Natural Resource Management: A Network Perspective

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Abstract

Network structures seem to characterize a lot of environmental problems and behaviours. In this paper, we study the role of networks in the management of natural resources by assuming a finite number of agents who exploit a specific natural resource. Harvesting is subject to three external effects, namely resource stock externalities, crowding externalities and positive technological spillovers. We show that the structure of network and the interaction among the agents, as well as the strength of the external effects, determine both the equilibrium and the optimal harvesting amount and the corresponding value of the network. We also study the decisions of harvesting agents with respect to the creation or elimination of cooperation links, which are shown to affect total harvest and aggregate welfare. Moreover, we introduce heterogeneity by assuming different geographical distance between each agent and the resource, which changes agents' incentives for collaboration. Finally, we show that conservation plans change the regulator's objective and increase even further the gap between the decentralized and the optimal outcomes.

JEL classification: D85, H23, Q30

Keywords: Environmental externalities, networks, natural resource management, optimal network structure.

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1 Introduction

The study of externalities and has been has been central in the analysis of environmental and resource economics and the design of appropriate policies aiming at correcting mainly the detrimental externalities associated with environmental and resource management issues. Another area where externalities have been central is the study of networks of social interactions. There are both positive and negative externalities underlying these networks and the emerging behavior of the agents comprising the social networks is shaped to a large degree by the externalities.

Environmental and resource management issues can be clearly considered in the context of a social network. The nodes of the network could be polluting firms, or firms adopting clean technologies, agents harvesting an exhaustible or a renewable resource, countries emitting greenhouse gases and adopting mitigation or adaptation policies, or consumers engaging in polluting or pollution reducing activities.

The main areas where social networks have been studied up to now (see Jackson and Zenou (2015) for an overview of the literature), include financial networks, labour markets, development economics, exchange theory, bargaining, and trade. However, despite the straightforward association of environmental issues with social networks very little research has been undertaken. A few exceptions include papers studying the adoption of innovative, environmentally-friendly technologies by firms (Conley and Udry, 2001), cooperative behavior in the context of an international environmental agreement (Heal and Kunreuther, 2012) or common-pool resource use with multiple sources and cities (İlkılıç, 2011), while a broad discussion on how networks can be used in order to facilitate the study of environmental issues can be found in Currarini et al. (2016).

A particular characteristic of environmental networks is the fact these networks can be characterized by strategic heterogeneity. That is, the network includes both strategic complementarities, emerging when the marginal payoff of an agent is increasing in the actions of his/her neighbors, and strategic substitutabilities, when the marginal payoff of an agent is decreasing in the actions of his/her neighbors. The first case may emerge in links indicating cost reducing technology agreements and cooperation among agents, while the second corresponds to situations the agents' s marginal payoff is decreasing in the choices of his/her neighbors. This, for example, could be the case of congestion effects, or increasing search or extraction costs when the stock of a resources exploited by the network is depleted. The study of this potential heterogeneity in a network context could provide new insights in terms of market outcomes and policy to attain the social optimum.

The purpose of this paper is to make a step towards the study of environmental issues in a network context, by studying a network associated with the exploitation of a depletable resource which is characterized by strategic heterogeneity. Our purpose is to study market outcomes associate with specific network structure and eventually to characterize the most efficient market structure. We also characterize the socially optimal network structure and examine policies under which market outcomes will reproduce the social optimal structure. The main advantage and contribution of the network approach is that by identifying the efficient structure, desirable or non-desirable links among the agents can be determined and policies can therefore be designed not just to control the level of externalities but also to control for the desired link structure among agents under strategic complementarities and substitutabilities. Disregarding the structure of the network - when this structure determines its value - may result in inefficient policies.

In this paper we consider in particular a network consisting of three agents located at distinct spatial locations who exploit a depletable resource which is located at a site different than the locations of the agents. The exploited quantity of the resource depends on congestion forces, technological advances and exchange of information between the agents and transportation costs. The existence of externalities implies that the market outcome differs from the optimal one. More precisely, in equilibrium the involved agents maximize their private profits. Then we study the optimal use of the resource by introducing two different measures. The first one (that is commonly used in the literature) is based on the maximization of the private value of the network which is the sum of the agents' payoffs. In the second approach, along with the private value of the network, the social planner takes into account the exhaustible nature of the resource by considering explicitly its conservation value. This could facilitate the discussions regarding conservation versus development, which is based on the fact that natural resources should not be treated in the same way as producible goods. Thus, one of the contributions of this paper is to show how the network structure and the associated payoffs are affected by this special nature of the natural resources. We show that by ignoring depletability, we end up in overexploitation of the resource.

The rest of the paper is organized as follows. In Section 2 we present the model and solve for the market outcome. In section 3 we describe the dynamics of network formation, while in section 4 we apply the dynamic theory in our framework. In section 5 we extend the model by introducing heterogeneity and in section 6 we solve for the optimal outcome using the two approaches described above. Section 7 concludes the paper.

2 Decentralized Competitive Exploitation

2.1 Resource Use under Congestion Externalities

Let us assume that the resource is exploited by three agents, as illustrated in Figure 1.

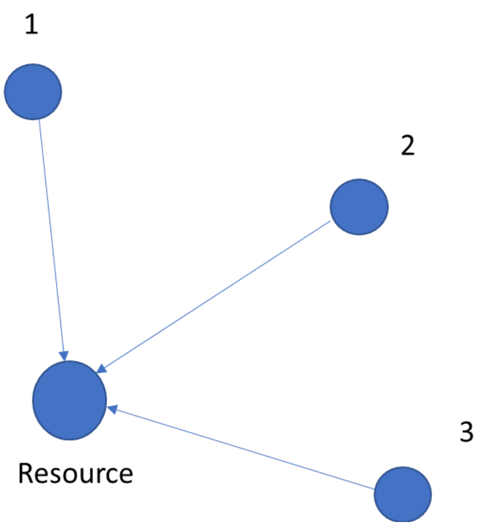

Figure 1: A 3-agent resource network with congestion externalities.

Harvest depends on the amount of effort, E, that is put during harvesting and on the size of the resource stock, S. Then the harvest function is given by:

$$H(E,S) = qES \tag{1}$$

where q is the "catchability-coefficient", which can translate one unit of effort into one unit of harvest. The pay-off of agent i will be:

$$u_i = pH_i - \frac{\beta}{2}(E_i)^2 - \gamma H_i \sum_{j=1}^{3} H_j \tag{2}$$

where $j \neq i$. p is the price of the resource. Note that we have a linear quadratic profit function, while the last term shows some type of congestion. The more the rest of the agents exploit the resource, the lower is my benefit. Solving (1) wrt E will give us:

$$E_i = \frac{H_i}{qS}$$

When the resource is more scarce, the agents need to put more effort to harvest it. The maximization problem becomes:

$$\max_{H_i} \; pH_i - \underbrace{\frac{\beta}{2}\left(\frac{H_i}{qS}\right)^2}_{\text{private cost}} - \underbrace{\gamma H_i \sum_{j=1}^{3} H_j}_{\text{congestion cost}}$$

Then, the individual pay-off functions will be given by:

$$\begin{aligned} u_1 &= pH_1 - \frac{\beta}{2}\left(\frac{H_1}{qS}\right)^2 - \gamma H_1(H_2 + H_3) \\ u_2 &= pH_2 - \frac{\beta}{2}\left(\frac{H_2}{qS}\right)^2 - \gamma H_2(H_1 + H_3) \\ u_3 &= pH_3 - \frac{\beta}{2}\left(\frac{H_3}{qS}\right)^2 - \gamma H_3(H_1 + H_2) \end{aligned}$$

FOC:

$$\begin{aligned} p - \beta\left(\frac{H_1}{q^2S^2}\right) - \gamma(H_2 + H_3) &= 0 \\ p - \beta\left(\frac{H_2}{q^2S^2}\right) - \gamma(H_1 + H_3) &= 0 \\ p - \beta\left(\frac{H_3}{q^2S^2}\right) - \gamma(H_1 + H_2) &= 0 \end{aligned}$$

and the solution is given by:

$$H_i^* = \frac{pq^2S^2}{\beta + 2\gamma q^2S^2} \tag{3}$$

Notice that

$$\frac{dH_i^*}{dS} = \frac{2\beta pq^2S}{(\beta + 2\gamma q^2S^2)^2} > 0$$

meaning that, as expected, the larger the stock of the resource, the higher the amount that is harvested. Notice also that in the case where there is no congestion, or in the case of a single user, price equals private marginal cost, $p = \beta\left(\frac{H_i}{q^2S^2}\right)$, which leads to $H_i^o = \frac{pq^2S^2}{\beta}$. It is easy to see that congestion reduces the use of the resource, i.e. $H_i^* < H_i^o$, since it apparently makes harvesting more costly.

Individual profits under the presence of this negative externality are given by:

$$u_i^* = \frac{\beta p^2q^2S^2}{2(\beta + 2\gamma q^2S^2)^2} \tag{4}$$

while aggregate profits are given by:

$$u_T^* = \frac{3\beta p^2 q^2 S^2}{2(\beta + 2\gamma q^2 S^2)^2} \tag{5}$$

2.2 Resource use under technological spillovers and congestion externalities

Let us assume now that the agents are linked to each other, taking advantage of some positive technology effect.

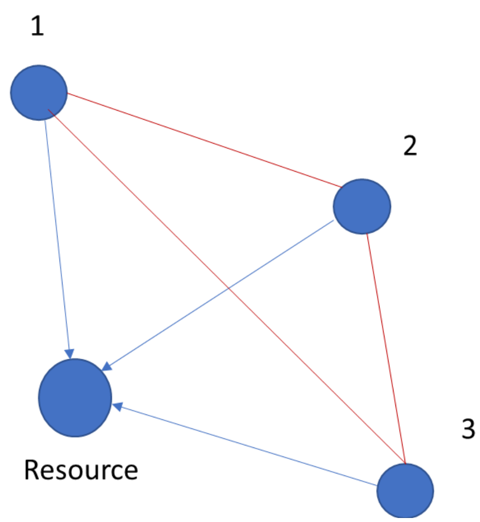

Figure 2: Resource network with technological spillovers and congestion externalities.

Then the payoffs are given by:

$$u_i = pH_i - \underbrace{\frac{\beta}{2}\left(\frac{H_i}{qS}\right)^2}_{\text{private cost}} - \underbrace{\gamma H_i \sum_{j=1}^{3} H_j}_{\text{congestion cost}} + \underbrace{\delta \sum_{j=1}^{3} g_{ij} H_i H_j}_{\text{technology spillover effect}}$$

Notice that g_{ij} shows the presence of a link between two agents. g_{ij} could take values $0 < g_{ij} < 1$, but here for simplicity we assume that when agents collaborate and exchange information and experience relating to technological progress, $g_{ij} = 1$, and $g_{ij} = 0$ otherwise. In general, harvesting is subject to three external effects: (i) *Resource stock externalities,* which occur when total private cost decreases when resource stock increases, (ii) *Crowding externalities*, which imply that cost is increasing in the harvesting of other agents' and (ii) *positive productivity externalities*, which occur when agents share technological advances and knowledge with respect to harvesting activity.[1]

Analytically, the payoffs of each agent are given by:

$$
\begin{aligned}
u_1 &= pH_1 - \frac{\beta}{2}\left(\frac{H_1}{qS}\right)^2 - \gamma H_1(H_2+H_3) + \delta H_1(H_2+H_3) \\
u_2 &= pH_2 - \frac{\beta}{2}\left(\frac{H_2}{qS}\right)^2 - \gamma H_2(H_1+H_3) + \delta H_2(H_1+H_3) \\
u_3 &= pH_3 - \frac{\beta}{2}\left(\frac{H_3}{qS}\right)^2 - \gamma H_3(H_1+H_2) + \delta H_3(H_1+H_2)
\end{aligned}
$$

FOC:

$$
\begin{aligned}
p - \beta\left(\frac{H_1}{q^2S^2}\right) + (\delta-\gamma)(H_2+H_3) &= 0 \\
p - \beta\left(\frac{H_2}{q^2S^2}\right) + (\delta-\gamma)(H_1+H_3) &= 0 \\
p - \beta\left(\frac{H_3}{q^2S^2}\right) + (\delta-\gamma)(H_1+H_2) &= 0
\end{aligned}
$$

From the FOC, we get:

$$\tilde{H}_i = \frac{pq^2S^2}{\beta + 2(\gamma-\delta)q^2S^2} \tag{6}$$

Individual profits are given by:

$$\widetilde{u}_i = \frac{\beta p^2q^2S^2}{2(\beta + 2(\gamma-\delta)q^2S^2)^2} \tag{7}$$

and aggregate profits:

$$\widetilde{u}_T = \frac{3\beta p^2q^2S^2}{2(\beta + 2(\gamma-\delta)q^2S^2)^2} \tag{8}$$

By simple inspection of equations (3) and (6), we can see that: $\tilde{H}_i > H_i^*$, which says that harvesting is higher when agents collaborate and share technological advances and knowledge. In this case, the positive technological spillovers (fully or partly) outweigh the negative congestion effect, lead to higher use of the resource and higher individual and aggregate profits (notice that $\widetilde{u}_i > u_i^*$ and $\widetilde{u}_T > u_T^*$). When it comes to the comparison between $\tilde{H}_i$ and H_i^o (where no externalities are taken into account), things are more unclear.

[1] For a discussion on external effects characterizing natural resource exploitation see Smith (1968, 1969).

More precisely, when $\gamma > \delta$, meaning that the negative congestion force is higher than the positive technology effect, then $H_i^o > \tilde{H}_i$. On the contrary, when the positive effect dominates, $H_i^o < \tilde{H}_i$.

3 Dynamics of Network Formation

In this section we examine whether the three harvesting agents will decide to create or sever links. We develop a simplified framework where at the beginning of the period the agents, given full information about congestion costs and cooperation spillovers, are going to decide to create new links or sever existing cooperation links. Their decisions will determine the structure of the network at the end of the period.[2]

The same approach can be applied to determine the socially efficient network structure. The regulator decides at the beginning of the period to retain or sever cooperation links using as objective the maximization of aggregate payoffs plus the conservation value of the resource. The structure of the network at the end of the period will characterize the socially efficient network structure. If this structure is different from the efficient "market structure" the regulator has an incentive to intervene in order to provide incentives schemes which will attain the socially efficient market structure.

3.1 Market Network Structure

Assume that at the beginning of the period the network is star shaped, that is no cooperation links exist. Let $\hat{u}_i\left(\mathbf{H}^S \mid -ij\right)$, $i,j = 1,2,3$, $i \neq j$, denote the maximized payoff of each agent, given that no links exist, with $\mathbf{H}^S$ the vector of profit maximizing harvesting when the network is star-shaped. For cooperation to emerge is should be profitable for both agents. Then the following results can be stated, where $\mathbf{H}$ denoted the vector of profit maximizing harvesting at each network structure, $+ij$ means the the link ij is created and $-ij$ means that the link is not created $i,j = 1,2,3$, $i \neq j$.

a. If

$$
\begin{aligned}
u_1\left(\mathbf{H} \mid +12,-13\right) &> \hat{u}_1\left(\mathbf{H}^S \mid -ij\right) \text{ and } u_1\left(\mathbf{H} \mid +12,-13\right) > u_1\left(\mathbf{H} \mid +ij\right) \\
u_2\left(\mathbf{H} \mid +21,-23\right) &> \hat{u}_2\left(\mathbf{H}^S \mid -ij\right) \text{ and } u_2\left(\mathbf{H} \mid +21,-23\right) > u_2\left(\mathbf{H} \mid +ij\right)
\end{aligned}
$$

[2] It should be noted that this not a fully dynamic set up. A fully dynamic set up would consider a multi period problem and examine the convergence to a stable network structure. Such a problem has been studied by Watts (2001) Jackson and Watts (2002). In these papers, the payoff functions were, however, relatively simple and allowed analytic results. We regard our approach to the problem as a first order approach with the development of a fully dynamic model being the next stage of our research.

There will be a link between 1 and 2 but not with 3.

Note that it is possible to have

$$\begin{aligned} u_3(\mathbf{H} \mid +ij) &> \hat{u}_3\left(\mathbf{H}^S \mid -ij\right) \\ u_3(\mathbf{H} \mid +13, -23) &> \hat{u}_3\left(\mathbf{H}^S \mid -ij\right) \\ u_3(\mathbf{H} \mid +23, -13) &> \hat{u}_3\left(\mathbf{H}^S \mid -ij\right) \end{aligned}$$

but there will be no cooperation with 3 since this is not profitable for the other agents.

b. Similar inequalities with case (a) will hold for the cases where a link is created with 1 and3, without 2 and or with 2 and 3 without 1.

c.

$$u_i(\mathbf{H} \mid +ij) > \hat{u}_i\left(\mathbf{H}^S \mid -ij\right), i, j = 1, 2, 3\ , i \neq j,$$

in this case all agents create cooperation links

d.

$$u_i(\mathbf{H} \mid +ij) < \hat{u}_i\left(\mathbf{H}^S \mid -ij\right), i, j = 1, 2, 3\ , i \neq j$$

in this case no cooperation links are created and the star shaped network will remain until the end of the period.

The networks created in cases (a)-(d) are pair wise stable in the sense of Jackson and Wolinsky (1996). The efficiency of the network depends on

$$u_h^M = \sum_{i=1}^{3} u_{ih}\ , h = a, b, c, d$$

The strongly efficient network is the one for which

$$u_h^M = \arg\max_h \sum_{i=1}^{3} u_{ih}\ , h = a, b, c, d$$

Given that the network is characterized by complementarities and substitutabilities it is not clear which structure will be the strongly efficient one.

In case (a) if

$$\begin{aligned} \left[u_3(\mathbf{H} \mid +13, -23) - \hat{u}_3\left(\mathbf{H}^S \mid -ij\right)\right] &> \left[u_1(\mathbf{H} \mid +12, -13) - u_1(\mathbf{H} \mid +ij)\right] \\ \left[u_3(\mathbf{H} \mid +23, -13) - \hat{u}_3\left(\mathbf{H}^S \mid -ij\right)\right] &> \left[u_2(\mathbf{H} \mid +21, -23) > u_2(\mathbf{H} \mid +ij)\right] \end{aligned}$$

agent 3 can bribe agent 1 or 2 to cooperate with instead her of the other agent.

We can have similar results for the social network.

4 Fully or Partly Connected Network?

According to the theory presented in the previous section, agents will decide to collaborate when it is more profitable for them compared to the non-collaboration case. As noted at the end of Section 2, individual profits in a fully connected network are higher than in an unconnected network, $\widetilde{u}_i > u_i^*$, meaning that agents will certainly create links with each other. In other words, the full network Pareto dominates the unconnected network which clearly promotes the cooperation among the harvesting agents. This will lead to higher aggregate use of the resource, $\tilde{H}_T > H_T^*$, and higher aggregate profits, $\tilde{u}_T > u_T^*$.

It is interesting to examine the case where two of the agents meet and decide to collaborate without including the third agent in this first step (as it is illustrated in Figure 3). The question that arises is if it will be profitable for all the agents to include the third one at a later stage. The answer is not so straightforward In terms of our modelling, agents 1 and 2 will be linked ($g_{12} = g_{21} = 1$), while agent 3 is just exploiting the resource, without having any links with the rest of the agents ($g_{13} = g_{31} = g_{23} = g_{32} = 0$).

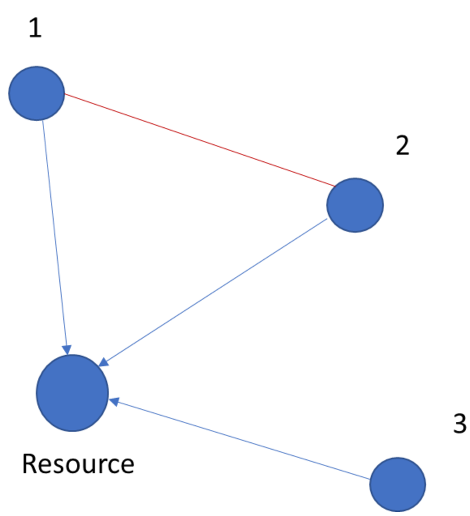

Figure 3: A partly-connected network

Then individual pay offs are given by:

$$
\begin{aligned}
u_1 &= pH_1 - \frac{\beta}{2}\left(\frac{H_1}{qS}\right)^2 - \gamma H_1(H_2+H_3) + \delta H_1 H_2 \\
u_2 &= pH_2 - \frac{\beta}{2}\left(\frac{H_2}{qS}\right)^2 - \gamma H_2(H_1+H_3) + \delta H_2 H_1 \\
u_3 &= pH_3 - \frac{\beta}{2}\left(\frac{H_3}{qS}\right)^2 - \gamma H_3(H_1+H_2)
\end{aligned}
$$

FOC:

$$
\begin{aligned}
p - \beta\left(\frac{H_1}{q^2S^2}\right) - \gamma(H_2+H_3) + \delta H_2 &= 0 \\
p - \beta\left(\frac{H_2}{q^2S^2}\right) - \gamma(H_1+H_3) + \delta H_1 &= 0 \\
p - \beta\left(\frac{H_3}{q^2S^2}\right) - \gamma(H_1+H_2) &= 0
\end{aligned}
$$

Then solving the FOC, we get:

$$\widehat{H}_1 = \frac{pq^2S^2(\beta - \gamma q^2S^2)}{(\gamma-\delta)\beta q^2S^2 + \beta^2 - 2\gamma^2q^4S^4} \tag{9}$$

$$\widehat{H}_2 = \frac{pq^2S^2(\beta - \gamma q^2S^2)}{(\gamma-\delta)\beta q^2S^2 + \beta^2 - 2\gamma^2q^4S^4} \tag{10}$$

$$\widehat{H}_3 = \frac{pq^2S^2(\beta - (\delta+\gamma) q^2S^2)}{(\gamma-\delta)\beta q^2S^2 + \beta^2 - 2\gamma^2q^4S^4} \tag{11}$$

Individual profits are given by:

$$\hat{u}_1 = \hat{u}_2 = \frac{\beta p^2q^2S^2(\beta - \gamma q^2S^2)^2}{2((\gamma-\delta)\beta q^2S^2 + \beta^2 - 2\gamma^2q^4S^4)^2} \tag{12}$$

and

$$\hat{u}_3 = \frac{\beta p^2q^2S^2(\beta - (\delta+\gamma) q^2S^2)^2}{2((\gamma-\delta)\beta q^2S^2 + \beta^2 - 2\gamma^2q^4S^4)^2} \tag{13}$$

and aggregate profits:

$$\hat{u}_T = \frac{\beta p^2q^2S^2(3\beta^2 - 2\beta(\delta+3\gamma)q^2S^2 + (\delta^2+2\delta\gamma+3\gamma^2)q^4S^4)}{2((\gamma-\delta)\beta q^2S^2 + \beta^2 - 2\gamma^2q^4S^4)^2} \tag{14}$$

Note that $\widehat{H}_1 = \widehat{H}_2 > \widehat{H}_3$ and $\hat{u}_1 = \hat{u}_2 > \hat{u}_3$, which means that the collaboration between the two agents allows them to harvest more of the resource, which leads to higher payoffs.

First, we show that it is profitable for agents 1 and 2 to start collaborating, i.e. $\hat{u}_{1,2} > u^*_{1,2}$.[3] Since individual payoffs for agents 1 and 2 are higher in the case where they start collaborating ($g_{12} = g_{21} = 1$), compared to the non collaboration case ($g_{12} = g_{21} = 0$), they will undoubtfully create these links. In order to study if it is profitable to include the 3rd agent, after the collaboration between the first two has already been established, we have to compare equations (12) and (7), as well as equations (13) and (7). More precisely, for the new collaboration to start, we need: $\tilde{u}_{1,2} > \hat{u}_{1,2}$ and $\tilde{u}_3 > \hat{u}_3$. Again, this means that it should be profitable for *all* the agents to move from a partly to a fully connected network, or:

$$\begin{aligned}
\tilde{u}_{1,2} &> \hat{u}_{1,2} \\
\frac{\beta p^2 q^2 S^2}{2(\beta + 2(\gamma - \delta)q^2 S^2)^2} &> \frac{\beta p^2 q^2 S^2 (\beta - \gamma q^2 S^2)^2}{2((\gamma - \delta)\beta q^2 S^2 + \beta^2 - 2\gamma^2 q^4 S^4)^2} \\
\beta &> 2\gamma q^2 S^2
\end{aligned}$$

and

$$\begin{aligned}
\tilde{u}_3 &> \hat{u}_3 \\
\frac{\beta p^2 q^2 S^2}{2(\beta + 2(\gamma - \delta)q^2 S^2)^2} &> \frac{\beta p^2 q^2 S^2 (\beta - (\delta + \gamma) q^2 S^2)^2}{2((\gamma - \delta)\beta q^2 S^2 + \beta^2 - 2\gamma^2 q^4 S^4)^2} \\
\beta &> \delta q^2 S^2
\end{aligned}$$

For high values of private marginal cost, all agents find it profitable to create links with each other and take advantage of the positive technological externalities, which increase harvest and individual payoffs. It seems though that the inclusion of the third agent is more unclear in the case where the first two agents are already connected compared to the transition from the unconnected to the fully connected network.

If $\tilde{u}_3 > \hat{u}_3$, but $\hat{u}_{1,2} > \tilde{u}_{1,2}$, this means that only agent 3 has a benefit to join the collaboration, while the already involved agents do not find it profitable anymore to include 3. In the particular case where $\tilde{u}_3 - \hat{u}_3 > 2(\hat{u}_{1,2} - \tilde{u}_{1,2})$, then agent 3 could offer a bribe equal to $\hat{u}_{1,2} - \tilde{u}_{1,2}$ to each one of agents 1 and 2 which will make them interested in collaborating with her, while agent 3 will still have positive profits, since $(\tilde{u}_3 - \hat{u}_3) - 2(\hat{u}_{1,2} - \tilde{u}_{1,2}) > 0$.

[3] Proof is provided in Appendix 1

5 Extension: Costly Transportation and Heterogeneity.

Let us assume now that the transportation of the resource is costly and the cost depends on the geographical distance between the agent and the resource. Until now, we had assumed that the agents involved in the exploitation of the resource were homogeneous. Costly transportation introduces heterogeneity in the model, since agents who locate further away from the resource have to pay a higher transportation cost, which increases the total cost of harvesting the resource, affects their harvesting decisions and decreases their payoffs.

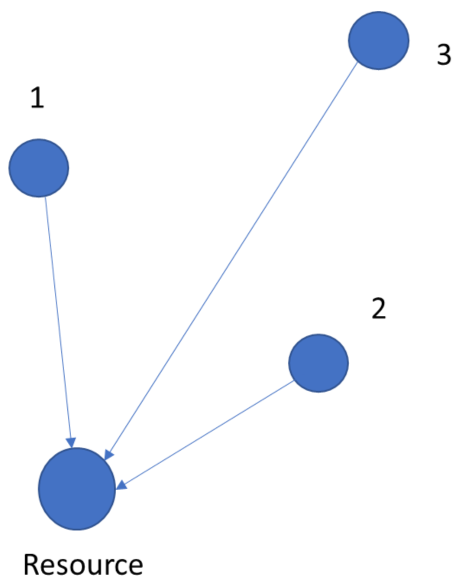

Figure 4: Introducing heterogeneity: different geographical distance between the agent and the resource.

Let $l_i \in (0, 1]$ represent the location of the agent i, defined as her distance from the resource, and τ represent the marginal transportation cost. Then, the pay-off of agent i will be:

$$u_i = pH_i - \frac{\beta}{2}(E_i)^2 - \tau l_i H_i - \gamma H_i \sum_{j=1}^{3} H_j \tag{15}$$

and individual pay-off functions will be given by:

$$
\begin{aligned}
u_1 &= pH_1 - \frac{\beta}{2}\left(\frac{H_1}{qS}\right)^2 - \tau l_1 H_1 - \gamma H_1(H_2 + H_3) \\
u_2 &= pH_2 - \frac{\beta}{2}\left(\frac{H_2}{qS}\right)^2 - \tau l_2 H_2 - \gamma H_2(H_1 + H_3) \\
u_3 &= pH_3 - \frac{\beta}{2}\left(\frac{H_3}{qS}\right)^2 - \tau l_3 H_3 - \gamma H_3(H_1 + H_2)
\end{aligned}
$$

FOC:

$$
\begin{aligned}
p - \beta\left(\frac{H_1}{q^2S^2}\right) - \tau l_1 - \gamma(H_2 + H_3) &= 0 \\
p - \beta\left(\frac{H_2}{q^2S^2}\right) - \tau l_2 - \gamma(H_1 + H_3) &= 0 \\
p - \beta\left(\frac{H_3}{q^2S^2}\right) - \tau l_3 - \gamma(H_1 + H_2) &= 0
\end{aligned}
$$

and the solution is given by:

$$
H_i^{**} = \frac{\left[\beta(p - \tau l_i) - \gamma q^2 S^2\left(p + \tau\left(l_i - \sum_{j \neq i} l_j\right)\right)\right] q^2S^2}{\left(\beta - \gamma q^2S^2\right)\left(\beta + 2\gamma q^2 S^2\right)} \tag{16}
$$

which implies positive harvesting when $\beta - \gamma q^2 S^2 > 0$. It is important to point out that H_i^{**} does not only depend on agents i spatial location, l_i, but also on the spatial location of the rest of the users, l_j. In other words, if agent i is located relatively closer to the resource, she will have to pay a lower aggregate transportation cost compared to the rest of the users, which allows her to harvest more than the agents who are located at a higher distance.

Notice that

$$
\frac{dH_i^{**}}{dl_i} = \frac{-\left(\beta + \gamma q^2 S^2\right)\tau q^2 S^2}{\left(\beta - \gamma q^2S^2\right)\left(\beta + 2\gamma q^2 S^2\right)} < 0 \tag{17}
$$

Higher transportation cost increases the cost of harvesting and leads to lower use of the resource. This implies that agents who are located further away find it profitable to harvest smaller amount of the resource compared to the ones that are located closer to the resource. Also,

$$
\frac{dH_i^{**}}{dl_j} = \frac{\gamma \tau q^4 S^4}{\left(\beta - \gamma q^2S^2\right)\left(\beta + 2\gamma q^2 S^2\right)} > 0 \tag{18}
$$

meaning that increasing the distance of another agent will increase her harvesting cost which in turn will decrease her use of the resource. However, this implies less congestion which will give an incentive to the rest of the agents to increase their harvesting amount.

Individual payoffs are given by:

$$u_i^{**} = \frac{\beta q^2 S^2 \left[\beta(p - \tau l_i) - \gamma q^2 S^2 \left(p + \tau\left(l_i - \sum_{j \neq i} l_j\right)\right)\right]^2}{2\left(\beta - \gamma q^2 S^2\right)^2 \left(\beta + 2\gamma q^2 S^2\right)^2}$$

Let us assume now that all agents are linked to each other ($g_{ij} = 1$), taking advantage of some positive technology effect.

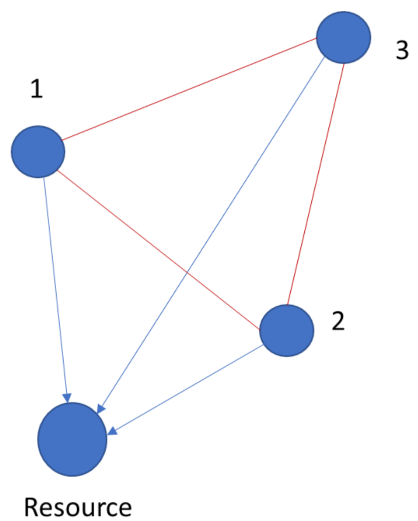

Figure 5: Technological spillovers between heterogeneous agents.

Then the payoffs are given by:

$$u_i = pH_i - \underbrace{\frac{\beta}{2}\left(\frac{H_i}{qS}\right)^2}_{\text{private cost}} - \underbrace{\tau l_i H_i}_{\text{transportation cost}} - \underbrace{\gamma H_i \sum_{j=1}^{3} H_j}_{\text{congestion cost}} + \underbrace{\delta \sum_{j=1}^{3} g_{ij} H_i H_j}_{\text{technology spillover effect}}$$

Analytically, the payoffs of each agent are given by:

$$\begin{aligned}
u_1 &= pH_1 - \frac{\beta}{2}\left(\frac{H_1}{qS}\right)^2 - \tau l_1 H_1 - \gamma H_1(H_2 + H_3) + \delta H_1(H_2 + H_3) \\
u_2 &= pH_2 - \frac{\beta}{2}\left(\frac{H_2}{qS}\right)^2 - \tau l_2 H_2 - \gamma H_2(H_1 + H_3) + \delta H_2(H_1 + H_3) \\
u_3 &= pH_3 - \frac{\beta}{2}\left(\frac{H_3}{qS}\right)^2 - \tau l_3 H_3 - \gamma H_3(H_1 + H_2) + \delta H_3(H_1 + H_2)
\end{aligned}$$

FOC:

$$
\begin{aligned}
p-\beta\left(\frac{H_1}{q^2S^2}\right)-\tau l_1+(\delta-\gamma)(H_2+H_3) &= 0\\
p-\beta\left(\frac{H_2}{q^2S^2}\right)-\tau l_2+(\delta-\gamma)(H_1+H_3) &= 0\\
p-\beta\left(\frac{H_3}{q^2S^2}\right)-\tau l_2+(\delta-\gamma)(H_1+H_2) &= 0
\end{aligned}
$$

From the FOC, we get:

$$
\bar{H}_i=\frac{\left[\beta(p-\tau l_i)+(\delta-\gamma)q^2S^2\left(p+\tau\left(l_i-\sum_{j\neq i}l_j\right)\right)\right]q^2S^2}{\left(\beta+(\delta-\gamma)q^2S^2\right)\left(\beta-2(\delta-\gamma)q^2S^2\right)} \tag{19}
$$

$$
\frac{d\bar{H}_i}{dl_i}=\frac{-\left(\beta-(\delta-\gamma)q^2S^2\right)\tau q^2S^2}{\left(\beta+(\delta-\gamma)q^2S^2\right)\left(\beta-2(\delta-\gamma)q^2S^2\right)}<0 \tag{20}
$$

$$
\frac{d\bar{H}_i}{dl_j}=\frac{-(\delta-\gamma)\tau q^4S^4}{\left(\beta+(\delta-\gamma)q^2S^2\right)\left(\beta-2(\delta-\gamma)q^2S^2\right)}<0 \tag{21}
$$

It is interesting to point out that both the agent's own geographical location and the other agents' spatial locations affect harvesting in the same way, under the presence of positive spillover effects. In other words, larger distance between either agent i and the resource, or agent j and the resource affects harvesting of agent i in the same way, that is it leads to smaller amount of harvesting. This is true in the case where $(\delta-\gamma)>0$, i.e., when the positive spillover effect is stronger than the congestion effect. In this case, larger distance between agent j and the resource, reduces harvesting of agent j, as expected, but since agent j (or agent's j harvest) affects the use of the resource by agent i positively, this will also result in the reduction of harvesting by agent i. This interaction between between technology spillover and relative distances (transportation costs) plays apparently a significant role on total harvesting and aggregate payoffs.

It is interesting to explore whether transportation cost and heterogeneity will make the formation of links easier, meaning that the agents will have a higher incentive to collaborate with each other. In order to do so we need to compare individual payoffs in different cases. If $\bar{u}_i$ denotes the payoff of agent i in a fully connected network with heterogeneity, then transportation costs make the formation of links easier iff:

$$
\bar{u}_i\left(\mathbf{H}\mid +ij\right)-u_i^{**}\left(\mathbf{H}^S\mid -ij\right)>\tilde{u}_i\left(\mathbf{H}\mid +ij\right)-u_i^{*}\left(\mathbf{H}^S\mid -ij\right)
$$

That is, heterogeneity creates a larger difference between the payoffs of the fully connected network and the corresponding ones of the star network. In terms of the inequality above, the LHS shows the difference between the payoffs of the connected and the unconnected network in case of heterogeneity, while the RHS shows the same difference in case where all agents locate at equal distance from the resource. Numerical simulations will give a clearer idea of whether heterogeneity could facilitate the creation of links between the agents.

6 Optimal Resource Exploitation

The existence of positive and negative externalities in efforts implies that Nash equilibrium is not efficient. If positive externalities are stronger, the Nash equilibrium is expected to lead to too little effort because individual agents ignore the positive impact of their effort on other agents. On the contrary, when the congestion effect outweighs the positive externality, the Nash equilibrium leads to too much effort. In the first case, there will be benefits from subsidizing effort while in the second case it will become beneficial to tax effort.

Let us study first the social optimum in the case harvesting creates congestion. In this case, the regulator will choose $H_1, H_{2,}H_{3,}$ to maximize total welfare, and the optimal problem can be described as follows:

$$\max W(H_i) = \max_{H_1,H_2,H_3} \sum_{i=1}^{3} u_i(H,g) = \max_{H_1,H_2,H_3} \sum_{i=1}^{3} \left[pH_i - \frac{\beta}{2}\left(\frac{H_i}{qS}\right)^2 - \gamma H_i \sum_{j=1}^{3} H_j \right]$$

The first order conditions are:

$$\begin{aligned} p - \beta\frac{H_1}{q^2S^2} - 2\gamma(H_2 + H_3) &= 0 \\ p - \beta\frac{H_2}{q^2S^2} - 2\gamma(H_1 + H_3) &= 0 \\ p - \beta\frac{H_3}{q^2S^2} - 2\gamma(H_1 + H_2) &= 0 \end{aligned}$$

which implies that:

$$H_i^S = \frac{pq^2S^2}{\beta + 4\gamma q^2 S^2} \tag{22}$$

while the value of the network is given by:

$$W(H_i^S) = \frac{3p^2q^2S^2}{2(\beta + 4\gamma q^2 S^2)} \tag{23}$$

Comparing the market (3) and the optimal harvesting (22) in a network where there is only one negative externality, namely congestion, it is easy to see that harvesting is lower at the optimum. Agents should reduce the amount of the resource they exploit in order to reduce the negative effects that are imposed to the rest of the agents through the described activity. A tax per unit of output that will fully internalize the damage caused by congestion will increase the cost of harvesting and will reduce the use of the resource to the optimal level.

Now we will examine the case where both externalities are present and there are links, in the form of positive technological spillovers, among all the agents. Then the regulator will choose $H_1, H_{2,}H_{3,}$ that maximize total welfare, that is:

$$\max W(H_i) = \max_{H_1,H_2,H_3} \sum_{i=1}^{3} u_i(H,g) = \max_{H_1,H_2,H_3} \sum_{i=1}^{3} \left[pH_i - \frac{\beta}{2}\left(\frac{H_i}{qS}\right)^2 + \delta \sum_{j=1}^{3} g_{ij} H_i H_j - \gamma H_i \sum_{j=1}^{3} H_j \right]$$

The first order conditions are:

$$\begin{aligned} p - \beta \frac{H_1}{q^2 S^2} + 2(\delta - \gamma)(H_2 + H_3) &= 0 \\ p - \beta \frac{H_2}{q^2 S^2} + 2(\delta - \gamma)(H_1 + H_3) &= 0 \\ p - \beta \frac{H_3}{q^2 S^2} + 2(\delta - \gamma)(H_1 + H_2) &= 0 \end{aligned}$$

which implies that:

$$\tilde{H}_i^S = \frac{pq^2S^2}{\beta + 4(\gamma - \delta)q^2 S^2} \tag{24}$$

while the value of the network is given by:

$$W(\tilde{H}_i^S) = \frac{3p^2q^2S^2}{2(\beta + 4(\gamma - \delta)q^2S^2)} \tag{25}$$

It is interesting to compare, again, the optimal use of the resource, with the decentralized use in the corresponding case, $\tilde{H}_i = \frac{pq^2S^2}{\beta + 2(\gamma-\delta)q^2S^2}$. When the congestion externality dominates, $(\gamma - \delta) > 0$, the use of the resource is smaller at the optimum than in the decentralized case, $\tilde{H}_i^S < \tilde{H}_i$. The analysis is similar to the case studied above where there was no positive externality. The only difference here is that the negative effect is outweighed by the positive effect, so the tax that will close the gap between the optimal and the market outcome will be lower.

On the contrary, when the positive externality dominates, $(\gamma - \delta) < 0$, the optimal use of the resource is higher than the market outcome, $\tilde{H}_i^S > \tilde{H}_i$. This means that the regulator should encourage agents to exploit the resource more and a way to do so is to subsidize the use of the resource with a per unit subsidy that will fully internalize the positive effect of the technological spillovers net of the congestion effect.

Notice that the optimal value of the network (or else aggregate welfare) under the presence of two externalities (given by 25) is higher than the optimal value of the network under congestion externality (described by 23) which clearly shows that the regulator has an incentive to enforce policies that will promote the collaboration between the agents.

6.1 Conservation and Optimal Use of the Resource

Note that the regulator's objective above is to maximize the agents' payoffs without considering the fact that the resource is depletable and that there is some welfare loss as a consequence of the reduction in the stock of the resource. When the regulator is considering some kind of preservation plan for the resource, her objective should change accordingly. Let us assume that $\kappa > 0$ reflects the fact that the regulator gets utility from leaving some resource unharvested. Then the optimal maximization problem will become:

$$\max W^P(H_i) = \max_{H_1,H_2,H_3} \sum_{i=1}^{3} u_i(H,g) + \kappa \left(S - \sum_{i=1}^{3} H_i \right)$$

The first order conditions are:

$$\begin{aligned} p - \beta \frac{H_1}{q^2 S^2} + 2(\delta - \gamma)(H_2 + H_3) - \kappa &= 0 \\ p - \beta \frac{H_2}{q^2 S^2} + 2(\delta - \gamma)(H_1 + H_3) - \kappa &= 0 \\ p - \beta \frac{H_3}{q^2 S^2} + 2(\delta - \gamma)(H_1 + H_2) - \kappa &= 0 \end{aligned}$$

which implies that:

$$\tilde{H}_i^P = \frac{(p-\kappa) q^2 S^2}{\beta + 4(\gamma - \delta) q^2 S^2} \tag{26}$$

and

$$W(\tilde{H}_i^P) = \frac{\left(2\beta\kappa + q^2 S\ [3(\kappa^2 + p^2) + 2\kappa(4S(\gamma-\delta) - 3p)]\right) S}{2(\beta + 4(\gamma - \delta) q^2 S^2)} \tag{27}$$

Equation (26) leads clearly to lower harvesting than equation (24). In particular, when the regulator takes into account the value of the unharvested resource and the fact that society has a benefit from preserving part of the natural resources for future use, then harvesting is lower at the optimum. The higher is the value of the preserved resource, the lower is the current exploitation of the resource. The table below shows how optimal harvesting (26) and optimal network value under preservation plan (27) change in different parameter values.

	β	γ	δ	S	κ
$\tilde{H}_i^P$	$-$	$-$	$+$	$+$	$-$
$W(\tilde{H}_i^P)$	$-$	$-$	$+$	$+$	$\pm$

Higher private cost of harvesting reduces both the optimal harvesting and aggregate welfare. The same is true when the congestion externality becomes stronger imposing a higher cost on agents. On the contrary, when the effect of the positive technological externality becomes stronger, harvesting as well as the value of network increase. The same happens in the case where the stock of the resource under study increases. Higher κ value, which basically implies that the regulator (as well as the society) values the unharvested resource more, reduces the current use of the resource. An alternative interpretation is to say that higher κ value implies that the regulator cares relatively more for future generations which again leads to lower exploitation of the resource in the current period. What is interesting here is that the effect of κ on welfare is ambiguous. More precisely, higher κ reduces harvest which in turn reduces aggregate payoffs, which basically constitute the first part of the welfare function. On the other hand, the higher κ increases the second part of the welfare function, which shows the value of the unexploited resource. The numerical simulations will help us understand which effect will potentially dominate.

7 Conclusion

In this paper, we have used network theory to study the market and the optimal outcomes in a natural resource management problem. The externalities characterizing the exploitation of the resource under study, in the form of positive technological spillovers, crowding effects and resource stock effects, open the gap between decentralized and optimal harvesting. Different network structures have been studied and shown how they affect harvesting and aggregate welfare. We have also analyzed the incentives of harvesting agents with respect to the formation or elimination of cooperative links. We show that agents always have a strong incentive to move from an unconnected to a fully connected network, which implies cooperation and exchange of information between them regarding technological advances and so on. However, when two of the three agents have agreed to cooperate without including the third agent in the fist stage, it is proved to be more difficult for the third agent (or else less profitable for all the agents) to join the network at a later stage.

Heterogeneity with respect to the distance of each agent to the resource, which implies higher or lower transportation cost for the agent who is located farther away or closer respectively, changes the harvesting amounts as well as the individual and aggregate payoffs. This also leads to different views regarding how profitable or not is the cooperation between the harvesting agents. We also study the regulator's problem using two different approaches: the one that is commonly used in the literature that is based on the maximization of aggregate profits and another approach that is more intuitive given the special nature of the natural resources that takes into account the conservation value of the resource. We show that the more the regulator cares about leaving part of the resource for future exploitation, the lower is the optimal harvesting amount in the current period. These approaches will help us examine and determine the optimal social structure of the resource network. When the optimal network structure has been identified, we will be able to design policies that will be more in line with the scarce nature of the resources and will reduce their use

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