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Governing a Common-Pool Resource in a Directed Network

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Summary

A local public-good game played on directed networks is analyzed. The model is motivated by one-way flows of hydrological influence between cities of a river basin that may shape the level of their contribution to the conservation of wetlands. It is shown that in many (but not all) directed networks, there exists an equilibrium, sometimes socially desirable, in which some stakeholders exert maximal effort and the others free ride. It is also shown that more directed links are not always better. Finally, the model is applied to the conservation of wetlands in the Gironde estuary (France).

Keywords: Common-pool Resource, Digraph, Cycle, Independent Set, Empirical Example

JEL Classification: C72, D85, H41

This work has been developed while Lionel Richefort was a post doctorate fellow at the Research Group on Theoretical and Applied Economics (GREThA) of the University of Bordeaux 4. The authors wish to thank the National Research Programme " Eaux et Territoires " (MEDAD - CNRS - CEMAGREF) for its financial support.

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Abstract. A local public-good game played on directed networks is analyzed. The model is motivated by one-way flows of hydrological influence between cities of a river basin that may shape the level of their contribution to the conservation of wetlands. It is shown that in many (but not all) directed networks, there exists an equilibrium, sometimes socially desirable, in which some stakeholders exert maximal effort and the others free ride. It is also shown that more directed links are not always better. Finally, the model is applied to the conservation of wetlands in the Gironde estuary (France).

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1 Introduction

In local public-good games played on networks, actions are assumed to be strategic substitutes.[1] Network games of strategic substitutes have the property that an action of an individual reduces the marginal payoff of his neighbors, i.e. each individual is less willing to exert a positive effort when he sees that his neighbors are doing so. There is a growing literature on network games with strategic substitutes (Ballester et al., 2006; Bramoullé and Kranton, 2007; Corbo et al., 2007; Ballester and Calvó-Armengol, 2009; Galeotti et al., 2010). However, one aspect that eluded the attention of this literature is the nature of network links. In this paper, we focus on directed links.[2]

Our investigation was motivated by efforts to conserve wetlands. We chose to model the effort to conserve wetlands as a means of investigating directed network links. Stakeholders (e.g. cities) choose the amount of effort that they are willing to expend on conserving wetlands. However, the results cannot be taken in isolation because there are often directed flows of hydrological influence that link cities together. When a city makes an effort to conserve wetlands, areas that are downstream of the water flow benefit. Herein, a model of common-pool resource (CPR) conservation in a natural directed network is constructed. We examine the incentive to conserve a CPR that is non-excludable[3] along natural one-sided links.[4]

[1]See Jackson (forthcoming) for an overview of social networks and economic applications, with respect to (a) how they influence social and economic activity, and (b) how they can be modeled and analyzed.

[2]Directed networks have been essentially analyzed in network formation games. For instance, Bala and Goyal (2000) model the network formation process as a noncooperative game and study both directed links and undirected links. Dutta and Jackson (2000) explore the question of endogenous formation, stability, and efficiency for directed communication networks. Johari et al. (2006) analyze a situation in which bilateral negotiation may result in a contractual agreement between two agents to form a directed link.

[3]Non-excludability means that no one can be effectively excluded from using the resource.

[4]Examples also include flows of polluted water between plots of an irrigated perimeter. When a farmer makes an effort to reduce his use of chemicals and fertilizers, his downstream successors benefit. Rivers and families are other examples of natural directed networks, determined respectively by geological and biological factors. In all these settings, natural flows and structures can influence the incentive to

The directed feature of natural links between stakeholders of a CPR raises a new set of research questions:

- How does the natural directed structure affect the level and pattern of CPR conservation?
- How do the pattern of directed links shape the efforts that stakeholders exert and the payoff they can hope to earn?
- How do new directed links - links between cities for example - affect contributions and welfare?

Herein, these questions are addressed by extending the model developed by Bramoullé and Kranton (2007). There is a fixed natural structure that is directed. Stakeholders manage a CPR - wetlands - that is costly to conserve. This CPR is non-excludable among naturally linked stakeholders. Stakeholders decide how much to contribute to the conservation of the resource, knowing that the resource is non-excludable in this way. We also analyze data from the Livenne river basin in the Gironde estuary to examine some predictions of the theory.[5]

Our analysis yields three main insights.

First, directed networks can lead to specialization. In many directed networks, there is an equilibrium in which some stakeholders contribute to the conservation of the resource and others free ride completely. This outcome can have welfare benefits, when free riders are preceded by several contributors.

contribute.

[5]Herein, we deliberately look at a complete information setting for one main reason. In the Livenne river basin application that we investigate empirically, word of mouth communication travels much faster than actions, so if a stakeholder behaves badly, other stakeholder hear about it quickly.

Second, not all directed networks lead to specialization. In some directed networks, there is a unique equilibrium in which all stakeholders contribute to the conservation of the resource. This outcome arises when stakeholders are linked in a very specific way.

Finally, having a greater number of directed links is not always better. A new directed link increases access to the CPR, but also reduces individual incentives to contribute. Hence, overall welfare can be greater even if there are holes in a directed network.

This paper contributes to several research areas.

First, it introduces the first directed network model of CPR conservation. The conservation of wetlands by cities of a river basin provided the primary reason for constructing the model. The model applies to any CPR that is non-excludable in a natural dimension and where there are no extraction costs.[6] Related work includes Bramoullé and Kranton (2007), Corbo et al. (2007) and Galeotti et al. (2010), who study local public goods that are non-excludable in a geographic or social dimension. More generally, this paper contributes to the extensive literature on the management of the commons initiated by Gordon (1954) and deeply discussed, from both theoretical and empirical perspectives, by Ostrom (1990) and Ostrom et al. (2002).[7] We study the conservation of a CPR embedded in a natural directed network structure. Our innovation is that we add direction to the links.

Second, the paper contributes to the economic theory of networks. We consider a game in which agents perform actions that are substitutes for their predecessors' actions. We relate the Nash equilibria to two graph-theoretic notions: maximal independent sets

[6] See İlkiliç (forthcoming) for a study of the extraction game played on (undirected) networks, where links connect agents (cities) with sources and agents decide how much resource units (water) to draw from each source they are connected to. Herein, we focus on the actual resource system itself, which may be jointly used. See Walker et al. (1990) for more detailed information on this distinction.

[7] See Seabright (1993) for a survey of the literature on the management of the commons.

and Hamiltonian cycles. An *independent set* of a directed graph is a set of agents such that no two agents who belong to the set are adjacent, i.e. there are no links connecting the two.[8] We show that equilibria where some agents contribute and other agents free ride often, but not always, exist and correspond to this structural property of a directed graph. A *cycle* in a directed graph is a directed sequence of linked agents, in which all arcs are traversed in their prescribed directions and every agent appears at most once, except for the first and the last agents, who coincide.[9] We show that the existence of equilibria where some agents contribute and other agents free ride is closely related to the non-existence of a cycle in directed graphs.

Finally, this paper has common features with the branch of the literature on networks that aims at identifying the effects of individuals' neighborhood patterns on behavior and outcomes.[10] Our analysis suggests that stakeholders who have active predecessors should have high benefits but exert little effort. We also expect stakeholders who have prominent natural positions to bear less of the effort costs, and instead to rely on other stakeholders' efforts. Using data from the Livenne river basin of the Gironde estuary, we examine some results of the model.

The remainder of the paper is organized as follows. In the next section, we present the model. In Section 3, we study the Nash equilibria of the game. In Section 4, we derive conditions for the existence of Nash equilibria. In Section 5, we study the stable equilibria of the game. In Section 6, we study economic welfare for a given directed graph;

[8]See Ore (1962), pp. 210-214.

[9]See Ore (1962), pp. 22-23.

[10]We can find applications in many areas of economics. For instance, Bala and Goyal (1998) analyze how the (fixed) structure of neighborhoods in a society effects how information is generated and disseminated. Morris (2000) analyzes a process of behavior contagion in a (fixed) network. Corominas-Bosch (2004) analyzes bargaining between buyers and sellers who are connected by a (fixed) network. Acemoglu and Ozdaglar (2007) analyze price competition among service providers in a (fixed) congested network.

then, in Section 7, we ask how changing the directed graph structure can affect welfare. In Section 8, we examine a natural directed network in the Livenne river basin of the Gironde estuary. Section 9 concludes. The proofs are given in the Appendix.

2 The model

There are n cities and the set of cities is $N = \{1, ..., n\}$. There is a CPR (wetlands) that can be jointly used by cities and we note $e_i \in [0, +\infty)$ city i's level of effort to conserve the CPR. We assume that the individual cost of effort can be represented by a twice differentiable cost function $c(e)$. An effort profile of all cities is denoted by $\mathbf{e} = (e_1, ..., e_n)$.

Cities are arranged in a directed network, which we represent as a finite directed graph (digraph) $\mathbf{g}$. We assume that $g_{ij} = 1$ if city j benefits naturally and directly from the results of city i's effort, and $g_{ij} = 0$ otherwise. Due to the fact that links between cities are directed, $g_{ij} \neq g_{ji}$. Given that city i knows the results of her own effort, we set $g_{ii} = 1$. Thus, the digraph that represents the directed network is formed by a finite set of vertices (the cities) and a finite set of arcs (the directed links) that connect, in an ordered way, some pairs of vertices. [11]

Let $N_i^s = \{j \in N \backslash i : g_{ij} = 1\}$ denote the set of cities connected to i that benefit directly from the results of city i's effort, which we call city i's *successors*. Let $N_i^p = \{j \in N \backslash i : g_{ji} = 1\}$ denote the set of cities connected to i that do not benefit directly from the results of city i's effort, which we call city i's *predecessors*. We note $d_i^+ = |N_i^s|$ the *out-degree* of i, i.e. the number of arcs having i as initial extremity, and $d_i^- = |N_i^p|$ the

[11] In our case study about the wetlands of the Gironde estuary, the directed links represent natural flows of hydrological influence that link cities together. This naturally directed network structure is illustrated in Section 8.

in-degree of i, i.e. the number of arcs having i as final extremity. City i's *neighborhood* is defined as herself, her set of successors, and her set of predecessors: i.e. $i \cup N_i^s \cup N_i^p$.

We assume that each city receives benefits from her own and her predecessors' effort. This means that efforts are supposed to be substitutable. We assume that each city receives benefits according to a twice differentiable strictly concave benefit function $b(e)$ where $b(0) = 0$, $b' > 0$ and $b'' < 0$. For reasons of simplicity, we assume that efforts are perfectly substitutable, that cities are homogeneous in that the CPR produces similar benefits to all cities and the costs of effort are identical, and the individual marginal cost of effort is constant and equal to c. A city i's payoff can then be written as follows:

$$U_i(\mathbf{e}; \mathbf{g}) = b(e_i + \bar{e}_i) - ce_i$$

where $\bar{e}_i = \sum_{j \in N_i^p} e_j$ denotes the total effort of city i's predecessors.[12] We specify the following game. Given a directed natural structure $\mathbf{g}$, cities simultaneously choose the amount of effort that they will expend (henceforth, effort levels). For a given effort profile $\mathbf{e}$, each city i earns payoffs $U_i(\mathbf{e}; \mathbf{g})$. We analyze pure strategy Nash equilibria, due to the fact that there are no mixed strategy equilibria because the benefit function is concave and costs are linear. In the following analysis, we study how network structure, in particular its directed characteristic, influences equilibrium effort levels.

[12]Note that the model with imperfect substitutability, heterogenous cities, and nonlinear cost of effort should be written as follows:

$$U_i(\mathbf{e}; \mathbf{g}) = b_i(e_i + \lambda \bar{e}_i) - c_i(e_i)$$

where $\lambda \in [0; 1]$ is a parameter which denotes the degree of substitutability between efforts.

3 Equilibrium contributions

Firstly, we characterize Nash equilibria. Let e^* denote the individual effort level at which the marginal benefit equals the marginal cost: $b'(e^*) = c$. Given $b(.)$ is strictly concave, an effort level $e^* > 0$ exists and is well-defined as long as $b'(0) > c$. Each city chooses her effort level by playing her best response to the effort level played by her predecessors. An effort profile $\mathbf{e}$ is a Nash equilibrium if and only if for every city i:

$$\begin{cases} e_i = 0 & \text{if } \bar{e}_i \geqslant e^* \\ e_i = e^* - \bar{e}_i & \text{otherwise} \end{cases}$$

Cities want to exert effort as long as their total benefits are less than $b(e^*)$. If the benefits they acquire from their predecessors are more than (or equal to) $b(e^*)$, they exert no effort. If the benefits they acquire from their predecessors are less than $b(e^*)$, they exert a positive effort until their benefits reach $b(e^*)$.

In this game, effort levels are perfectly substitutable. The more effort a city's predecessors exert, the less a city exerts herself. As in the undirected framework, three equilibrium profiles may emerge. There may exist a *specialized* profile in which every city either exerts the maximum amount of effort [13] or exerts no effort: for every city $i \in N$, either $e_i = e^*$ or $e_i = 0$. There may exist a *distributed* profile in which every city exerts a strictly positive effort that is less than the maximum amount of effort: for every city $i \in N$, $0 < e_i < e^*$. Finally, there may exist an *hybrid* profile that falls between the specialized profile and the distributed profile: for every city $i \in N$, $0 \leqslant e_i \leqslant e^*$. The following example illustrates the differences between these different types of Nash equilibria in a directed network.

[13] In this case, a city would be called a *specialist*. See Bramoullé and Kranton (2007).

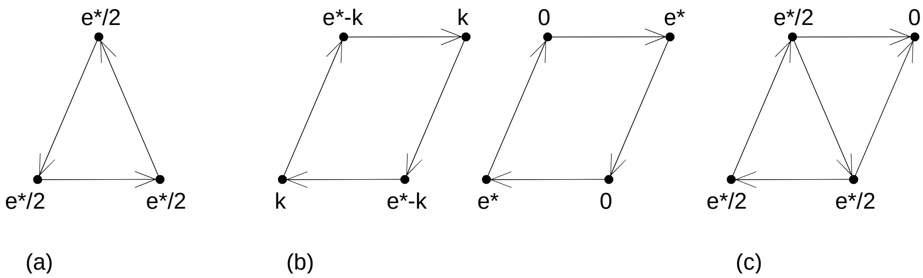

Figure 1: Nash equilibria in simple digraphs

Example 1. Nash equilibria in a directed network. Figure (1) shows three simple directed graphs. The triangle shown in (a) admits a unique distributed Nash equilibrium given by the profile $\mathbf{e} = (e^*/2, e^*/2, e^*/2)$. The quadrangle shown in (b) admits a continuum of distributed Nash equilibria given by the profile $\mathbf{e} = (k, e^* - k, k, e^* - k)$, $\forall k \in]0; e^*[$, and two specialized equilibria (when $k = 0$ or e^*). The digraph shown in (c) admits an hybrid Nash equilibrium given by the profile $\mathbf{e} = (0, e^*/2, e^*/2, e^*/2)$.

4 The existence of Nash equilibria

We now derive conditions for the existence of Nash equilibria in a directed network. We first focus on the existence of distributed equilibria. Then, we analyze specialized equilibria.

4.1 Distributed equilibria

Firstly, we identify an important characteristic of digraphs that do not admit any distributed Nash equilibrium. Then, we point out important digraphs in which we are able to count the distributed equilibria, using concepts from graph theory: the path, the cycle and the Hamiltonian digraph.

A *path* in a digraph is a directed sequence of vertices linked between each other by arcs. A path is simple if every vertex appears at most once and it is closed if its last vertex is also its first vertex. A *cycle* in a digraph is a simple closed path: it is a directed sequence of vertices linked between each other by arcs, in which every vertex appears at most once, except for the first and the last vertices, which coincide. A sequence of vertices $\{a_0, a_1, ..., a_{k-1}, a_k\}$ of a digraph is thus called a cycle if $a_0, a_1, ..., a_{k-1}$ are distinct vertices and $a_0 = a_k$. Note also that a cycle is called *Hamiltonian* if it goes through every vertex of the digraph. A digraph that contains a Hamiltonian cycle is called a *Hamiltonian digraph.*[14]

In numerous digraphs, there exists one or several agents whose in-degree is identical and equal to one. The case of a digraph containing a cycle is a natural example. Nevertheless, in a directed network, at least one of these agents may be connected to another agent outside the cycle without affecting the presence of the cycle within the digraph. In order to ensure the presence of a distributed Nash equilibrium in such a digraph, the direction of the connection outside the cycle is crucial. We then get the following property.

Lemma 1. *If a directed network* $\mathbf{g}$ *contains at least one agent that does not possess any predecessor, then* $\mathbf{g}$ *does not admit any distributed Nash equilibrium.*

Proof. All proofs are provided in the appendix.

Lemma 1 entails that there are a lot of digraphs that do not admit any distributed Nash equilibrium. Note also that a digraph that does not contain a cycle contains at

[14]Research has been done on algorithms to list all the elementary cycles in (unweighted) directed graphs. See e.g. Weinblatt (1972) or Chen and Ryan (1981).

least one agent who does not possess any predecessor. This well-known result from graph theory allow us to state that if a directed network does not contain any cycle, the network does not admit any distributed Nash equilibrium. The following example illustrates the concepts of cycle and in-degree of an agent, as long as their connection with the existence of distributed equilibria.

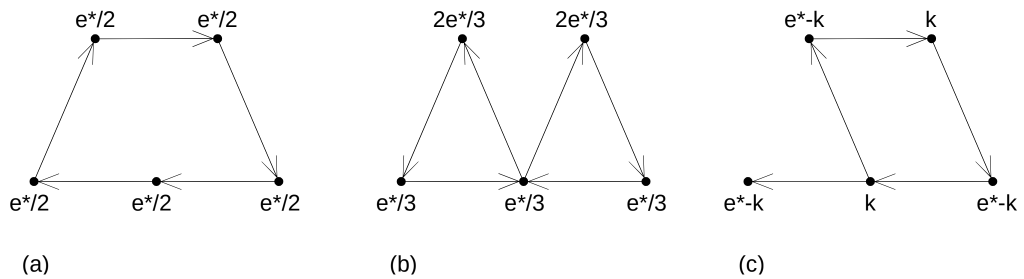

Figure 2: Distributed Nash equilibria in digraphs containing cycle(s)

Example 2. Directed network, cycle, in-degree of agents and existence of distributed equilibria. Figure (2) shows three cases of a directed network formed by five cities. The digraph shown in (a) admits a unique distributed Nash equilibrium given by the profile $\mathbf{e} = (e^*/2, e^*/2, e^*/2, e^*/2, e^*/2)$. Note that in this network, for every city $i \in N$, $d_i^+ = d_i^- = 1$. The digraph shown in (b) admits a unique distributed Nash equilibrium given by the profile $\mathbf{e} = (e^*/3, e^*/3, e^*/3, 2e^*/3, 2e^*/3)$. Note that in this network, there exists one city $i \in N$ such that $d_i^- = 2$, while for every other city $j \neq i \in N$, $d_j^- = 1$. The digraph shown in (c) admits a continuum of distributed Nash equilibria given by the profile $\mathbf{e} = (k, e^* - k, k, e^* - k, k)$ and two specialized Nash equilibria (when $k = 0$ or e^*). Note that in this network, the individual in-degree is equal to one for every city.

We remark that the existence of a distributed Nash equilibrium within a directed network depends closely on the individual in-degree of agents, which should generally be equal to one, except for some specific cases, as shown in Figure (2) case (b). Suppose that a digraph verifies this condition for in-degree equality. We can then see that the number of distributed Nash equilibria within such a directed network is characterized by the following property.

Lemma 2. *Let* $\mathbf{g}$ *be a digraph such that* $\forall i \in N$, $d_i^- = 1$. *If* $\mathbf{g}$ *contains a cycle formed by an even number of agents, then* $\mathbf{g}$ *admits a continuum of distributed Nash equilibria. If* $\mathbf{g}$ *does not contain any cycle formed by an even number of agents, then* $\mathbf{g}$ *admits a unique distributed Nash equilibrium.*

The following example illustrates the connection between the number of agents within the cycle of a directed network that admits (at least) one distributed Nash equilibrium and the number of distributed equilibria.

Example 3. Directed network, cycle, number of agents and number of distributed equilibria. We consider cases (a) and (b) of Figure (1) as well as case (c) of Figure (2). Case (a) of Figure (1) shows a Hamiltonian digraph with an odd number of cities in which, for every city $i \in N$, $d_i^- = 1$, i.e. it shows a Hamiltonian digraph that does not contain any other cycle. This network admits a unique distributed Nash equilibrium. Case (b) of Figure (1) shows a Hamiltonian digraph with an even number of cities (four cities) in which, for every city $i \in N$, $d_i^- = 1$. This network admits a continuum of distributed Nash equilibria. Case (c) of Figure (2) shows a digraph that contains a cycle formed by an even number of cities (four cities) in which an agent is connected to another agent outside the cycle, i.e. a network in which for every agent $i \in N$, $d_i^- = 1$. This network admits a continuum of distributed Nash equilibria.

4.2 Specialized equilibria

We now derive conditions under which a directed network admits at least one specialized Nash equilibrium. We first identify an important characteristic of digraphs that do not admit any specialized equilibrium. Then, we identify a common property of all the digraphs that admit at least one specialized Nash equilibrium. Given that efforts are substitutable only in a unilateral way, we note that a specialized Nash equilibrium is characterized by the fact that a free rider must always be preceded by at least one specialist. We then obtain, for a specific group of digraphs, the following property.

Lemma 3. *If a digraph* $\mathbf{g}$ *contains a cycle* Γ *formed by an odd number of agents where* $\forall i \subset \Gamma$, $d_i^- = 1$, *then* $\mathbf{g}$ *does not admit any specialized Nash equilibrium.*

We then use a concept from graph theory: the maximal independent set. An *independent set* I of a digraph $\mathbf{g}$ is a set of vertices, no two of which are adjacent, i.e. $\forall i, j \in I$, $g_{ij} = g_{ji} = 0$). An independent set of a digraph $\mathbf{g}$ is *maximal* if and only if adding every vertex to I makes the set not independent. Thus, given a maximal independent set I, every agent $i \in N$ belongs to I or is connected to an agent who belongs to I. The population of agents can then be divided in two distinct sets of agents: those belonging to the maximal independent set I and those belonging to an agent who belongs to I.[15]

In so far as a single vertex can constitute a maximal independent set, every digraph

[15]The problem of determining the number of (maximal) independent sets has been, and still is, extensively analyzed by mathematicians. See e.g. Zhang (1990) or Ageev (1994) for classic results as well as Butenko and Trukhanov (2007) for recent results.

g contains at least a maximal independent set. The presence of such a set is a necessary condition for the presence of a specialized Nash equilibrium within a directed network; but it not sufficient. Consider the case of a Hamiltonian digraph formed by five agents that does not contain another cycle. In such a network, there exist several maximal independent sets, each of which is formed by two agents. This digraph does not admit a specialized Nash equilibrium because, for every maximal independent set, there exists an agent who does not possess a predecessor that belongs to the maximal independent set. It follows that the existence of at least one specialized Nash equilibrium within a directed network is characterized by the following structural property of a digraph.

Proposition 1. *A directed network* **g** *admits one specialized Nash equilibrium if and only if* **g** *contains a maximal independent set* I *such that* $\forall i \notin I$, $\exists j \in I$ *such that* $g_{ji} = 1$.

Proposition 1 entails that there exist few digraphs that do not admit a specialized Nash equilibrium. The following example illustrates the concepts of maximal independent set and neighborhood, as long as their connection with the existence of specialized Nash equilibria.

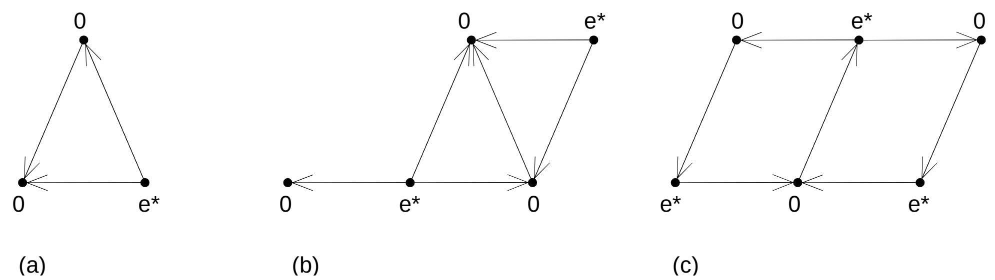

Figure 3: Specialized Nash equilibria in some digraphs

Example 4. Maximal independent set, neighborhood and existence of specialized equilibria. Figure (3) shows three digraphs. The triangle without cycle shown in (a) admits a unique specialized Nash equilibrium because it contains only one maximal independent set, thereby verifying Proposition 1. The digraph shown in (b) admits a unique specialized Nash equilibrium. Note that within this digraph, there exists one agent whose in-degree is equal to zero. The hexagon shown in (c) admits two specialized Nash equilibria. The first is shown by Figure (3). The second is such that those who exert a maximum amount of effort would exert no effort, and conversely.

5 The selection of Nash equilibria

For numerous digraphs, there exists a variety of equilibrium situations. In particular, a digraph may admit several types of Nash equilibria (distributed, specialized and/or hybrid), so it is relevant to determine which type of equilibrium is the most likely to obtain. In such a situation of multiple equilibria, we can try to reduce the number of equilibria by using a selection criterion founded on a notion of stability based on Nash tâtonnement (Bramoullé and Kranton, 2007; Corbo et al., 2007).[16] We define $f_i(\mathbf{e})$ as city i's best response to the profile $\mathbf{e}$ and $\mathbf{f} = (f_1, ..., f_n)$ as the collection of these individual best responses. An equilibrium $\mathbf{e}$ is stable if and only if there exists $\rho > 0$ such that for any vector $\boldsymbol{\varepsilon}$ satisfying $\forall i$, $|\varepsilon_i| \leqslant \rho$ et $e_i + \varepsilon_i \geqslant 0$ the sequence $\mathbf{e}^{(n)}$ defined by $\mathbf{e}^{(0)} = \mathbf{e} + \boldsymbol{\varepsilon}$ et $\mathbf{e}^{(n+1)} = \mathbf{f}\left(\mathbf{e}^{(n)}\right)$ converges to $\mathbf{e}$.[17]

According to this criterion, a Nash equilibrium profile is unstable if and only if there

[16]See Funderberg and Tirole (1991), pp. 23-25.

[17]In our context of wetlands, Nash tâtonnement seems to be a natural way to analyze the stability of equilibria. For example, imagine a new subsidy that would be given to one city of the river basin. This subsidy could be considered as a perturbation introduced into the network.

exists at least one city who modifies her best response following the introduction of perturbation ε within the digraph. By using this notion of Nash tâtonnement, we first realize that some directed networks have no stable equilibria. [18] This is the case when all stakeholders have exactly one predecessor.

Lemma 4. *If a directed network* $\mathbf{g}$ *contains a cycle* Γ *such that* $\forall i \subset \Gamma$, $d_i^- = 1$, *then* $\mathbf{g}$ *does not admit any stable equilibrium.*

Lemma 4 entails that a lot of distributed Nash equilibria are unstable. However, this property cannot be generalized to every distributed equilibria. [19] The following example illustrates the instability of equilibria admitted by a Hamiltonian digraph that does not contain any other cycle, i.e. such that $\forall i \in N$, $d_i^- = 1$.

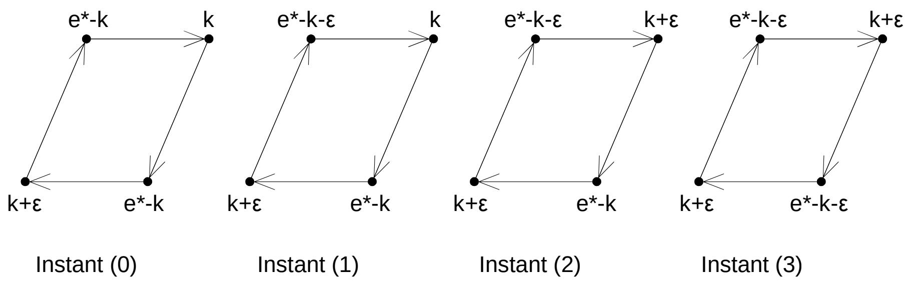

Figure 4: The nondegeneration of a perturbation in a Hamiltonian digraph that does not contain any other cycle

Example 5. Instability of equilibria of a Hamiltonian digraph in which every agent possesses an in-degree equal to one. Figure (4) shows a Hamiltonian digraph formed by

[18]Another way to test the stability of Nash equilibria would be to make the degree of substitutability varying at equilibrium. This could be a less restrictive criterion and it might be that some equilibria that appear unstable in the sense of Nash tâtonnement would be stable. This point is left for further research.

[19]Consider a digraph composed by two directed triangles linked by a common vertex, as shown by Figure (2), case (b). This digraph admits a unique distributed Nash equilibrium that is stable.

four cities that does not contain another cycle. We know from Lemma 2 that such a digraph admits a continuum of distributed Nash equilibria. We also know from Proposition 1 that such a digraph admits (at least) one specialized Nash equilibrium. If we introduce a perturbation $\boldsymbol{\varepsilon}$ into this directed network, the perturbation never disappears and makes all cities modify their equilibrium choices.

We have seen that every digraph containing a cycle in which every agent possesses only one predecessor, i.e. his predecessor within the cycle, does not admit any stable equilibrium. Consider a specialized Nash equilibrium admitted by a digraph that contains a cycle. Following the introduction of a perturbation $\boldsymbol{\varepsilon}$, every free rider should exert an effort level equal to $0 + \varepsilon$, and every specialist should exert an effort level equal to $e^* - \varepsilon$. If a free rider i in the cycle possesses two predecessors, at least one of these predecessors is a specialist; otherwise, Proposition 1 tells us that the digraph does not admit any specialized equilibrium. If i's second predecessor is also a specialist, then $\bar{e}_i = 2e^* - 2\varepsilon$; thus agent i's best response is still $e_i = 0$. If i's second predecessor is not a specialist, then $\bar{e}_i = e^*$; thus agent i's best response is still $e_i = 0$. It is equivalent if agent i possesses more than two predecessors because at least one of these predecessors is a specialist. We then get the following property.

Proposition 2. *A specialized Nash equilibrium admitted by a directed network* $\mathbf{g}$ *is stable if and only if, for every cycle contained in* $\mathbf{g}$, *there exists at least one free rider* i *such that* $d_i^- \geqslant 2$.

Proposition 2 says that a lot of specialized equilibria are stable, but we know from

Lemma 4 that this is not the case for all specialized equilibria. Consider the case of a Hamiltonian digraph formed by four agents and that does not contain any other cycle. This digraph admits two specialized Nash equilibria that are not stable, as shown in Figure (4). Suppose that a new directed link is created between the free riders. A perturbation introduced in the network will disappear because the best response of the agent who possesses two predecessors will always be to exert no effort. This example illustrates the positive effect of new arcs on the stability of specialized equilibria.

6 Welfare analysis

We now evaluate the welfare yielded by different allocations of effort within a directed network. The social value of the networks is measured by a social welfare function that corresponds to the sum of each individual payoff. Formally, the social welfare function of profile **e** for a digraph **g** can be written as follows:

$$W(\mathbf{e};\mathbf{g}) = \sum_{i \in N} b(e_i + \bar{e}_i) - c \sum_{i \in N} e_i$$

where it will be remembered that $\bar{e}_i$ corresponds to the total effort of city i's set of predecessors.

6.1 Efficient allocations

We say that a profile **e** is *efficient* for a given directed network **g** if and only if there does not exist another profile **e'** such that $W(\mathbf{e'};\mathbf{g}) > W(\mathbf{e};\mathbf{g})$. In so far as the welfare function is concave, an efficient profile, for every city i such that $e_i > 0$, must verify

$\partial W(\mathbf{e};\mathbf{g})/\partial e_i = 0$; i.e. for all $e_i > 0$:

$$b'(e_i + \bar{e}_i) + \sum_{j \in N_i^s} b'(e_j + \bar{e}_j) = c \quad (1)$$

where the left hand side corresponds to the marginal social benefit that is derived from city i's effort. We note that $\bar{e}_j$ corresponds to the sum of the efforts of city j's set of predecessors. Note also that agent j belongs to city i's set of successors.

Consider a Hamiltonian digraph formed by n cities and that does not contain any other cycle. There always exists an efficient profile in which each city chooses to exert the same level of effort e where e verifies $b'(2e) = c/2$. Each city benefits from her own effort and her predecessor's effort; hence, each city earns $b(2e)$. Furthermore, the individual marginal cost is $c/2$. This allocation of effort solves the first-order conditions of welfare maximization. Given that the welfare function is concave, the allocation of effort must be efficient.

In some digraphs which do not contain any cycle, there may exist cities that do not contribute in the efficient allocation. Consider every digraph without a cycle in which the set of successors of an agent is a strict subset of the set of successors of another agent. In this context, the agent whose set of successors is the smallest should exert no effort. For every digraph $\mathbf{g}$ with two agents i and j such that $i \cup N_i^s \subsetneq j \cup N_j^s$, $e_i = 0$ in any efficient profile.

The comparison of the efficient condition (1) to the Nash equilibrium conditions leads us to notice that cities do not internalize the positive externality their effort produces on their successors. At the individual level, each city $i \in N$ considers only her own marginal benefits and chooses her effort level such that $b'(e_i + \bar{e}_i) = c$. In this noncooperative context, the CPR is either underprovided or overpaid. It then follows that no effort profile that constitutes a Nash equilibrium within a digraph is efficient. We illustrate the difference between an efficient allocation and an equilibrium allocation in the following example.

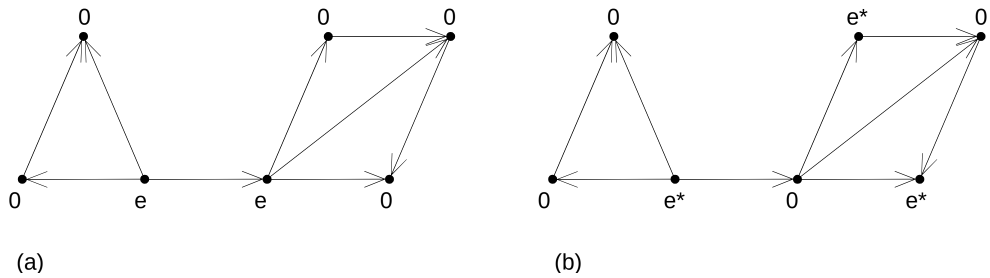

Figure 5: Efficient allocation vs. equilibrium allocation

Example 6. Efficient vs. equilibrium allocation. Consider the digraph in Figure (5) which represents two connected communities. In the efficient allocation shown in (a), cities that linked the two communities make all the contributions to the CPR. The successors of every other city form a strict subset of the successors of these two cities. Condition (1) implies that the two cities both exert effort e, such that $b'(2e) + 3b'(e) = c$. The unique Nash equilibrium admitted by this digraph is different from this allocation. In the equilibrium allocation shown in (b), the city who belongs to the quadrangle and is connected to the triangle exerts no effort. Thus, effort e^* should be exerted by two of the three successors of this city.

6.2 The best Nash equilibrium

Even though no Nash equilibrium that is admitted by a directed network is efficient, we propose to investigate which equilibria yield the highest welfare. Remember that in equilibrium, each city receives benefits from an effort level at least equal to e^*. Thus, $nb(e^*)$ represents the minimum aggregate benefit of each equilibrium profile. However, there exist some equilibria in which some cities exert no effort but are preceded by several specialists. Thus, these cities earn more than $b(e^*)$. The increase in welfare yielded by their benefits is equal to $\sum_{j:e_j=0} [b(\bar{e}_j) - b(e^*)]$ where the sum concerns every city that exerts no effort. The welfare of an equilibrium can thus be written as follows:

$$W(\mathbf{e};\mathbf{g}) = nb(e^*) + \sum_{j:e_j=0} [b(\bar{e}_j) - b(e^*)] - c\sum_i e_i \tag{2}$$

where the second term corresponds to the *benefit premium* that may arise when the total effort of the predecessors of a city exceeds e^*.

Distributed equilibria do not produce benefit premia, while specialized equilibria and hybrid equilibria may produce such a premium. In Equation (2), we see a trade-off between benefit premia and effort costs. It might then be that sometimes, when a digraph admits both a distributed Nash equilibrium and another type of Nash equilibrium (specialized or hybrid), the distributed equilibrium would not be preferable in terms of welfare. We illustrate the emergence of benefit premia within a digraph in the following example.

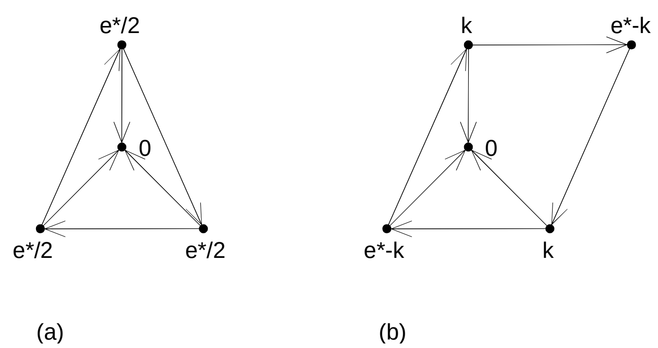

Figure 6: Some digraphs producing a benefit premium

Example 7. Specialized equilibria, hybrid equilibria and benefit premium. Figure (7) shows two digraphs. The digraph shown in (a) admits a unique hybrid Nash equilibrium. According to Equation (2), the welfare produced by this equilibrium is equal to $4b(e^*) + [b(3e^*/2) - b(e^*)] - 3ce^*/2$. The term between brackets corresponds to the benefit premium produced by this hybrid Nash equilibrium, which benefits the city outside the cycle. The digraph shown in (b) admits two specialized Nash equilibria and a continuum of hybrid Nash equilibria. Consider first the specialized equilibrium where $k = e^*$. The welfare of this equilibrium is equal to $5b(e^*) + [b(2e^*) - b(e^*)] - 2ce^*$. The term between brackets corresponds to the benefit premium produced by this specialized Nash equilibrium, which benefits the city outside the cycle. Consider now the hybrid equilibrium where $k = e^*/2$. The welfare of this equilibrium is equal to $5b(e^*) + [b(3e^*/2) - b(e^*)] - 2ce^*$. The term between brackets corresponds to the benefit premium produced by this hybrid Nash equilibrium, which benefits the city outside the cycle. We note that, in terms of welfare, the specialized equilibrium where $k = e^*$ produces the highest benefit premium and is thus preferable to any other Nash equilibria admitted by this digraph.

7 The effects of new directed links

In the preceding section, we identified the Nash equilibria of a directed network that yield the highest aggregate welfare. We now analyze the effects on welfare of changes within the digraph itself. We examine the effects in term of welfare of adding a new arc within a given digraph.

We consider changes that appear in the set of Nash equilibria when a new directed link is created. We say that an equilibrium profile $\mathbf{e}$ is a second-best equilibrium for a given digraph $\mathbf{g}$ if and only if there does not exist any other equilibrium profile $\mathbf{e'}$ such that $W(\mathbf{e'}; \mathbf{g}) > W(\mathbf{e}; \mathbf{g})$. We consider a digraph $\mathbf{g}$ and two agents i and j who are not connected in $\mathbf{g}$. We denote by $\mathbf{g} + ij$ the digraph obtained by connecting i towards j in $\mathbf{g}$. We consider that the directed link induces a loss in welfare when the level of welfare of the second-best equilibrium for digraph $\mathbf{g} + ij$ is lower than that for $\mathbf{g}$. We illustrate the positive and negative effects of a new directed link in the following example.

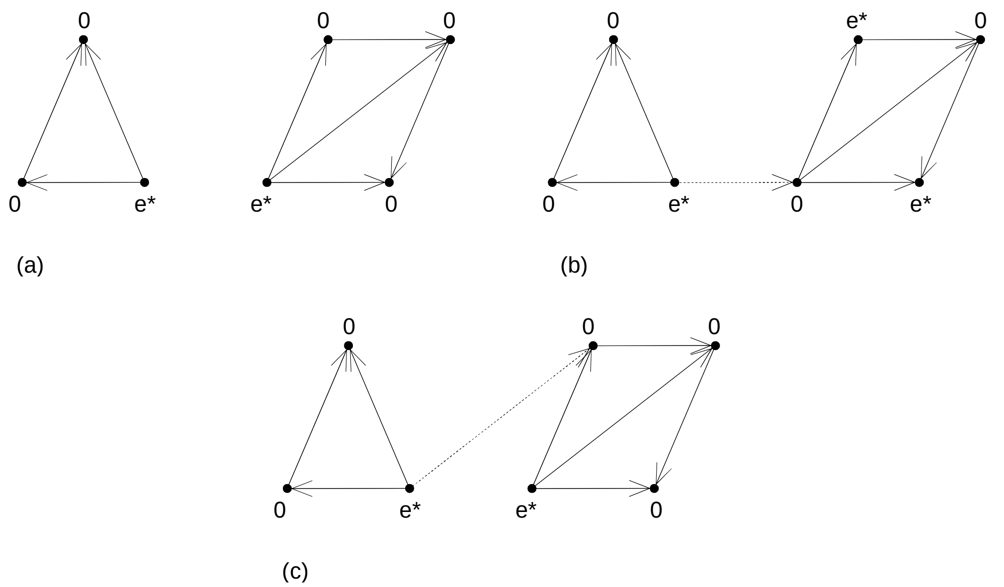

Figure 7: Connecting two digraphs

Example 8. Positive and negative effects of new directed links. We consider the two digraphs of case (a) in Figure (7). This figure shows the unique second-best equilibrium admitted by this directed network. In this case, the overall welfare is equal to $7b(e^*) - 2ce^*$. If we create a new directed link from the specialist of the triangle towards the specialist of the quadrangle, as shown by case (b) in Figure (7), the initial equilibrium is modified. This new directed link modifies the overall welfare by decreasing it, since it takes the value of $7b(e^*) - 3ce^*$. On the other hand, if we create a new directed link between the specialist of the triangle and a free rider of the quadrangle, as shown by case (c) in Figure (7), the initial equilibrium is not modified. However, the overall welfare increases because it now becomes equal to $b\left(2e^{*}\right)+6b\left(e^{*}\right)-2ce^{*}$. In this case, a free rider has two predecessors who are specialists. The welfare of this city increases because the total effort of her predecessors is now equal to $2e^{*}$.

8 Numerical example

Environmental applications in network analysis are just beginning to appear, and so far have focused on understanding characteristics of social networks that increase the likelihood of collective action and successful natural resource management (Schneider et al., 2003; Bodin and Crona, 2009). Moreover, by linking well-known concepts of social network analysis to issues and theories found in the literature on resource management, these applications have tried to show how knowledge gained from analyzing the social networks of stakeholders can be used to select stakeholders for participation in initiatives for the management of natural resources (Prell et al., 2008; Prell et al., 2009). Though these studies have been quite appealing with respect to the analysis of the efficiency of the governance of common-pool resources, they lack economic intuition because they do not identify the effects of agents' neighborhood patterns, i.e. their social network, on behavior and outcomes.

Our case study for the model developed herein is the conservation of wetlands by cities of a river basin linked by flows of hydrological influence. We focus on the Livenne river basin, located in the Gironde estuary (France). This river basin contains 24 cities. None of these cities has a population of more than 3500 citizens and only seven have more

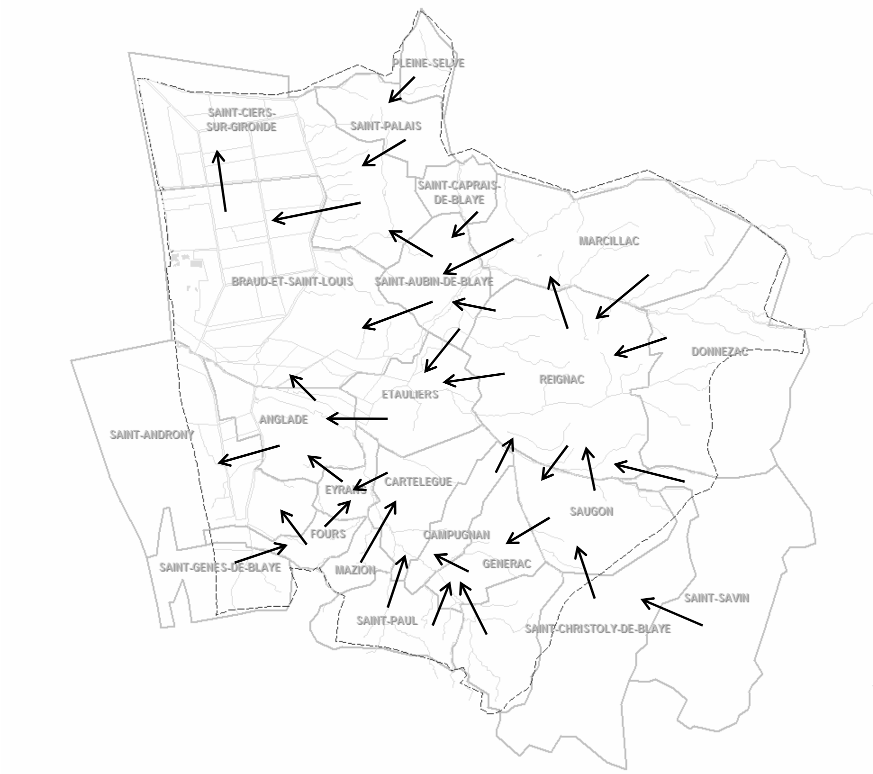

Figure 8: The links of hydrological influence between cities of the Livenne river basin

than 1000 citizens. Their surface area varies from 245 to 3743 hectares. The links of hydrological influence between cities of the Livenne river basin are shown in Figure 8. From Figure 8, we can draw any random representation of the Livenne directed network. We use the software program Pajek [20] to achieve this (see Figure 9).

We then calculate the in-degree and out-degree indices for every city of the network. These results are reported in Table 1. Nine cities have an in-degree equal to zero. This means that these cities have no predecessor. Applying Lemma 1 to this context, we know that the Livenne directed network does not admit any distributed equilibrium. It is interesting to note that only two cities have an out-degree equal to zero. This means that only two cities have no successor. We also note that a large majority of cities has

[20] http://pajek.imfm.si/doku.php

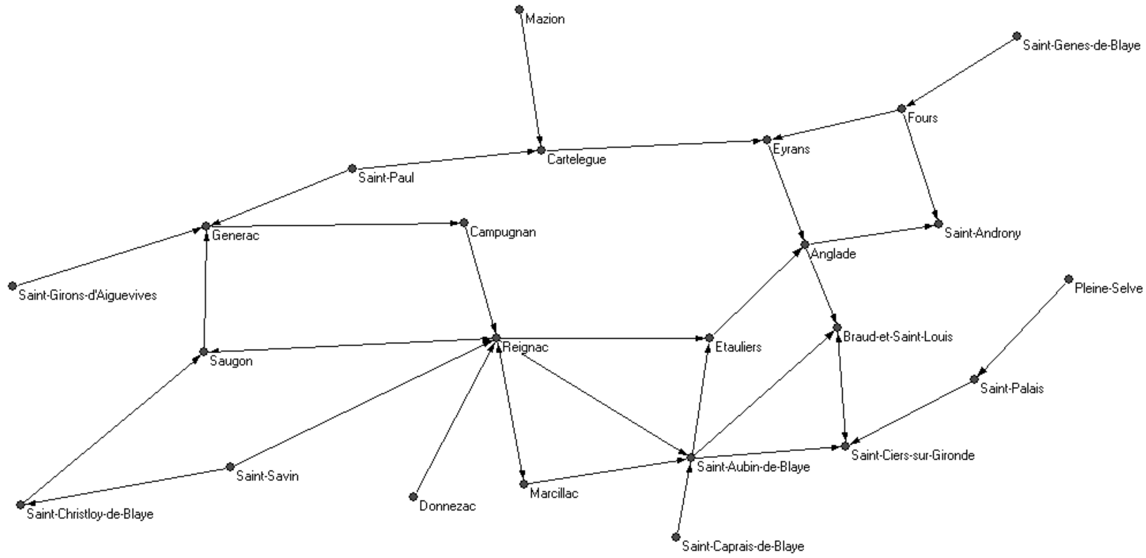

Figure 9: Random draw of the Livenne directed network

an out-degree equal to one. The city with the highest out-degree, Reignac, also has the highest in-degree. All flows are directed except for three, which are two-way. There are several paths in the network, and one cycle.[21]

The Livenne directed network admits two specialized equilibria and a continuum of hybrid equilibria. Nevertheless, only two cities, Braud-et-Saint-Louis and Saint-Ciers-sur-Gironde, could exert different equilibrium effort. Moreover, eight cities have a unique best-response, which is to free ride. According to Proposition 2, there are Nash equilibria that are stable. We also note that five cities would get a benefit premium, according to their position in the network. It is interesting to note that the city with the highest in-degree and out-degree would get the highest benefit premium. However, a majority of cities (15) would exert maximal effort without getting any premium.

[21] Saugon - Générac - Campugnan - Reignac - Saugon.

Table 1: Individual statistical measures of the Livenne directed network

City	In-degree	Out-degree	Equilibrium effort	Benefit premium
Saint-Androny	2	0	e^*	-
Saint-Genès-de-Blaye	0	1	e^*	-
Fours	1	2	0	-
Mazion	0	1	e^*	-
Anglade	2	2	0	e^*
Eyrans	2	1	e^*	-
Cartelègue	2	1	0	e^*
Campugnan	1	1	e^*	-
Générac	3	1	0	$2e^*$
Saint-Paul	0	2	e^*	-
Saint-Christoly-de-Blaye	1	1	0	-
Saint-Savin	0	2	e^*	-
Saugon	0	2	e^*	-
Reignac	5	4	0	$4e^*$
Donnezac	0	1	e^*	-
Marcillac	1	2	e^*	-
Saint-Aubin-de-Blaye	3	3	0	e^*
Braud-et-Saint-Louis	3	1	$e^* - k$ [1]	-
Etauliers	2	1	e^*	-
Saint-Caprais-de-Blaye	0	1	e^*	-
Saint-Palais	1	1	0	-
Saint-Ciers-sur-Gironde	3	1	k [1]	-
Pleine-Selve	0	1	e^*	-
Saint-Girons-d'Aiguevives	0	1	e^*	-

[1] $\forall k \in [0; e^*]$

9 Conclusion

We have presented a model of CPR conservation in a directed network. In this model, there is a fixed natural structure that connects stakeholders, and stakeholders choose how much to contribute to the conservation of the CPR, which is non-excludable and can be jointly used. The game is noncooperative, i.e. actions are strategic substitutes. This theoretical work was motivated by a desire to understand the conservation of wetlands in a river basin of the Gironde estuary, where stakeholders (cities) are connected by flows of hydrological influence. Due to the fact that these flows are almost always one-way, our model was also motivated by a desire to understand directed networks.

By adding a direction to the links, our model extends the local public goods game played on networks that is developed in Bramoullé and Kranton (2007). We find two fundamental differences between our model and that of Bramoullé and Kranton. First, those authors show that every undirected network admits a specialized equilibrium, while our model shows that many, but not all, directed networks admit a specialized equilibrium. Second, while those authors show that no distributed equilibrium is stable, our model shows that some directed networks admit a distributed equilibrium that is stable. In contrast, the welfare analysis reveals three main similarities with the undirected framework. First, we find that no Nash equilibrium is efficient. Second, we find that benefit premia may appear in directed networks in which free riders are preceded by many contributors. Finally, we show that structural holes in directed networks may sometimes be beneficial to society as a whole.

A useful direction for further research would be to investigate how the nature of links affects behavior and outcomes. In this regard, the effect of weak ties in comparison with strong ties was first pointed out by Granovetter (1973). In the example of wetlands that we used when developing our model, it is very clear that flows of hydrological influence vary in their intensity. This fact suggests to study weighted directed networks, which may provide more precise results concerning the existence of Nash equilibria. A further issue for investigation, which is related to the first, is how flows vary over time in addition to varying in their intensity. Finally, it would also be pertinent to examine outcomes if it is assumed that effort substitutability is imperfect and heterogenous among stakeholders because this could provide a more intuitive approach for testing the stability of Nash equilibria.

Appendix

Proof of Lemma 1. Suppose that in a digraph $\mathbf{g}$, there exists an agent $i \in N$ such that $d_i^- = 0$. Due to the fact that agent i has no predecessor, $\bar{e}_i = 0$. Note that in equilibrium, agent i chooses her level of effort e_i such that $b'(e_i + \bar{e}_i) = b'(e^*) = c$. It follows that $e_i = e^*$, i.e. agent i always chooses to exert the maximum level of effort. All equilibrium profiles admitted by $\mathbf{g}$ contain at least an agent who exerts a maximal level of effort; hence, $\mathbf{g}$ does not admit any distributed Nash equilibrium. $\square$

Proof of Lemma 2. Let $\mathbf{g}$ be a digraph in which $\forall i \in N$, $d_i^- = 1$, i.e. $\mathbf{g}$ contains a unique cycle or several disconnected cycles.

Suppose that $\mathbf{g}$ is a Hamiltonian digraph, i.e. that $\forall i \in N$, $d_i^+ = 1$ and the cycle is unique. Assume that an agent i chooses to exert an effort level $e_i = k$ such that $k \in \,]0, e^*[$. Her successor, agent $i+1$, will choose to exert an effort level $e_{(i+1)}$ such that $e_i + e_{(i+1)} = e^*$, so $e_{(i+1)} = e^* - k$. In the same way, the successor of agent $i+1$ will choose to exert an effort level equal to k, and so on until the predecessor of agent i, i.e. agent $i-1$. If agent $i-1$ chooses to exert an effort level equal to $e^* - k$, $\mathbf{g}$ will be composed of an even number of agents. In this case, we obtain $e_i + e_{(i-1)} = e^*$, $\forall k \in [0, e^*]$. If agent $i-1$ chooses to exert an effort level equal to k, then $\mathbf{g}$ is composed of an odd number of agents. In this case, $e_i + e_{(i-1)} = e^*$ if and only if $k = e^*/2$.

Suppose now that $\mathbf{g}$ contains a cycle Γ in which there exists (at least) an agent $j \subset \Gamma$ who represents the initial extremity of one (or several) path, i.e. $\exists j \in N$ such that $d_j^+ \neq 1$. Thus, agent j has (at least) two successors. Every successor of agent j outside the cycle will choose to exert an effort level identical to the successor of agent j within the cycle (because under our initial assumption, every agent has only one predecessor). Thus, whatever the size and the number of paths connected to Γ, the number of equilibria admitted by $\mathbf{g}$ depends only on the number of agents that belong to Γ. $\square$

Proof of Lemma 3. Lemma 2 tells us that if a directed network $\mathbf{g}$ verifying the assumption $\forall i \in N$, $d_i^- = 1$, contains a cycle composed of an odd number of agents, then the unique Nash equilibrium admitted by $\mathbf{g}$ is a distributed Nash equilibrium in which $\forall i \in N$, $e_i = e^*/2$. $\square$

Proof of Proposition 1. Suppose that a specialized profile $\mathbf{e}$ is a Nash equilibrium of a directed network $\mathbf{g}$. Thus, for every agent i and j belonging to the set of specialists $I_{\mathbf{e}}$, $e_i = e_j = e^*$. This implies that $g_{ij} = g_{ji} = 0$, because otherwise, e^* is not their best response. Thus $I_{\mathbf{e}}$ is an independent set.

Consider an independent set of specialists $I_{\mathbf{e}}$ that is not maximal. By definition, there exists a set of agents $J \in N$ such that $J \cup I_{\mathbf{e}}$ is independent. However, $\forall j \in J$, $e_j = 0$ cannot be a best response because agent j is not preceded by one (or several) specialists. Thus $I_{\mathbf{e}}$ is a maximal independent set.

Suppose now that $\forall j \in I_{\mathbf{e}}$, $\exists i \notin I_{\mathbf{e}}$, such that $g_{ji} = 0$. As agent i is not preceded by one (or several) specialist, $e_i = 0$ is not her best response. On the other hand, if $\forall i \notin I_{\mathbf{e}}$, $\exists j \in I_{\mathbf{e}}$, such that $g_{ji} = 0$, then free riders are all preceded by a specialist and exert their best response. $\square$

Proof of Lemma 4. Let $\mathbf{g}$ be a digraph containing a cycle Γ in which $\forall i \subset \Gamma$, $d_i^- = 1$.

We consider an equilibrium such that $\forall i \subset \Gamma$, $e_i = f_i(\mathbf{e})$ where $f_i(\mathbf{e})$ represents the best response of individual i to the profile $\mathbf{e}$. We note $\mathbf{f} = (f_1, ..., f_n)$ the collection of best responses of every agent i belonging to Γ. We define a perturbation $\boldsymbol{\varepsilon}$ such that $\forall i \in N$, $\varepsilon_i = \rho$ where ρ is a small positive number. We introduce the perturbation in the cycle Γ, i.e. $\mathbf{e}^{(0)} = \mathbf{e} + \boldsymbol{\varepsilon}$. At time 0, there exists an agent i belonging to Γ whose effort level is equal to $e_i' = e_i + \varepsilon_i$. At the next time, the successor of this agent, marked $i+1$, will reduce the amount of effort she exerts because from now on, $\bar{e}_{i+1} = e_i + \varepsilon_i$. Thus, every agent in the cycle reflects the perturbation on her own effort level, until the predecessor of agent i, marked $i-1$. Lemma 2 tells us that if the number of agents belonging to Γ is even, then $e_{i-1}' = e^* - e_i'$, i.e. a new equilibrium arises and the sequence $\mathbf{e}^{(n)}$ will never converge to $\mathbf{e}$. If the number of agents belonging to Γ is odd, then $e_{i-1}' = e_i'$. Agent i will be led to modify her effort level by choosing $e_i'' = e_i - \varepsilon$. The successor of agent i will then modify her effort level, and so on. The network no longer admits an equilibrium and the sequence $\mathbf{e}^{(n)}$ will never converge to $\mathbf{e}$. $\square$

Proof of Proposition 2. Let $\mathbf{g}$ be a digraph that admits a specialized Nash equilibrium.

We first suppose that $\mathbf{g}$ does not contain any cycle. Thus, there exists (at least) one agent $i \in N$, such that $d_i^- = 0$. In equilibrium, the best response of agent i is $e_i = e^*$. If we introduce a perturbation $\boldsymbol{\varepsilon}$ within the digraph, then the best response of agent i will always be $e_i = e^*$. It is the same for every agent who has no predecessor within $\mathbf{g}$. Furthermore, $\forall j \in N_i^d$, $e_j = 0$ because in equilibrium, $b'(e_j + \bar{e}_j) = c$, where $\bar{e}_j \geqslant e_i$. In addition, $\forall h \in N_j^d$, i.e. contained in the maximal independent set built from agent i, $e_h = e^*$, etc. The network always admits the initial specialized equilibrium and the sequence $\mathbf{e}^{(n)}$ will always converge to $\mathbf{e}$.

We have shown that the specialized Nash equilibrium admitted by a digraph that does not contain any cycle is stable. Suppose now that $\mathbf{g}$ contains one or several cycles. We know from Lemma 4 that if there exists a cycle Γ such that $\forall i \subset \Gamma$, $d_i^- = 1$, $\mathbf{g}$ does not admit any stable equilibrium. Assume there exists an agent $j \subset \Gamma$ such that $d_j^- \geqslant 2$. We know from Proposition 1 that one of the two predecessors of agent j is inevitably a specialist. Without perturbation, $\bar{e}_j = e^*$ and $e_j = 0$. With a very small perturbation $\varepsilon > 0$, $\bar{e}_j = (e^* - \varepsilon) + (0 + \varepsilon) + ...$ and $e_j = 0$. The perturbation within Γ will disappear because of agent j, who does not modify her best response. This logic applies to every cycle contained within $\mathbf{g}$. $\square$

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