/(\beta_i + 2\gamma_i + \delta_i)]_{n\times 1}$, $\mathbf{B} = [b_{i,j}]_{n\times n}$ is such that

$$b_{i,j} = \begin{cases} 0 & \text{for } i = j \\ \dfrac{\gamma_i}{\beta_i + 2\gamma_i + \delta_i} & \text{for } i \neq j \end{cases}$$

and $\mathbf{C} = [c_{i,j}]_{n\times n}$ is such that

$$c_{i,j} = \begin{cases} 0 & \text{for } i = j \text{ or for } (i \neq j \text{ and } j \notin N_i) \\ \dfrac{\delta_i}{\beta_i + 2\gamma_i + \delta_i} & \text{for } i \neq j \text{ and } j \in N_i. \end{cases}$$

□

Proof of Proposition 1. Part 1. Since $\mathbf{C} - \mathbf{B}$ is nonnegative and $\rho(\mathbf{C} - \mathbf{B}) < 1$, it holds that $\mathbf{C} - \mathbf{B}$ is convergent (Berman and Plemmons, 1994, Lemma 2.1, p.133). Hence, $[\mathbf{I} - (\mathbf{C} - \mathbf{B})]^{-1}$ exists and

$$\mathbf{q}^* = [\mathbf{I} - (\mathbf{C} - \mathbf{B})]^{-1}\,\mathbf{a} = \sum_{k=0}^{\infty}(\mathbf{C} - \mathbf{B})^k\mathbf{a}.$$

Part 2. Since $\mathbf{B} - \mathbf{C}$ is nonnegative and $\rho(\mathbf{B} - \mathbf{C}) < 1$, it holds that $\mathbf{B} - \mathbf{C}$ is convergent, so $(\mathbf{B} - \mathbf{C})^2$ is also convergent.[8] Hence, $[\mathbf{I} - (\mathbf{B} - \mathbf{C})^2]^{-1}$ exists and

$$\left[\mathbf{I} - (\mathbf{B} - \mathbf{C})^2\right]^{-1} = \sum_{k=0}^{\infty}(\mathbf{B} - \mathbf{C})^{2k}.$$

Furthermore, it holds that

$$\begin{aligned} & [\mathbf{I} + (\mathbf{B} - \mathbf{C})]\,[\mathbf{I} - (\mathbf{B} - \mathbf{C})] &=& [\mathbf{I} - (\mathbf{B} - \mathbf{C})^2] \\ \Longleftrightarrow \quad & \mathbf{I} + (\mathbf{B} - \mathbf{C}) &=& [\mathbf{I} - (\mathbf{B} - \mathbf{C})^2]\,[\mathbf{I} - (\mathbf{B} - \mathbf{C})]^{-1} \\ \Longleftrightarrow \quad & [\mathbf{I} + (\mathbf{B} - \mathbf{C})]^{-1} &=& [\mathbf{I} - (\mathbf{B} - \mathbf{C})^2]^{-1}\,[\mathbf{I} - (\mathbf{B} - \mathbf{C})]\,. \end{aligned}$$

Hence,

$$\mathbf{q}^* = [\mathbf{I} + (\mathbf{B} - \mathbf{C})]^{-1}\,\mathbf{a} = \sum_{k=0}^{\infty}(\mathbf{B} - \mathbf{C})^{2k}\,[\mathbf{I} - (\mathbf{B} - \mathbf{C})]\,\mathbf{a},$$

that is,

$$\mathbf{q}^* = \left[\sum_{k=0}^{\infty}(\mathbf{B} - \mathbf{C})^{2k} - \sum_{k=0}^{\infty}(\mathbf{B} - \mathbf{C})^{2k+1}\right]\mathbf{a}.$$

□

Proof of Proposition 2. Totally differentiating i's best-response function (while keeping

[8] By Gelfand's Formula, it holds that $\rho((\mathbf{B} - \mathbf{C})^2) \leq \rho(\mathbf{B} - \mathbf{C})\rho(\mathbf{B} - \mathbf{C}) < 1$.

$d\beta_i = d\gamma_i = d\delta_i = dn_i = 0$) yields

$$\begin{aligned} dq_i = & \frac{1}{\beta_i + 2\gamma_i + \delta_i} d\alpha_i - \frac{\gamma_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{-i} + \frac{\delta_i / n_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{N_i} \\ = & \frac{1}{\beta_i + \gamma_i + \delta_i} d\alpha_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{\delta_i / n_i}{\beta_i + \gamma_i + \delta_i} dQ_{N_i} \\ = & \frac{1}{\beta_i + \gamma_i + \delta_i} d\alpha_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{e_i}{n_i} dQ_{N_i}. \end{aligned}$$

Then, summing across all i,

$$\begin{aligned} dQ = & \sum_{i \in N} \left\{ \frac{1}{\beta_i + \gamma_i + \delta_i} d\alpha_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{e_i}{n_i} dQ_{N_i} \right\} \\ = & k \sum_{i \in N} \left\{ \frac{1}{\beta_i + \gamma_i + \delta_i} d\alpha_i + \frac{e_i}{n_i} dQ_{N_i} \right\} \end{aligned}$$

where

$$k = \left(1 + \sum_{i \in N} \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} \right)^{-1} \in (0, 1).$$

Let $d\alpha_i \neq 0$ for one agent i and $d\alpha_j = 0$ for all other agent $j \neq i$. It follows that

$$dQ = \frac{k}{\beta_i + \gamma_i + \delta_i} d\alpha_i + k \sum_{i \in N} \frac{e_i}{n_i} dQ_{N_i}.$$

Under condition (2), it holds that

$$\sum_{i \in N} \frac{e_i}{n_i} dQ_{N_i} = \frac{e_1}{n_1} dQ_{N_1} + \ldots + \frac{e_n}{n_n} dQ_{N_n} = \sum_{i \in N_1} \frac{e_i}{n_i} dq_1 + \ldots + \sum_{i \in N_n} \frac{e_i}{n_i} dq_n = v dQ$$

where $0 < v < 1$. Thus,

$$dQ = \sigma_i d\alpha_i$$

where

$$\sigma_i = \frac{k}{(1 - kv)(\beta_i + \gamma_i + \delta_i)} > 0.$$

□

Proof of Proposition 3. Totally differentiating i's best-response function (while keeping

$d\alpha_i = d\gamma_i = d\delta_i = dn_i = 0)$ yields

$$\begin{aligned}
dq_i = & \frac{-(\alpha_i - \gamma_i Q_{-i} + \delta_i \bar{Q}_i)}{(\beta_i + 2\gamma_i + \delta_i)^2} d\beta_i - \frac{\gamma_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{-i} + \frac{\delta_i / n_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{N_i} \\
= & \frac{-q_i^*}{\beta_i + 2\gamma_i + \delta_i} d\beta_i - \frac{\gamma_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{-i} + \frac{\delta_i / n_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{N_i} \\
= & \frac{-q_i^*}{\beta_i + \gamma_i + \delta_i} d\beta_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{\delta_i / n_i}{\beta_i + \gamma_i + \delta_i} dQ_{N_i} \\
= & \frac{-q_i^*}{\beta_i + \gamma_i + \delta_i} d\beta_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{e_i}{n_i} dQ_{N_i}.
\end{aligned}$$

Then, summing across all i yields

$$\begin{aligned}
dQ = & \sum_{i \in N} \left\{ \frac{-q_i^*}{\beta_i + \gamma_i + \delta_i} d\beta_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{e_i}{n_i} dQ_{N_i} \right\} \\
= & k \sum_{i \in N} \left\{ \frac{-q_i^*}{\beta_i + \gamma_i + \delta_i} d\beta_i + \frac{e_i}{n_i} dQ_{N_i} \right\}
\end{aligned}$$

where

$$k = \left(1 + \sum_{i \in N} \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} \right)^{-1} \in (0, 1).$$

Let $d\beta_i \neq 0$ for one agent i and $d\beta_j = 0$ for all other agent $j \neq i$. The rest of the proof follows the same lines as that of Proposition 2. Hence,

$$dQ = -\sigma_i q_i^* d\beta_i$$

where

$$\sigma_i = \frac{k}{(1 - kv)(\beta_i + \gamma_i + \delta_i)} > 0.$$

□

Proof of Proposition 4. Totally differentiating i's best-response function (while keeping $d\alpha_i = d\beta_i = d\delta_i = dn_i = 0)$ yields

$$\begin{aligned}
dq_i = & \frac{-Q_{-i}^*(\beta_i + 2\gamma_i + \delta_i) - 2(\alpha_i - \gamma_i Q_{-i}^* + \delta_i \bar{Q}_i^*)}{(\beta_i + 2\gamma_i + \delta_i)^2} d\gamma_i - \frac{\gamma_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{-i} + \frac{\delta_i / n_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{N_i} \\
= & \frac{-Q_{-i}^* - 2q_i^*}{\beta_i + 2\gamma_i + \delta_i} d\gamma_i - \frac{\gamma_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{-i} + \frac{\delta_i / n_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{N_i} \\
= & \frac{-Q^* - q_i^*}{\beta_i + \gamma_i + \delta_i} d\gamma_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{\delta_i / n_i}{\beta_i + \gamma_i + \delta_i} dQ_{N_i} \\
= & \frac{-Q^* - q_i^*}{\beta_i + \gamma_i + \delta_i} d\gamma_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{e_i}{n_i} dQ_{N_i}.
\end{aligned}$$

Then, summing across all i yields

$$\begin{aligned} dQ = & \sum_{i\in N}\left\{\frac{-Q^*-q_i^*}{\beta_i+\gamma_i+\delta_i}d\gamma_i - \frac{\gamma_i}{\beta_i+\gamma_i+\delta_i}dQ + \frac{e_i}{n_i}dQ_{N_i}\right\} \\ = & \ k\sum_{i\in N}\left\{\frac{-Q^*-q_i^*}{\beta_i+\gamma_i+\delta_i}d\gamma_i + \frac{e_i}{n_i}dQ_{N_i}\right\} \end{aligned}$$

where

$$k = \left(1+\sum_{i\in N}\frac{\gamma_i}{\beta_i+\gamma_i+\delta_i}\right)^{-1} \in (0,1).$$

Let $d\gamma_i \neq 0$ for one agent i and $d\gamma_j = 0$ for all other agent $j \neq i$. The rest of the proof follows the same lines as that of Proposition 2. Hence,

$$dQ = -\sigma_i\left(Q^* + q_i^*\right)d\gamma_i$$

where

$$\sigma_i = \frac{k}{(1-kv)(\beta_i+\gamma_i+\delta_i)} > 0.$$

□

Proof of Proposition 5. Totally differentiating i's best-response function (while keeping $d\alpha_i = d\beta_i = d\gamma_i = dn_i = 0$) yields

$$\begin{aligned} dq_i = & \ \frac{\bar{Q}_i^*(\beta_i+2\gamma_i+\delta_i)-(\alpha_i-\gamma_i Q_{-i}^*+\delta_i\bar{Q}_i^*)}{(\beta_i+2\gamma_i+\delta_i)^2}d\delta_i - \frac{\gamma_i}{\beta_i+2\gamma_i+\delta_i}dQ_{-i} + \frac{\delta_i/n_i}{\beta_i+2\gamma_i+\delta_i}dQ_{N_i} \\ = & \ \frac{\bar{Q}_i^*-q_i^*}{\beta_i+2\gamma_i+\delta_i}d\delta_i - \frac{\gamma_i}{\beta_i+2\gamma_i+\delta_i}dQ_{-i} + \frac{\delta_i/n_i}{\beta_i+2\gamma_i+\delta_i}dQ_{N_i} \\ = & \ \frac{\bar{Q}_i^*-q_i^*}{\beta_i+\gamma_i+\delta_i}d\delta_i - \frac{\gamma_i}{\beta_i+\gamma_i+\delta_i}dQ + \frac{\delta_i/n_i}{\beta_i+\gamma_i+\delta_i}dQ_{N_i} \\ = & \ \frac{\bar{Q}_i^*-q_i^*}{\beta_i+\gamma_i+\delta_i}d\delta_i - \frac{\gamma_i}{\beta_i+\gamma_i+\delta_i}dQ + \frac{e_i}{n_i}dQ_{N_i}. \end{aligned}$$

Then, summing across all i yields

$$\begin{aligned} dQ = & \sum_{i\in N}\left\{\frac{\bar{Q}_i^*-q_i^*}{\beta_i+\gamma_i+\delta_i}d\delta_i - \frac{\gamma_i}{\beta_i+\gamma_i+\delta_i}dQ + \frac{e_i}{n_i}dQ_{N_i}\right\} \\ = & \ k\sum_{i\in N}\left\{\frac{\bar{Q}_i^*-q_i^*}{\beta_i+\gamma_i+\delta_i}d\delta_i + \frac{e_i}{n_i}dQ_{N_i}\right\} \end{aligned}$$

where

$$k = \left(1 + \sum_{i \in N} \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i}\right)^{-1} \in (0, 1).$$

Let $d\delta_i \neq 0$ for one agent i and $d\delta_j = 0$ for all other agent $j \neq i$. The rest of the proof follows the same lines as that of Proposition 2. Hence,

$$dQ = \sigma_i \left(\bar{Q}^* - q_i^*\right) d\delta_i$$

where

$$\sigma_i = \frac{k}{(1 - kv)(\beta_i + \gamma_i + \delta_i)} > 0.$$

□

Proof of Proposition 6. Totally differentiating i's best-response function (while keeping $d\alpha_i = d\beta_i = d\gamma_i = d\delta_i = 0$) yields

$$\begin{aligned} dq_i = & \frac{-\delta_i Q_{N_i}^*/(n_i)^2}{\beta_i + 2\gamma_i + \delta_i} dn_i - \frac{\gamma_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{-i} + \frac{\delta_i/n_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{N_i} \\ = & \frac{-\delta_i \bar{Q}_{N_i}^*/n_i}{\beta_i + 2\gamma_i + \delta_i} dn_i - \frac{\gamma_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{-i} + \frac{\delta_i/n_i}{\beta_i + 2\gamma_i + \delta_i} dQ_{N_i} \\ = & \frac{-\delta_i \bar{Q}_{N_i}^*/n_i}{\beta_i + \gamma_i + \delta_i} dn_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{\delta_i/n_i}{\beta_i + \gamma_i + \delta_i} dQ_{N_i} \\ = & \frac{-\delta_i \bar{Q}_{N_i}^*/n_i}{\beta_i + \gamma_i + \delta_i} dn_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{e_i}{n_i} dQ_{N_i}. \end{aligned}$$

Then, summing across all i yields

$$\begin{aligned} dQ = & \sum_{i \in N} \left\{ \frac{-\delta_i \bar{Q}_{N_i}^*/n_i}{\beta_i + \gamma_i + \delta_i} dn_i - \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i} dQ + \frac{e_i}{n_i} dQ_{N_i} \right\} \\ = & k \sum_{i \in N} \left\{ \frac{-\delta_i \bar{Q}_{N_i}^*/n_i}{\beta_i + \gamma_i + \delta_i} dn_i + \frac{e_i}{n_i} dQ_{N_i} \right\} \end{aligned}$$

where

$$k = \left(1 + \sum_{i \in N} \frac{\gamma_i}{\beta_i + \gamma_i + \delta_i}\right)^{-1} \in (0, 1).$$

Let $dn_i = dn_j = \pm 1$ for two agents i and j, and $d\delta_k = 0$ for all other agent $k \neq i, j$. The rest of the proof follows the same lines as that of Proposition 2. Hence,

$$dQ = -\sigma \left(\frac{e_i}{n_i} \bar{Q}_i^* dn_i + \frac{e_j}{n_j} \bar{Q}_j^* dn_j \right)$$

where

$$\sigma = \frac{k}{1-kv} > 0.$$

□

Proof of Proposition 7. Part 1. Since $q_i^o > 0$ for all $i = 1, \ldots, n$, the first order condition of total welfare maximization with respect to q_i is given by

$$\frac{\partial W}{\partial q_i} = \alpha_i - \beta_i q_i - \gamma_i (q_i + Q) - \delta_i \left(q_i - \bar{Q}_i\right) - \sum_{j \in N \setminus \{i\}} \gamma_j q_j + \sum_{k \in N_i} \frac{\delta_k}{n_k} \left(q_k - \bar{Q}_k\right) = 0.$$

Hence, it holds that

$$q_i = \frac{\alpha_i - \gamma_i Q_{-i} + \delta_i \bar{Q}_i - \sum_{j \neq i} \gamma_j q_j + \sum_{k \in N_i} \frac{\delta_k}{n_k} \left(q_k - \bar{Q}_k\right)}{\beta_i + 2\gamma_i + \delta_i} \quad \text{for all } i \in N.$$

Let $N_i^2 = \{k \in N \text{ such that } k \in N_j \text{ for all } j \in N_i,\ k \neq i\}$ denote the set of neighbours (except i) of i's neighbours. Then, in matrix notation, it holds that

$$\mathbf{q} = \mathbf{a} - \mathbf{Bq} + \mathbf{Cq} - \mathbf{Nq}$$

where $\mathbf{N} = [\eta_{i,j}]_{n \times n}$ is such that

$$\eta_{i,j} = \begin{cases} \dfrac{\sum_{k \in N_i} \frac{\delta_k}{(n_k)^2}}{\beta_i + 2\gamma_i + \delta_i} & \text{for } i = j \\ \dfrac{\gamma_j - \frac{\delta_j}{n_j} + \sum_{k \in N_i \cap N_j} \frac{\delta_k}{(n_k)^2}}{\beta_i + 2\gamma_i + \delta_i} & \text{for } i \neq j \text{ s.t. } j \in N_i \text{ and } j \in N_i^2 \\ \dfrac{\gamma_j - \frac{\delta_j}{n_j}}{\beta_i + 2\gamma_i + \delta_i} & \text{for } i \neq j \text{ s.t. } j \in N_i \text{ and } j \notin N_i^2 \\ \dfrac{\gamma_j + \sum_{k \in N_i \cap N_j} \frac{\delta_k}{(n_k)^2}}{\beta_i + 2\gamma_i + \delta_i} & \text{for } i \neq j \text{ s.t. } j \notin N_i \text{ and } j \in N_i^2 \\ \dfrac{\gamma_j}{\beta_i + 2\gamma_i + \delta_i} & \text{for } i \neq j \text{ s.t. } j \notin N_i \text{ and } j \notin N_i^2. \end{cases}$$

Part 2. Comparing the equilibrium profile (Fact 1) to the socially optimal profile (Part 1 above), we find that $\mathbf{q}^* = \mathbf{q}^o$ if and only if the following condition holds:

$$\mathbf{Nq}^* = \mathbf{0}.$$

Using Fact 1, this is equivalent to

$$\mathbf{N}\left[\mathbf{I}-(\mathbf{C}-\mathbf{B})\right]^{-1}\mathbf{a}=\mathbf{0}.$$

□

Proof of Fact 2. Since $q_i^o > 0$ for all $i = 1, \ldots, n$, the first order conditions of total welfare maximization yield

$$\mathbf{q}=\mathbf{a}-\mathbf{B}\mathbf{q}+\mathbf{C}\mathbf{q}-\mathbf{N}\mathbf{q} \Longleftrightarrow \mathbf{q}^o=\left[\mathbf{I}-(\mathbf{C}-\mathbf{B})+\mathbf{N}\right]^{-1}\mathbf{a}.$$

□

Proof of Proposition 8. In equilibrium, the first order conditions are

$$\alpha_i-\beta_i q_i^*-\gamma_i(q_i^*+Q^*)-\delta_i(q_i^*-\bar{Q}_i^*)=0 \quad \text{for all } i\in N,$$

since $q_i^* > 0$ for all $i = 1, \ldots, n$. Hence, in matrix notation, we obtain

$$\mathbf{q}^*=\mathbf{a}-\mathbf{B}\mathbf{q}^*+\mathbf{C}\mathbf{q}^* \Longleftrightarrow \left[\mathbf{I}-(\mathbf{C}-\mathbf{B})\right]\mathbf{q}^*=\mathbf{a}.$$

Moreover, since $q_i^o > 0$ for all $i = 1, \ldots, n$, the first order conditions for the efficient profile are

$$\alpha_i-\beta_i q_i^o-\gamma_i\left(q_i^o+Q^o\right)-\delta_i\left(q_i^o-\bar{Q}_i^o\right)-\left[\sum_{j\in N\setminus\{i\}}\gamma_j q_j^o-\sum_{k\in N_i}\frac{\delta_k}{n_k}\left(q_k^o-\bar{Q}_k^o\right)\right]=0 \quad \text{for all } i\in N.$$

Under condition (3) it follows that

$$\alpha_i-\beta_i q_i^o-\gamma_i\left(q_i^o+Q^o\right)-\delta_i\left(q_i^o-\bar{Q}_i^o\right)>0, \quad \text{for all } i\in N.$$

Hence, in matrix notation, we obtain

$$\mathbf{q}^o<\mathbf{a}-\mathbf{B}\mathbf{q}^o+\mathbf{C}\mathbf{q}^o \Longleftrightarrow \left[\mathbf{I}-(\mathbf{C}-\mathbf{B})\right]\mathbf{q}^o<\mathbf{a}$$

Then,

$$[\mathbf{I}-(\mathbf{C}-\mathbf{B})]\,\mathbf{q}^{*}=\mathbf{a}>[\mathbf{I}-(\mathbf{C}-\mathbf{B})]\,\mathbf{q}^{o}$$

$$[\mathbf{I}-(\mathbf{C}-\mathbf{B})]^{-1}\,[\mathbf{I}-(\mathbf{C}-\mathbf{B})]\,\mathbf{q}^{*}>[\mathbf{I}-(\mathbf{C}-\mathbf{B})]^{-1}\,[\mathbf{I}-(\mathbf{C}-\mathbf{B})]\,\mathbf{q}^{o}$$

$$\mathbf{q}^{*}>\mathbf{q}^{o}$$

Since $\mathbf{C}>\mathbf{B}$ and $\rho(\mathbf{C}-\mathbf{B})<1$, so $[\mathbf{I}-(\mathbf{C}-\mathbf{B})]^{-1}\geq\mathbf{I}$.

□

Proof of Proposition 9. Let $\delta_i<0$ for all $i=1,\ldots,n$ such that the society of agent is guided by anti-conformism. Suppose that $\beta_i+2\gamma_i>-\delta_i$ for all $i\in N$. Thus it is equivalent to $\beta_i+2\gamma_i+\delta_i>0$ and consequently, all diagonal entries of $\mathbf{M}$ are positive. The rest of the proof follows the same line at that of Theorem 1. □

Calculations of examples for social norms' measurements

Graph	G1	G2	G3
$\bar{Q}_j$	$\frac{(q_k-q_j)^2+(q_m-q_j)^2}{2}$	$\frac{(q_k-q_j)^2+(q_l-q_j)^2+(q_m-q_j)^2}{3}$	$(q_k-q_l)^2$
$\bar{Q}_k$	$\frac{(q_j-q_k)^2+(q_l-q_k)^2}{2}$	$\frac{(q_j-q_k)^2+(q_l-q_k)^2+(q_m-q_k)^2}{3}$	$\frac{(q_j-q_k)^2+(q_l-q_k)^2}{2}$
$\bar{Q}_l$	$\frac{(q_k-q_l)^2+(q_m-q_l)^2}{2}$	$\frac{(q_k-q_l)^2+(q_j-q_l)^2+(q_m-q_l)^2}{3}$	$\frac{(q_k-q_l)^2+(q_m-q_l)^2}{2}$
$\bar{Q}_m$	$\frac{(q_j-q_m)^2+(q_l-q_m)^2}{2}$	$\frac{(q_j-q_m)^2+(q_l-q_m)^2+(q_l-q_m)^2}{3}$	$(q_l-q_m)^2$

Graph	G4	G5
$\bar{Q}_j$	$\frac{(q_k-q_j)^2+(q_m-q_j)^2}{2}$	$\frac{(q_k-q_j)^2+(q_l-q_j)^2+(q_m-q_j)^2}{3}$
$\bar{Q}_k$	$\frac{(q_j-q_k)^2+(q_m-q_k)^2}{2}$	$(q_j-q_k)^2$
$\bar{Q}_l$	$(q_m-q_l)^2$	$(q_j-q_l)^2$
$\bar{Q}_m$	$\frac{(q_j-q_m)^2+(q_l-q_m)^2+(q_l-q_m)^2}{3}$	$(q_j-q_m)^2$

Table 2: Variance norms with 4 agents

Graph	G1	G2	G3	G4	G5
$\bar{Q}_j$	$\frac{2q_k+2q_m}{4}$	$\frac{3q_k+3q_l+3q_m}{9}$	$\frac{2q_k}{2}$	$\frac{2q_k+3q_m}{5}$	$\frac{q_k+q_l+q_m}{3}$
$\bar{Q}_k$	$\frac{2q_j+2q_l}{4}$	$\frac{3q_j+3q_l+3q_m}{9}$	$\frac{q_j+2q_l}{3}$	$\frac{2q_j+3q_m}{5}$	$\frac{3q_j}{3}$
$\bar{Q}_l$	$\frac{2q_k+2q_m}{4}$	$\frac{3q_j+3q_k+3q_m}{9}$	$\frac{2q_k+q_m}{3}$	$\frac{3q_m}{3}$	$\frac{3q_j}{3}$
$\bar{Q}_m$	$\frac{2q_j+2q_l}{4}$	$\frac{3q_j+3q_k+3q_l}{9}$	$\frac{2q_l}{2}$	$\frac{2q_j+2q_k+q_l}{5}$	$\frac{3q_j}{3}$

Table 3: Strength of weak ties with 4 agents

Graph	All graphs
$\bar{Q_j}$	$\frac{q_k\delta_k+q_l\delta_l+q_m\delta_m}{\delta_k+\delta_l+\delta_m}$
$\bar{Q_k}$	$\frac{q_j\delta_j+q_l\delta_l+q_m\delta_m}{\delta_j+\delta_l+\delta_m}$
$\bar{Q_l}$	$\frac{q_j\delta_j+q_k\delta_k+q_m\delta_m}{\delta_j+\delta_k+\delta_m}$
$\bar{Q_m}$	$\frac{q_j\delta_j+q_k\delta_k+q_l\delta_l}{\delta_j+\delta_k+\delta_l}$

Table 4: Closeness norm with 4 agents

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Tel. +39 02.520.36934
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