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Evolution, Social Norms, and the Sustainability of Common Property Resources

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Jean-Philippe ATZENHOFFER

Jury

Advisor:	Gisèle UMBHAUER	-	University of Strasbourg
Reviewers:	Sandrine SPAETER-LOEHRER	-	University of Strasbourg
	Katheline SCHUBERT	-	University of Paris 1
	Cees WITHAGEN	-	VU University, Amsterdam
Examinator:	Benteng ZOU	-	University of Luxembourg

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Contents

Chapter 1

Introduction

Contents

1.1 The Commons in Human Societies

Fisheries, forests, grazing lands, wildlife, wetland, water basins, irrigation water. What is the common point of all these natural resources? In fact, they are all members of the large family of the *commons*. The commons can be grossly defined as resources which, rather than being hold by a single individual, are accessible either to all or to specific communities of people. These natural resources are important, in many different respects, for maintaining and improving livelihood and quality of life of human populations. Food consumption, biodiversity, quality of the air and the water, or recreational activities are several examples among the benefits humans can take from the commons.

Common property resources play a particularly important role in the livelihood of rural regions. In India and West Africa, while taking a central role in many cultural and social activities, the commons contribute crucially to household income in rural areas (Beck Cathy, 2001). In developing countries, small-scale fisheries have particular significance. Recent estimates of the FAO (2010) indicate that they represent more than half of the world's fish catch. These fisheries employ more than 90 percent of the world's 35 million capture fishers, while supporting another 84 million people in related sectors such as fish processing, distribution and marketing. In many developing countries, the contribution of fish is essential for economic and social development, as well as for protein intake.

More generally, fisheries resources, by supplying 17 kg of human food per capita in 2008, are of great importance for alimentation (FAO, 2010). Around 150 million tonnes of fish are supplied every year for feeding human populations. In many poor countries, the fishing sector still represents a significant share of GDP. For example, it accounts for 4% of GDP and directly employ more than 650,000 fishers in Vietnam, and 3% of GDP for 100,000 people in Mozambique (Béné et al., 2010).

While marine resources are subject to widespread attention, the commons located on the solid ground are important as well for human populations. Because of the wide diversity of benefits provided by forests, preserving them is another concerning challenge. Quite evidently, forests, which cover 31 percent of terrestrial land on Earth (FAO, 2011), supply wood that serve for construction and furniture industries. Less visible but not less important, forests play a profound role in offering diverse amenities. For example, residential locations with forests may be more attractive since they have more amenable climate (Hand et al., 2008). In rural regions of developing countries, fuelwood gathered from forested commons is a very important source of domestic energy (Heltberg et al., 2000; Pattanayak et al., 2004). Besides, forest lands also generate indirect benefits. At a local level, they are often crucial for the quality of soil and water (Islam and Weil, 2000; Neary et al., 2009; Biao et al., 2010). At the global scale, wood cover is considered by many scientists as a means for carbon storage in the perspective of mitigating the impact of CO2 emissions (Sohngen and Mendelsohn, 2003; Richards and Stokes, 2004; Bonan, 2008).

Protecting wildlife is a prominent objective for biodiversity conservation and for food provision. At the worldwide scale, harvest of wildlife is valued at several billion dollars annually, while providing a key source of meat for hundreds of millions of rural people (Brashares et al., 2011). Also important, in particular for rural development, wildlife can also be used for recreational activities. In Zimbabwe, local communities have authority over wildlife management, which is directed toward the selling of safaris to tourists and trophy hunters (Frost and Bond, 2008).

Human populations are also highly dependent on water resources for survival and welfare. Fresh water is a fundamental resource for food and energy production, industrial development, and human health. If keeping watersheds, aquifers, and rivers in the most pristine state is hardly compatible with increasing development, preserving water quality is a major priority for now and the distant future (Loucks, 2000). Given the importance of fresh water, its relative scarcity in some regions of the world creates situations of conflicts, thus threatening international security (Gleick, 1993).

Examples of this kind, which highlight the role of common natural resources for human populations, could be enumerated endlessly. People in every country in the world rely to some extend on their commons for maintaining or improving their quality of life. In poor and rural regions, it is often simply the livelihood of local populations that is at stake.

1.2 The Problem of Resource Overuse

The problem with the commons is that they are often subject to degradation and depletion due to excessive human exploitation. Fisheries are well-known for being subjected to severe overexploitation worldwide (Costello et al., 2008; Worm et al., 2009). According to the FAO (2010), the proportion of world fish stocks that are underexploited or moderately exploited declined from 40 percent in the mid-1970s to only 15 percent in 2008. In contrast, the share of overexploited, depleted or recovering stocks raised from 10 percent to 2 percent during the same period. The cod fishery in Canada has become a famous, and dramatic, example of fish depletion. Several stocks of Atlantic cod collapsed to the point that a memorandum on fishing was introduced in 1993 (Myers et al., 1997).

Although the state of world forests is globally improving, deforestation remains a major concern, especially in developing countries. The FAO (2011) estimates that deforestation rates, though slowing down, are still high. Between 2000 and 2010, the loss of forest land reached 13 million hectares per year. Annual deforestation rates are still superior to 1 percent in Central America and in East and West Africa. Employing imaging capabilities of Earth-observing satellites, Achard et al. (2002) calculate that around 6 million hectares of humid tropical forest cover were lost every year between 1990 and 1997. Agriculture and logging are the main cause of deforestation in many countries. The Amazonian forest, facing logging and land conversion for cattle ranching and agriculture, is still at risk (Fearnside, 2009; Rodrigues et al., 2009). The loss of forest cover has potentially harmful side effects. In Ethiopia, water availability declined as a result of the clearance of the majority of forest lands (Dessie and Kleman, 2007). Once mainly covered by forests, Haiti is now mostly deforested. The consequence has been a significant deterioration of land suitable for agriculture (Williams, 2011). In Thailand, rapid conversion of forests to agricultural and pastoral land resulted in dramatic reduction of wildlife (Chaiyarat and Srikosamatara, 2009).

Besides, the provision of fresh water constitute a serious challenge in many regions as water resources are under heavy pressure. As water demands are rising, a large proportion of the world's population is experiencing water stress (Vörösmarty et al., 2000). Water tables in aquifers are in decline in populated regions due to excessive consumption of fresh water (von Rohden et al., 2010). Perhaps the most spectacular catastrophe of a common resource destroyed by human activities is given by the shrinking of the Aral Sea. Mainly because of excessive diversion of water for irrigation, the size of the sea declined dramatically during the last decades such as the water represents only around a tenth of its original volume (Micklin, 2007).

The awareness of these problems of overexploitation started to growth with the publication of the article of Garett Hardin, entitled "The Tragedy of the Commons" (Hardin, 1968). He stated that, since common resources are held by no one, thereby being accessible to all, humans will inevitably destroy the commons. Factors like the increase in human populations or the continuous improvements of harvesting technologies shall intensify pressures over natural resources. As a result, the commons may be condemned to suffer severe damage at a worldwide scale.

The academic literature related to the problem of the commons has considerably flourished after Hardin's article, especially during the last twenty years, and is now very vast.[1] Many contributions have recently emerged from different disciplines. Biologists, economists, legal scholars, anthropologists, as well as scholars from other disciplines have studied the consequences of human exploitation on the state of common natural resources. Either being theoretical or more empirically oriented, the literature on the commons has tried to identify the causes of overexploitation and degradation, and has also proposed a variety of solutions for coping with resource overuse.

[1] Some statistics on the rapid growth of interdisciplinary scientific work on the commons are given in Dietz et al. (2002, pp.6-7).

1.3 Resource Overuse in Theory

The first path toward an economic theory of common property resources has been taken by Gordon (1954). His formal representation of an open-access fishery showed how fishers, instead of extracting the maximum rent of the resource, dissipate their own revenues through overexploitation. Since then, microeconomic and game theory has been extensively applied for analyzing a large variety of common resources. The theoretical literature on the commons, coupled with experimental analyzes and cases studies, has led to significant accomplishments in the understanding of the problems related to the use of common resources.

Theoretical modeling of common resource exploitation is largely based on the use of game theory. In this theory, the problem of resource overuse can be explained by the logic of a "social dilemma". Concretely, a social dilemma is a situation in which individual interests are in contradiction with collective interests. In other words, a strategy that is optimal from the point of view of each agent is inefficient when aggregated at a collective level. More precisely, the tragedy of the commons has been often described as a type of "prisoner's dilemma". The logic is straightforward. Suppose that individuals have two possible choices, either exploiting the resource reasonably or, on the contrary, extracting it intensively. The best outcome for all resource users would be that everyone conforms with reasonable use. However, the problem is that the best interest for any individual would be to increase its returns by overexploiting the resource, while others keep on with reasonable harvesting. Now, if others are already overexploiting, the best individual choice would be also to practice intensive use, since the resource units left free will probably be appropriated by others. Therefore, the individual interest would be to deviate toward more intensive use, whatever the choices made by others. If everyone uses this kind of reasoning, the situation will end on a rush to the resource that is harmful for all. Unfortunately, since individual harvesters are incited to extract more of the resource than the level that would correspond to the collective optimum, the commons are fundamentally prone to overexploitation.

Describing resource use through the logic of the prisoner's dilemma gives the feeling that overexploitation is an inevitable outcome when humans have access to common-pool resources. This vision was prevalent from the 1960s to the 1980s, decades during when it was recommended for governments to take control over natural common resources. Instead of being opened to all, access to natural common resources should be restricted by coercion. However, in many cases, government took control of natural resources that were not in open access, but managed under common property regimes. In reality, resource users have often developed local institutions for overcoming problems of overuse. Numerous case studies on the commons have highlighted the central role of norms and institutions when resources are self-managed by communities of local users (see in particular Ostrom (1990)). Then, while the logic of the prisoner's dilemma can explain why many common resources are severely overexploited, a great number of case studies have shown that individuals can find solutions for escaping the dilemma.

In its standard formulation, game theory is founded on strong assumptions regarding the behavior of individuals. Economic agents are supposed to behave "rationally" in the sense that they are able to compute their best strategies from complete knowledge of the interaction situation. Each player makes the best possible decision, taking into account the decisions of others. When everyone has made a decision such that no one has an interest to change his choice, the game reaches a state of equilibrium. Such equilibrium is called the Nash equilibrium, which is the main concept used for defining optimal individual behavior in games. The standard game theoretical framework have been significantly applied to the problem of resource use. Common-pool resource games have been proposed for analyzing incentives faced by exploiters, and determining how to change the structure of interactions in order to promote sound exploitation.

Yet, without denying the profound achievements made by scientists through the use of standard game theory, there are still shortcomings to be addressed. Many experiments conducted over different situations have demonstrated that individual behavior often deviate from the Nash prediction. In resource economics, experimental and empirical studies have also shown that resource exploitation is not always in accordance with the usual outcomes predicted by the Nash equilibrium (see Ostrom (2000a) for a review). The differences between Nash behavior and the behavior observed in reality suggest that some elements are not taken into account in standard game theory. In particular, the classical assumption of rationality have been questioned. Instead of computing their optimal strategies given the optimal choices of the others, individuals may follow other behavioral rules.

During the last decades, the scope of game theory has been extended with the introduction of evolutionary principles. The theory of evolution is based on two fundamental notions, natural selection and mutations. In economics, the principle of selection corresponds to the fact that agents adapt progressively their behavior by comparing their performances with the ones realized by the others. As for the principle of mutation, its signification is that instead of looking at choices made by the others, a few players may experiment alternative strategies. Instead of assuming perfectly rational agents, evolutionary game theory postulates that individuals are only able to follow simple heuristic rules, such as copying what the others are doing. Essentially, they adapt their strategies by imitating each other. Evolutionary adaptation means that players select the strategies that yield relatively high payoffs. Hence, the proportion of the best performing strategies tends to increase at the expense of less performing ones.

As for the standard game theory, the evolutionary version is interested in the study of stable states. Although the evolutionary theory is fundamentally dynamics in its design, processes of adaptation usually lead to outcomes characterized by stability. In fact, the motivation for changing strategies is driven by the differences of payoffs between participants. As agents are exploiting their opportunities of profits, the differences in payoffs will tend to reduce over time, until a state of equilibrium is reached. Once attained under the evolutionary dynamics, an evolutionary equilibrium is defined as a state that offers some resistance to invasion of "mutant" behavior. In other word, for representing a credible prediction, an outcome should remain stable when a few players choose to experiment alternative strategies.

Imitation has received both theoretical and experimental support for describing behavior in economic interactions (Apesteguia et al., 2007). As a consequence, evolutionary game theory have an appeal for explaining outcomes that have not found convincing enough interpretations in the standard framework. Although they remain quite marginal, applications of evolutionary games to the common resource problem have started to come through during the last fifteen years. The first significant contribution has been made by Sethi and Somanathan (1996), who demonstrate that instead of systematically defecting, resource users can cooperate on sound exploitation levels. Through self-enforcement activities, by sanctioning those who overexploit the resource, harvesters can agree on social norms that restrict the intensity of resource use. Particularly important in common resource dilemmas, evolutionary game theory is suited for including social norms and institutional arrangements. Social norms can be seen as informal behavioral rules that are developed by agents for guiding their actions toward collectively desirable outcomes.

Our thesis falls within the scope of the evolutionary literature on the exploitation of common resources. By using evolutionary game theory, our aim is to help explaining outcomes that have not been satisfactorily addressed within the standard game theoretical framework. We will argue that the principle of evolutions are well-adapted for analyzing interactions that take place in common resource exploitation, and propose three applications. We will see how resource users can engage in more intensive exploitation than predicted by the standard Nash equilibrium, thereby highlighting experimental and empirical patterns showing that overexploitation can be worse than expected. Taking the opposite direction, we will see in two other applications how the design of appropriate institutional arrangements can help coping with resource overuse. In particular, we will analyze respectively the role of self-enforcement activities and property rights in the establishment of social norms. The content of the thesis is described in more details in the next section.

1.4 Plan of the Thesis

In chapter 2, we will recall the fundamental logic that causes overexploitation of common resources, before proposing a review of the institutional solutions that have been advocated for coping with problems of resource overuse. The principal objective is to highlight the main characteristics of systems of resource governance that are effectively used in real situations. In the commonly-held vision, solutions are separated into three categories: i) direct resource control by the state (nationalization), ii) control by private owners (privatization), iii) community-based resource management by local users. The third option is generally seen as an alternative way to the classic dichotomy between private actors and the state (see for example the influential book of Ostrom (1990)).

The classification adopted in our interpretation differs from this view. We distinguished systems of resource management according to their degree of centralization or decentralization. In other words, we oppose systems of governance which are of top-down nature and those who have bottom-up foundations. In this categorization, what defines the nature of a resource management system is the level where the different responsibilities are taken, rather than who is taking the decisions. Defining institutional systems through the degree of centralization of decisional powers allows to apprehend the great diversity of institutions. It gives a more accurate representation of approaches of resource governance that are based on the involvement of different kind of actors, and is in line with the recent empirical literature. In our classification, direct state control of natural resources, as well as systems of tradable permits, are considered as types of top-down management. On the contrary, community-based resource management and initiatives of joint management between communities and governmental authorities are viewed as bottom-up approaches of governance.

The chapter 3 describes the developments and main concepts of the theory of evolution, with an essential focus on evolutionary game theory. It discusses the relevance of the evolutionary approach for analyzing problems encountered in environmental economics. In particular, we will try to weight the advantages and limits of evolutionary game theory in the study of the problems related with common resource use. From the characteristics of resource exploitation and governance described in the preceding chapter, we will argue that evolutionary games are well-adapted for representing interactions between resource users in common-pool resources. In particular, evolutionary game theory is a relevant tool for describing how local communities can develop and sustain social norms for coping with problems of overuse. The evolutionary concepts presented in this chapter will be used in the applications that constitute the three following chapters.

In chapter 4, we propose a first application which is aimed at answering some interrogations that have come out of several experimental and empirical studies. Many studies of common-pool resource exploitation have questioned the relevance of the Nash equilibrium, as the effective level of extraction often deviates from its predictions. Most of these results found that problems of overuse are not as worse as suggested by the Nash equilibrium. However, in this chapter we are interested in opposite cases where individuals exploit more than the Nash level, that is where the problem of the commons is exacerbated regarding the standard prediction. Several experiments have indeed warned that situations where resource exploitation is greater than Nash can indeed happen. However, the question of deviations toward higher resource use have not been really addressed in the theoretical literature, which focus almost uniquely on the way people may achieve more efficient outcomes. We will try to fill this gap by explaining how resource users can engage into a race to the resource with greater intensity that the Nash equilibrium would suggest. When they behave as imitators by copying the strategies that yield the best performance in the population, harvesters can be stuck in a harmful competition for appropriation that may ultimately destroy all resource rents. This result holds even in the case the number of harvesters is very limited.

Chapter 5 takes an opposite view from the preceding application. In the line of other papers in the evolutionary literature on the commons, it proposes to introduce social norms and sanctions into the arena of interaction. It is supposed that individual harvesters, instead of free-riding by overexploiting the resource, can cooperate on a social norm. Concretely, they can voluntarily decide to restrict their level of extraction for preserving the resource and the rents that are derived from it. Besides, they can also individually monitor and sanction others who do not respect the norm. Such situations, where resource users restrict their harvest and sanction those who do not cooperate, have been largely documented. They are particularly prevalent where local communities play an important role in management.

Our model, though it is base on Sethi and Somanathan (1996), offers an important difference with the rest of the literature. Other models with enforcement of norms always assumes that those who sanction poachers and rule-breakers are those who comply with the rules. Yet, somewhat surprisingly, some studies have found that users who overexploit also sanction others. This attitude has been judged negatively in the literature, which considers it as perverse and immoral. Beyond judgment values, we ask whether such behavior can help to cope with overexploitation. We found that, by forcing other harvesters to comply with the norms, individuals who overharvest but nevertheless also sanction can help to solve partially the problem of overuse. This result suggests that the incentives driving this behavior may be used for improving systems of governance based on self-enforcement.

In chapter 6, as in the previous application, we try to identify social norms used by actors for coping with overuse problems. However, this time the central question is how local users are able to develop systems of individual property rights over resources that are held in common. In a first intuition, common property and private property are fundamentally exclusive concepts. However, the notion of property is far more complex than a simple opposition private versus collective. A property can be viewed as a bundle of rights that have several attributes, thereby giving to its owner different kind of rights. Hence, the rights associated with a property can be divided among several actors, at different levels. Consequently, a resource held in common property does not exclude the presence of individual rights.

Extensive evidence has shown that common property resources, where decisions management are taken at the collective level, confer important private rights to individual users. Usually, these private rights are not defined and enforced by an external authority, but by the local users themselves. Given the empirical importance of such arrangements between collective and private property, we propose in this chapter an evolutionary game design aimed at introducing the opportunity for local actors to implement private rights over the resource stock, while other rules are still decided at the collective level. We try to see how resource users could be able to maintain individual property, and whether some restrictions should be placed on the use of this property for achieving resource conservation.

As for the last chapter, it summarizes the main elements of the previous chapters. As well, it argues that the evolutionary approach can be extended further, especially given the increasing importance of decentralized resource governance at the scale of the world.

Chapter 2

Top-Down Vs Bottom-up Solutions

Contents

2.1 Introduction

The influential book of Ostrom (1990) represents the principal starting point of modern approaches for coping with the problem of the commons. Ostrom's book and the subsequent literature on the commons have established a distinction between different forms of resource governance, which are of fundamentally opposite nature. Generally, solutions are classified in three different categories. The first policy prescription is the direct control of resources by the state. The presumption that central government must control most of natural resource systems has been advocated, and widely applied, from the 1960s onwards. However, this solution of highly centralized nature has received many critics, as numerous evidence of failures emerged worldwide. An alternative solution, which is often seen as the exact opposite to government control, is to privatize access and use of natural resources. By giving private property to individual users, they would internalize the detrimental incentives that push them to overexploit (Demsetz, 1967). Systems of tradable quotas, by introducing private harvesting rights, are often viewed as a privatization of the commons. Though effects of such systems are highly debated, it has received much more positive appreciations in the literature than the first solution. Besides "nationalization" and "privatization" of the commons, Ostrom has highlighted the role of local actors in the governance of the commons. In many situations, resources are held in common property by local communities. The importance of local actors in resource governance has received an increasing support from both scholar and policy-makers during the last twenty years. Given the failures of centralized state control and the difficulties to implement private property in resource that are common by nature, it is supposed to represent a credible alternative for governing the commons.

By summing up, in this recent but already traditional vision, there are three solutions of different natures for coping with the tragedy of the commons: centralized control by the government, privatization through the introduction of private property rights, and management based on the participation of local communities. Yet, in our view, based on the recent developments in the understanding of common resource governance, the most relevant angle of approach is to establish a distinction between management initiatives that stem from the global or the local. In other terms, we propose a classification that distinguish bottom-up governance and top-down management.

Indeed, reality is complex. The term commons refers to many different kind of resources which vary greatly in their respective biological and environmental characteristics. As well, the social and economical environment in which resource users interact is changing through both time and space. The environment, defined in its larger sense, is always specific to the particular arena of action. However, being confronted to ever changing situations does not signify that it is impossible to make quite general prescriptions for resource management. It is not because the world is complex that there are no regularities between different common-pool interactions. Some conditions for sustainable resource use are even necessary almost every time and everywhere. For example, for achieving sound exploitation, it is almost inevitable that some rules need to be enforced through monitoring and sanctions.

Since all situations are different, complex, and changing, solutions for common resource governance may also be different, complex, and changing. Institutional arrangements that define the rules and the norms of resource use can involve several kinds of actors. Beyond the simplifications of distinguishing governance by either communities, government officials, or private companies, in reality resource management often integrates several actors at different levels. Thus, the most important question is not whether resource control is detained by the government or by communities. It is rather whether responsibilities are held at the right level with the people that have the right incentives for promoting sound management.

Of course, in reality there is a large choice of intermediate options ranging from totally decentralized management to absolutely centralized control. Nevertheless, the different institutional structures designed for coping with resource overuse can be considered as belonging to the top-down or the bottom-up approach. According to the center of gravity of decision-making responsibilities, from the local to the global, we can classify institutional solutions in one of these two approaches. Systems of resource management can be considered as top-down when the power remains largely at a high level of decision-making. On the contrary, bottom-up resource governance implies that decisional power stays at a low level, close to the field. For example, either theoretically or in its application, resource governance that favors the role of communities can be viewed as bottom-up (i.e decentralized), while resource control by the central government can be seen as top-down (i.e centralized) management.

In accordance with this general framework, we attempt here to classify different systems of resource governance used in the commons worldwide. Using the literature on the commons of the last decades, we review the main approaches that have been advocated by scholars and applied in real situations. However, the aim of this chapter is not to provide an exhaustive review of the literature, which would represent a tremendous task and would be out of the scope of our objectives, nor to repeat what has already been said in other books or surveys. By selecting and singling out the elements that are relevant regarding our angle of analysis, we rather try to give here a fair representation of the actual situation of common resources, with a particular focus on how institutions for resource management are structured.

Yet, since recent initiatives of governance are involving several levels of actors sharing responsibilities, we have to admit that our classification of solutions for resource management may be subject to discussion. Obviously, a truly fifty-fifty partnership between communities and governments is neither bottom-up or top-down. This difficulty also arise in cases where management initiatives are decentralized in their objectives and theoretical conception, but remain centralized in concrete application. Should such initiatives be considered as belonging to the top-down or the bottom-up approach? Keeping these limitations in mind, we tried to identify, from studies covering various situations, the most important characteristics that allow to categorize resource governance as top-down or bottom-up approach.

The plan of this chapter is the following. In section 2.2, we precise the concept of a common-pool resource. Section 2.3 describes the logic underlying the tragedy of the commons. Further, top-down solutions and bottom-up solutions for coping with the tragedy are reviewed respectively in sections 2.4 and 2.5. Section 2.6 concludes.

2.2 Definition and Classification

A common-pool resource (or simply *common resource* or *commons*) is a natural or man-made type of good defined by two attributes: i) the difficulty of excluding potential beneficiaries, ii) subtractability of use. Natural renewable resources such as fisheries, forests, wildlife, pastures or aquifers, as well as non-renewable resources like oil fields or gold mines, fit this definition. Man-made resources which are shared among a community of users, for example the Internet bandwidth, also pertain to this categorization. Hereafter, in the line of the literature on the commons, the analyses and references will essentially cover the area of natural renewable resources. Table 2.2 provides a general classification of goods, which establishes the distinction between a common-pool resource and others types of goods (see also Ostrom et al. (1994)).

Unlike for private goods, preventing access and usage of the resource to anyone is not an easy task. Excluding and limiting potential beneficiaries from exploiting a common resource is challenging because of high costs of fencing. Let us take the example of fisheries. From a technical standpoint, fencing a large sea zone is a tremendous task for fishermen, while the economic cost of marking the boundary would be prohibitive. Moreover, to be effective, the fenced zone should be endorsed by other fishers (as well as the government) as

Table 2.1: Classification of goods

	Excludable	*Non-excludable*
Subtractable	Private goods	Common-pool resources
Non-subtractable	Club goods	Public goods

a legitimate property right. This is not obvious as legal systems often consider that common resources should potentially benefit to everyone, at least at a community level. Then, individual property rights aimed to deny access to outsiders are difficult to enforce for both technical and legal reasons.

Unlike public goods, common resources are subtractable (i.e. rivalrous). One resource unit harvested by someone is no longer available to other users of the common-pool. In the case of a public good like free-to-air television, an additional viewer would not reduce the availability of a programme to others. On the contrary, resource units that are taken in a common-pool are withdrawn once and for all, until the resource regenerates for renewables. For example, when a tree is cut down by a logger in a forest, it cannot benefit to other woodcutters anymore.

An important distinction between the *resource systems* and the *flow of resource units* has to be made in order to understand properly how common resources are exploited and managed. A flow of resource units is the outcome produced by a resource system over a period of time. For instance, the quantity of trees cut in a year represents a flow of resource units, while the forest land from which the wood is taken represents the resource system. Depending on the characteristics of both the resource units and the resource system, the structure of rules that are designed for achieving proper management may sensibly differ. Keeping the forestry example, we know that the rights to trees can be different from the rights to land (Fortman, 1985), which raises the arduous question of property. Are owners of the trees also owners of the forest land, and should it be so in order to achieve sound exploitation? In fact, property may include a large variety of rights that may or may not be in the hands of a unique actor (Sikor, 2006). The issue of designing the proper imbrication of rights attached to the resource is of central importance for resource management.

For resource governance, another important factor is the size of the resource system. Small-scale resources such as a parcel of forest or hunting land, a fishing lake, or an underground water basin, do not require same management structures as global commons such as the atmosphere or even the outer space. As we will see hereafter, extensive evidence have demonstrated that, for achieving sound resource use, small and medium-scale resources need the involvement of local users in governance. In opposition to global commons, which are managed under centralized governmental structures, resource conservation at lower scales functions better when local communities are implicated in management activities. Our description of resource governance will essentially focus on small and medium-scale resources hereafter.

One of the fundamental and original concern about common resources is their *sustainability* over the long run. The intuition lying behind the concept sustainability is quite straightforward. It requires that the viability of the resource system must be preserved for now and the distant future. Yet, since various objectives can be taken into account in defining sustainability, there are several definitions of this notion. For our purpose, sustainability means that a common resource must be preserved in its biological and economic functions in the long run. From a biological perspective, a common resource is sustainable only if the average rate of withdrawal does not exceed the average rate of replenishment. If this condition is attained under harvesting activities, then exploitation of the resource will be considered sustainable.

2.3 The Tragedy of the Commons

The interest of scientists for common resources started significantly during the late 1960s. Hardin (1968) draws attention to the fact that, due to overpopulation, natural common resources are more and more exploited, thereby leading to ineluctable extinctions as the human population keeps increasing. To illustrate his claim, he used the example of a grazing pasture open to all. Since each individual herdsman benefits from the entire revenue derived from the sale of his animals, everyone will try to maximize his profit by adding more grazing animals to his herd. The problem is that adding animals damages the pasture, thereby creating a negative effect borne by every other herdsman. Because this appropriation externality[1] caused by overgrazing is not taken into account by individual herders, they will put more animals on the meadow than what would be collectively optimal. Then, individuals are trapped in a logic that compels them to increase resource use without limit. The pasture, prone to degradation, sees its productivity undermined, or even worse, becomes definitely unusable. The conclusion is unambiguous, free access to the commons brings the ruin to all. Hardin viewed in a coercive population control the only viable solution to the problem of overexploitation in the long run.

However, Hardin was not the first scholar to warn about the danger of overuse of common resources. Before him, Gordon (1954), using a formal model of fishery exploitation, proposed a more detailed analysis of the problem of the commons. Suppose that, in a fishing spot exploited by several fishers, it becomes increasingly difficult to catch fish as long as total extraction increases. In economic formulation, the marginal and average productivity of

[1] A negative (positive) externality is a cost (benefit) inflicted to others which is not transmitted through prices. Hence, agents tend to neglect it in their economic decisions. In the commons, the negative appropriation externality is caused by the fact that individuals do not integrate the degradation of the resource in their economic calculus.

fishing effort diminishes when the resource becomes scarce. When deciding the quantity of fish to catch given its harvesting function, an individual fisher will undoubtedly take into account the decreasing returns on his own catch level. However, he will not necessarily care about the fact that his catch reduces the yield of the others. By acting according to his self-interest only, his behavior creates a negative appropriation externality on other fishers. If everyone follows this behavior, resource exploitation is higher than the optimal collective level (i.e. the maximum net economic yield), although harvesting decisions are optimal from an individual standpoint. As a consequence, the resource faces overexploitation and economic rents evaporate.

Since then, the common-pool problem has been, and still is, formalized by considering strategic interactions between resource users. In game theory, the tragedy of the commons refers to a particular class of social dilemma, the *commons dilemma*. Essentially, the commons dilemma is a free-rider problem caused by the negative appropriation externality just described above (see Ostrom et al. (1994) for a description). Formal models of strategic interactions between rational individuals are widely used in the academic literature for analyzing phenomena of rent dissipation and resource deterioration. Our approach falls within the scope of game theoretical literature. However, contrary to the mainstream approach, we will use a particular development of game theory based on the principles of evolution.

The principal critic that has been addressed to Gordon and Hardin is that they did not really analyze the question of the institutional regimes that could potentially help to govern the commons. Resources are considered by these authors to be owned by no one in particular, hence common resources are *open access resources*. Because excluding potential beneficiaries is costly, common-pool resources are indeed seldom owned by private individuals. However, instead of being accessible to all, many resources are nowadays controlled by the government, although it was not necessarily the case before the 1970s.

Maybe less visible, but not less important, lots of resources which were earlier considered as open access resources are managed, either successfully or not, by local communities. The picture of inhabitants of a village living nearby a natural resource gives an overall idea of the identity of a local community, although it can take diverse forms. Resources that are held and managed under communal regimes are known as *common property resources*. Historically, the role of local actors were probably ignored both because of the geographical isolation of many communities and the often informal nature of institutional arrangements aimed at governing the commons.

A semantic clarification is now needed to avoid any possibility of misunderstanding. Serious confusions had been created by the use of the terms *common-pool resources*, *common property resources*, or related expressions (Dietz et al., 2002). These terms, though they may appear as similar, can be classified in two categories. On one hand, common-pool resource, common resource or Common can be used interchangeably to name a resource characterized by the two features of subtractability and non-excludability. On the other hand, open-access resource, common property resource or state-owned resource refer in addition to the institutional regime under which the resource is managed (or not). The term common-pool resource represent only the characteristics of the resource itself, whereas a common property resource also implies the human-made norms and arrangements designed to govern its use.

The distinction between the intrinsic characteristics of the resource and the institutions crafted to rule the use of the resource is not idle talk. It is important, for designing effective solutions to the problem of the commons, to understand that human interventions are more likely to modify the rules that govern the commons rather than the natural attributes of the resource. In the remainder of this chapter, we review the set of the different solutions that have been advocated for coping with resource overexploitation.

2.4 Coping with Resource Overuse: Top-Down Solutions

As stated in the introduction, in the early 90s, scientists like Elinor Ostrom categorized the solutions to resolve commons dilemmas in three qualitatively different types: state control, market-based management, and community level management. This classification, though it has become usual, is not entirely satisfactory, since these categories may overlap each other in some cases. For example, in modern fisheries in developed countries, market mechanisms are implemented by governmental agencies. On the contrary, some traditional communities have for a long time developed systems of private rights that are tradable for governing their fisheries. Hence, market-based management can be viewed differently given the institutional framework in which it is implemented.

In our view, resource management should be defined according to the level at which decisional responsibilities are set. Therefore, our discussion distinguishes between *top-down* and *bottom-up* approaches for dealing with resource overuse. These expressions, which are quite familiar in the literature, refer to the level at which decisions regarding resource exploitation and management are taken. Hereafter, we will discuss initiatives of resource management that are of centralized nature. Centralized control over common resources have been tested during the last decades but are now being progressively abandoned given the numerous failures it generated worldwide. The following sections describe government control of resource governance in both developed and developing countries, and conclude with some explanations of the overwhelming number of failures.

2.4.1 Direct State Control

The presumption that a central government should take control of natural common resources emerges during the 1970s, basically for two reasons. Firstly, because initially the commons have been largely viewed as belonging to nobody, the state had to implement a form of property to prevent access to all. In many cases, the fact that common resources where already owned under a common property regime was usually neglected until the 1990s. Secondly, for commons held by private or communal owners, it was considered that their proprietors were unable to set well-functioning institutions for resource management. Then, a governmental agency had to take over the responsibility over the resource to correct the failures of local management.

Extensively adopted in developing countries, but not only, the involvement of the state in resource exploitation can take two different forms. Either a public company directly extracts the resource as a monopolist, or the government sets up regulations designed to use it reasonably. According to the classic economic theory, a unique owner would internalize all decisions and set the exploitation level such as achieving the highest possible value. Because a monopolist company faces no externality, it is theoretically able, by setting its harvesting effort to the level that equalize marginal revenues and costs, to reach the rent maximizing level.[2] Most of the time, exploitation of natural resources by state-owned enterprises concerns non-renewable common-pools, such as petrol or mines. Meanwhile, though there are still a few examples of state firms in renewables, there is no widespread evidence of public monopolies

[2]The level that maximize the rent extracted from the resource is sometimes called the *Optimum Sustainable Yield* (OSY). It must not be confused with the *Maximum Sustainable Yield* (MSY), which maximizes the total catch extracted but does not consider the cost side. Although, the MSY is economically inefficient and corresponds to a higher level of exploitation than the OSY, this concept is still largely used by governmental agencies in charge of the regulation of many fisheries worldwide.

in the renewable fishing industries.[3]

As for the regulation of resources by the state, it basically means that an external governmental agency decides who can exploit, how and when. The adjective *external* means that the authority is not formed or ruled by local resource users or people from communities who live nearby. Rather, its composition involves government officials that are not living directly from the resource. Taking the classification of Libecap (2007), external control is mainly implemented through restrictive harvesting measures such as: a) limitations on access, or on time of use; b) controls on the technology used; c) regulations on catch (such as harvesting quotas). Also, the government has to ensure that these measures, which can take various forms, are enforced correctly. State enforcement of harvesting rules is done principally through monitoring activities carried on by public guards, as well as sanctions such as fines or judicial sentences for rule-breakers.

2.4.1.1 State Control in Developing Countries

Centralized regulation by the state over natural resources were often recommended (and followed) to cope with resource overuse, particularly in developing countries during the 1950s and 1960s (Ostrom, 1999). The results of these top down policies have been widely criticized in the academic literature. Nationalization of forests in Niger, Nepal, Thailand or India, provide overwhelming evidences of deforestation (Ostrom 1990 and 1999, Agrawal and Ostrom 2001). Under Suharto's rule in Indonesia, when control over natural resources was highly centralized, loose monitoring of logging concessions resulted on degradation of lowland forests (Wollenberg et al., 2006). State appropriation of communal forest lands also contributed to degradation and deforestation in Southeast Asia and West Africa (Ascher, 1999), as well as in

[3] A counter example is given by Honduras, as well as Malaysia, where the wood is cut by a public enterprise in forest lands (Ascher, 1999).

Russia (Murota and Glazyrina, 2010).

In Vietnamese coastal fisheries, the collectivization process initiated by the state after the reunification in 1975 has manifestly failed, ultimately resulting in a nationwide collapse of fisheries cooperatives (Ruddle, 1998). The central governance during the 1980s has been all the more dramatic since the traditional rules, that managed fisheries quite effectively, have become irrelevant. Previous community-based institutions were abandoned, substituted by fisheries collectives which were under direct control of government officials. The extinction of former local institutions caused by nationalization of common resources is a feature that goes far beyond the Vietnamese case. Evidence of such crowding-out effect can be found almost everywhere collectivization has taken place. The consequences of this kind of nationalization are undoubtedly unfortunate, especially when the pre-existing institutions were well-working.

In Chongming Island, located in eastern China near Shanghai, the Dongping National Forest Park is a conservation project of forest land that offers also various recreational activities. The government decided to create a human-made forest area where people can enjoy horse riding, karting, rock climbing and others. If combining conservation measures with economic and social development may be a good idea in itself, our feeling is however that the forest park was designed without assessing properly the needs of the people living around.[4] Although the park is of recent construction, almost all activities seems to be completely disused. On the same island, the Chongming Dongtan Wetland has been arranged for purifying waste water. Alike for the forest park, infrastructure were build up in these natural wetlands, this time essentially for walking and cycling. In this case too, it is dubious that the demand will fit the recreational services, especially in a poor rural region. Both situations showed us that resource conservation seems to come at a high cost

[4] The author visited the Dongping National Forest Park, as well as the Chongming Dongtan Wetland, in June 2011.

because of overinvestment or malinvestment bias. Excessive investment and poor design are undoubtedly the consequences of a highly centralized decision-making process that is struggling to take into account the needs of the local inhabitants, particularly when they lack a voice within the political system.

In other cases, when governments lack the capacity, or simply the willing, to enforce sound regulations, the often encountered outcome is that former communal resources are transformed into open access resources, thereby exacerbating their degradation. For local fishers in the South-Eastern coast of Bangladesh, or Tanzanian fishers in the Lake Victoria, government ownership resulted in open access situations (Jentoft et al., 2010). Many inshore fisheries in Africa and Asia faced similar problem when national agencies extended their jurisdiction over coastal waters.

Corruption and the lack of ability to monitor and enforce proper harvesting rules are often cited as the root problems to explain the failure of regulation by the state. Governments may have the willing to preserve natural resources, but they have only weak capacity to implement their measures. Also, poachers can easily pursue their illegal activities by bribing local state agents in charge of the monitoring of the resource. Because of these two reasons, regulations enacted by central governments have usually no – or limited – effect on the ground. In this case, state property is synonymous with open-access.

However, a general assessment of the broad amount of case studies on centralized state management in developing countries would tell us that the lack of enforcement capacities to implement sound resource policies may not be the sole problem. Perhaps more fundamentally, bad policies are also the result of deliberate manipulations of resource policies, especially when the resources have enough economic value to be interested in. Government officials have their own interests that are not necessarily compatible with the objective of managing common resources in a sustainable way. As asserted by Ascher (1999) in its review of sixteen case studies covering the waste of natural resources by governments in developing countries, officials are tempted to distort resource exploitation in order to capture higher revenues. This is particularly the case when the resource industry contributes to a non-negligeable part of the state budget.

2.4.1.2 State Management in Developed Countries

Contrary to the situation of developing countries, the state of common resources is less worrying in developed ones. Rich countries are equipped with better functioning institutions, that have higher capacities to design efficient resource management and control. One striking example of the difference between low and high-income countries is given by the global state of forest resources. While forest lands in South America, Africa and Asia face widespread pressure toward deforestation, forest cover in North America and Europe tends to increase nowadays.[5] National parks in the United States of America offer another example of sound resource management. Administered by a federal agency, the National Park Service, it appears that ecosystems and wildlife habitat are preserved, even if conflicts on the purpose of land use can ignite congressional and public debates over policy.[6]

Yet, if the issues of corruption and the difficulty to enforce measures of resource conservation, which typifies many developing countries, are less problematic in developed countries, the tendency to delegate some responsibilities to local actors is nevertheless also present. Indeed, we stated above that centralized state control can generate unsound regulations since the government officials do not always have the right incentives to manage the natural resource cautiously. Unfortunately, such problems arise in developed countries as well.

In European fisheries, the centralized Common Fisheries Policy (CFP),

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[5] Food And Agriculture Organization, Global Forest Resources Assessment, 2010, Rome.

[6] Carol Hardy Vincent and David Whiteman, National Park Management and Recreation, *Congressional Research Service*, 2002.

plagued by short term decision-making, has failed to preserve the fish stock from overfishing. The European Commission indicates that "a centralized, top-down approach makes it difficult to adapt the CFP to the specificities of the different sea-basins in the EU".[7] Under the proposal of the European Commission for the reform of the CFP, the stakeholders involved in the fishing industry will take more responsibility for resource management. Decentralizing decision-making from Brussels to regional authorities and to vessels' owners is aimed at developing a culture of compliance. It is expected that, by giving self-management responsibilities to the fishermen, they will accept more easily restrictions on harvest, instead of fishing systematically more than their allowed quotas. More fundamentally, the reform would introduce *transferable fishing concessions*, with the objective of regulating fishing levels through the mechanisms of market.

One patent failure of the fisheries policy in Europe is the high level of subsidies given to the industry. Funding fishermen in order to help them keeping positive revenues is not a solution for having an economically viable industry, as acknowledged by the European Commission. This kind of measures, which are unfortunately not an exclusivity of the European Union, are harmful at all levels. Subsidizing fishing activities incite fishermen to put more effort and therefore worsen overfishing. As fish stocks decrease, the outcome is obviously bad from an ecological viewpoint, especially for those which are facing strong pressure and are near collapse. Among the humans who are impacted by the subsidies, the situation is not better. The fish consumers see a reduction of food available on the market[8], while the taxpayer has to bear the cost of the

[7]European Commission, Reform of the Common Fisheries Policy, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 13 July 2011.

[8]If the fishing effort is initially higher than the maximum sustainable yield, which is the case in most of fisheries in Europe and elsewhere.

transfer. On the side of the fishermen, one could initially think that it is necessarily good for them to get the money. However, subsidies will increase competition in the sector, and as fishing effort increase, economic returns fall down. If getting the funding could be a relief in the short run, once adjustments materialized it is highly doubtful that fishermen are better off in the end.

In this light, subsidizing the oil that fills the tanks of vessels, as it is systematically done in France, is the worst possible response to the problems that face the industry. Yet, if everybody is ultimately loosing, why do we see these kinds of policies coming up? The answer may be that when fishermen are facing serious economic difficulties, struggling for survival, they tend to focus only on the very short run. Hence, they are asking for financial help, particularly those who are close to bankruptcy. This short-sighted behavior is consistent with the experiment of Maldonado and Moreno-Sanchez (2008), where fishermen rush on the resource more intensively when fish stocks and revenues are low. The problem is that when government officials are involved in resource management, vessels' owners can get access to subsidies far more easily than if the fishery was ruled under a local community regime.

2.4.1.3 Roots of Resource Policy Failures

Although direct government control over common natural resources might not always result in patent failures, the whole picture of centrally-oriented management looks rather grim. The factors that generate unsound resource policies are various and complex. Basically, the difficulties to enforce sustainable harvesting rules are of two kinds: a lack of technical, financial or human capabilities; and a lack of willingness due to a poor incentive structure faced by government officials.

The lack of capability for governments to monitor and control resource use efficiently is often pointed up as the main reason why the commons are endangered. Often, resource controls fall into a downward regulatory spiral where government imposes harvesting restrictions, resource users then develop strategies to counter the restrictions, forcing the government to enact new complex and onerous regulations, and so forth. Insufficient capacity to enforce regulations is particularly problematic in developing countries. Since the issues of corruption and the shortage of funding for resource conservation are mostly prevalent in these countries, it would also explain why the tragedies of the commons are usually more critical in poor regions than in developed ones. In poor countries, governmental agencies may face great difficulties to collect accurate information for assessing the state of resources, and to use this knowledge for designing adequate policies.

However, given the fact that natural resources often represent a significant share of the employment and production in developing countries and the elaborateness of manipulations that distort regulations, policy failures are certainly not only due to technical mistakes or weak governmental capacity to enforce appropriate management rules. Agents in governmental bodies may also manipulate voluntarily resource policies in order to accomplish other objectives (see Ascher (1999, chap. 7) for details on strategies used by government officials to distort resource policies). In some cases, weak enforcement capacity looks like a deliberate consequence of maneuvers from policy-makers, rather than an inevitable feature. In Costa Rica, the state agency in charge of the forests was not able to prevent overcutting during the 1970s and 1980s. One reason behind this failure is that the government denied the budget needed for forest guards to monitor the lands effectively (Lutz and Herman, 1991). Vehicles used by inspectors even lacked gasoline to drive into the forest. Though, paying gasoline so that inspectors can use their vehicles to do their job should not have represented an enormous investment. Thus, by denying guards to monitor tree logging, it seems that some officials in the government had an interest for the forest to be exploited at a higher rate than required by the principles of sound management.

Improper resource policies in centralized systems are then often the result of distortions or manipulations, which stem from wrong incentives themselves induced by flawed institutional structures. In the Canadian clam fishery of Nova Scotia, policy inconsistencies have their sources in constitutional uncertainty, and in lack of coordination between the government and regulating agencies (Wiber et al., 2010). Various experiences have shown that when resources are under direct control of the government, the temptation to distort exploitation rules is strong. Without entering deeply into the details, we can say that motives behind resource manipulations are very diverse and depend on the institutional structure in place. For example the nature of interactions with the government and companies – wherever public or private – can have a great influence on the way a resource is exploited. Within the government itself different types of conflicts between particular interests can arise, leading to harmful regulations. Besides, poor conservation policies stem also from a lack of internalization of the damage by regulatory authorities. If resource depletion do not impinge upon officials, the latter will not face incentives strong enough to engage themselves seriously in conservation programmes. This problem can be serious in locations where people who suffer most from resource degradation are unable to put some political pressure on their representatives.

Assume now that a governmental agency, insensitive to the temptation of resource manipulation, is fully committed to the objective of protecting a resource. There is still a problem to deal with: the question of knowledge. Even when the management authority can rely on a relatively high degree of expertise, having scientific and technical knowledge about the resource characteristics and the environment may not be enough for elaborating sound policies. Even armed with the best expertise from specialists who have at their disposal a scientific and objective knowledge, the regulator may lack of relevant knowledge. A regulatory body can draw up an accurate assessment of the level of fish stocks and its speed of regeneration, but fails to take in the particular knowledge held by fishermen. Through their everyday fishing experiences, the latter would have build up some valuable knowledge on the characteristics of the resource system. Even more importantly, local resource users would have also a deep knowledge on the informal arrangements and social norms that govern the behavior of the community of users. This knowledge, which is dispersed among individuals and therefore extremely difficult to integrate for an external body, corresponds to the *knowledge of the particular circumstances of time and place* defined by Hayek (1945). As in a large society, the question of the best use of knowledge in the commons is of main importance for designing an efficient regulation system. Hayek suggested that the price system constitutes the finest tool for creating harmony between the individual plans in the society. In the case of common resources, experiences have shown it is not that simple. If the price system is effectively used in fisheries in several developed countries, as we will see in the next section, resource users in many kind of commons have devised institutions and behavioral norms through their specific knowledge of the arena in which they interact. In the end, an excessively centralized regime of decision-making may create rules that are inefficient and difficult to implement. Indeed, failing to take into account the specific knowledge held by every individuals can lead the regulatory agency to set up rules that conflict with systems of informal rules used by local actors, thereby generating perverse incentives that may result on resource misuse.

Another factor explaining why centralized management can worsen the situation of the commons is the *crowding-out effect*. Put it briefly, this effect describes the fact that imposition of external rules or incentives tend to dissipate intrinsic motivations of individuals, such as norms of other-regarding or cooperative behavior. Crowding out phenomena have been analyzed by economists to evaluate failures of monetary incentives (see Frey and Oberholzer-Gee (1997)). For example, Mellström and Johannesson (2008) have found that paying blood donors can affect negatively their volition to donate. Apart from monetary rewards, the crowding out effect has also been tested to estimate the effectiveness of external regulations. Concerning the commons, some elements have shown that institutional crowding out is taking place too. When external rules are implemented, there is a risk that they undermine existing local rules and social norms build up by resource users. In Colombian communities living nearby forests, the introduction of government restrictions on collecting firewood resulted on a decrease of other-regarding behavior (Cardenas et al., 2000). An experiment conducted by Ostmann (1998) found that external control of a common-pool resource have a negative effect on informal established institutions. This study questions the capacity of external rulers to increase cooperative behavior through monitoring and sanctioning when these activities are coming from outside of the community of commoners.

Apart from the problem of efficiency of resource exploitation and sustainability, there is a risk that centralized control over common resources will neglect the interests of local populations. Rents generated by exploitation may feed individuals that are not the most dependent on the resource for their livelihood. This could be a real worry in poor rural areas, where local people still need to benefit from their natural resources to safeguard their quality of life. The lack of recognition of the interests of local actors is also blatant in national parks and protected areas. At the worldwide scale, despite rhetoric, preservation is often dominated by the desire to exclude local people, rather than to involve them in conservation activities (Pimbert and Pretty, 1997).

The patterns of policy failures described above suggest that some actions are needed to improve the exploitation of common resources. One kind of solution is to reform the institutional structures of the government so that it would reduce the incentives and the possibilities of resource manipulation. Ascher (1999, pp. 271-277) proposes some recommendations to enhance the quality of state control over natural resources. By simplifying the mandates of state agencies, clarifying their jurisdictions, prioritizing through the central budget of the state, or reforming the arrangements between government and state companies, the state would be able to ameliorate its capacity to handle resources cautiously.

However, if it is worth trying to improve resource management by reforming high level government bodies, such improvements may be insufficient, or merely inadequate, to deal with the problem of the commons. Even if state officials are confronted with a virtuous incentive structure and have a sincere desire to promote sound resource use, they are not necessarily able to do so in a centralized structure of decision-making. As stated before, the knowledge of local communities and individuals resource users about the specific circumstances in which they interact is often crucial for the design of proper institutions. Thus, the fundamental question is not how to ameliorate decision-making within highly centralized institutions. Rather, it is how to devise a management system that will integrate in an efficient manner the appropriate knowledge and the capacity of all actors involved. In other words, who should have some control of common resources, and at which level decisions over resource management have to take place? This problematic has led scholars and state officials to look for more decentralized approaches to cope with resource overuse. Over the last thirty years, resource management based on the principles of price system has then emerged as an alternative to what has been considered an excessively rigid control by the state.

2.4.2 The Market-Based Approach

Mitigated experiences over centrally-managed resources led scholars and legal authorities to turn toward a more decentralized approach, based on harvesting quotas and market principles. In light of the observation that despite regulating harvesting efforts, exploitation still degenerates into races to the resources, the idea was the following. When resource controls are focused on limiting entry, they fail to prevent commoners to continuously increase their level of effort and harvesting capacities. Thus, rather than regulating inputs, which is inefficient for mitigating excessive investment, it would be better to control outputs. By giving harvesters a secure right to harvest a restricted amount of the resource, they would no longer face incentives to rush on it. On the contrary, they would restrict their harvest in the limit of their quotas, and arrange to extract the highest possible value from it by spreading their efforts over time. Tradable permits started being implemented in new systems of resource management, mostly in commercial fisheries where they are known as *Individual transferable quotas* (ITQs). While tradable permit systems are used for pollution control, water resource management, and some other situations such as livestock grazing, they are primarily used for fishery management in developed countries. For this reason, our discussion will essentially focus on fisheries. The next section discusses the concept of ITQ, the second the initiatives of self-governance by local actors in ITQ programmes, while the latest draws a brief assessment of ITQS.

2.4.2.1 Individual Transferable Quotas

An ITQ is a right held by a resource user to harvest a given quantity of resource. The principle is that a total allowable catch is divided up into individual quotas that are allocated between harvester (see Moloney and Pearse (1979) for a description). The particularity of this kind of quota is the possibility for resource users to trade them like goods on a market. As a tradable permit, it can be sold or buy by resource users, at a fluctuating price determined by the law of supply and demand. ITQs are expected to increase economic outcomes because operators with the lowest harvesting costs are incited to buy ITQs to less efficient ones. As a result the overall productivity of the industry should increase. Yet, beyond the issue of productivity, economic inefficiencies are mainly due to excessive levels of investment in harvesting. Therefore, setting a limit over the total catch is the primary objective in ITQ management. The total allowable catch, which conditions the number and size of ITQs in circulation, should be determined at a level that guarantees the sustainability of the resource and high rents for resource users. This task is assigned to the regulator, who has to set the allowable catch via biological stock assessments. Besides, by monitoring and sanctioning those who harvest more than allowed by their quotas, the authority in charge of resource management also carries on the enforcement of ITQs (see Squires et al. (1995) for an extensive description of ITQs in fisheries, or Tietenberg (2002) for a more general discussion on tradable permits in the commons).

An ITQ is generally considered as a private property right. However, if getting an intuition of the notion of private property seems evident (something owned by an individual), discussions about this concept are sometimes confusing, since ownership can be defined according to different attributes. In common resources, we can distinguish the rights over the resource system itself, which include the resource stock, or the rights over the flow of resource units generated by it. In modern fisheries, the growing use of individual quotas represents essentially a development of private rights on fish catches. Then, ITQs are indeed rights over the flow of resource units, that is the harvest. In this way, ITQs are often simply called *harvesting rights*. As for the resource system, it usually remains under the control of the state. For example, though there are still exceptions, marine areas and underlying fish stocks that lie in coastal jurisdictions are the property of public authorities.[9] Put it briefly, ITQs are just private rights over a limited quantity of catch, while the resource system and the management of the ITQ regime essentially remains in the hand of the state, that is common property.

Moreover, the notion of private property in ITQ systems is further limited by the fact that, most of the time, harvesting quotas are not "full" property rights. In order to create efficient usage of property, economists usually consider that a private right must confer to its holder four benefits: (i) complete security, (ii) full exclusivity, (iii) permanence, and (iv) unrestrained transferability (Sumaila, 2010). Yet, it is rarely the case that ITQs fulfill exactly these requirements. Due to their inherent nature of common property, ITQ fisheries are generally unable to support the implementation of full harvesting rights. For example, ITQ fisheries in USA have sunset clauses, thereby making ITQs non-permanent. In other cases, transferability is restricted to avoid excessive concentration of the industry, and so forth. In the end, by a way or another, rights given to quota holders are restricted by the regulator according to the particular characteristics of the resource and the environment in which users interact. However, to achieve a sustainable fishery, the constraints placed on harvesting rights must not be too strong. ITQs must remain a durable, transferable, and exclusive property right (Grafton, 1996).

Yandle and Dewees (2003) use the expression "privatizing the commons" for designating the ITQ experience in New Zealand. In fact, due to the creation of private harvesting rights, the management through tradable quota systems is indeed often considered as a privatization of the commons (Anderson and Hill, 1983; Anderson, 1995; Spulber and Sabbaghi, 1998; Clark

[9] A counterexample, where ITQs are given to the resource stock rather than the harvest, is given by abalone fisheries in Australia (Prince et al., 1998). In fact, when the resource stock is sedentary, like in shellfisheries, quotas can take the form of a right over defined areas.

et al., 2010). This term would suggest that the state gives up completely the regulation of the resource, thereby preferring to confer it to private hands. However, in our view this terminology is misleading since individual property rights, as we just stated above, takes only the form of constrained harvesting rights. On a general basis, an individual quota cannot be seen as a complete property right, in the sense that the right is given on the harvest and not on the resource system. In fact, the resource system usually remains state-owned (or commonly-owned) and the maximum catch allowed or other limiting constraints are defined by the regulator. In this view, since they are usually implemented and essentially managed by governmental agencies, ITQ systems can also be considered as a kind of state control, even if the use of the price mechanism introduces more flexibility than previous resource policies.

Given the fact that ITQ programmes are supposed to represent a decentralized approach, since it relies on the flexible price system of the market, one may think this approach should be classified in the category of bottom-up resource management. In fact, ITQ systems used in modern fisheries are not as decentralized as they primarily seem, even though there are some initiatives to delegate some responsibilities to fishermen and vessels owners. Basically, the reason is the following. In a "regular" market, prices and quantities are determined freely by the forces of demand and supply. In an ITQ system, only the prices of quotas are the result of the willingness of vessels owners to buy or sell fishing quotas. The total quantity of quotas, however, are fixed by the regulator, through the help of scientific expertise over the state of the fish stocks. Then, if prices are determined by the decentralized interactions of resource exploiters, the quantities are usually decided by a state agency. In this sense, ITQ programmes could be viewed as a *half* market-based approach, where the intervention of governmental bodies are needed to keep the system functioning. The same logic also applies in all tradable quota systems, such as CO2 emissions schemes.

In our view, the example of the new fishery policy in the European Union confirms that ITQ systems can be seen as a top-down approach. Though the implementation of ITQs is a complex process that involves negotiations and consultations with a multitude of actors, propositions are coming from the highest possible institution, the European Commission. As well, the fishery policy must be endorsed by top European institutions, including the European Parliament. Then, despite some gains in the representation of fishermen's organizations, the core competence of the Common Fishery Policy lies with the European institutions (Van Hoof and Van Tatenhove, 2009). As for the United States of America, Tietenberg (2002) also show evidence of top-down management, highlighting the role of high-level governmental agencies in tradable quota regimes.

Of course, ITQ regimes should not be viewed uniquely as management policies stemming from an outside authority disconnected from the preoccupations of resource users. For example, the red sea urchin fishery in British Columbia offers a case where individual transferable quotas were self-imposed by local fishers. In 1994, the fishermen gathered and agreed on a voluntary quota system aimed at coping with excessive harvesting, before the Department of Fisheries and Oceans sanctioned the programme from 1996 onwards (Featherstone and Rogers, 2008). Besides, initiatives to involve local users in resource management have recently emerged in ITQ programmes, as we will see in the next section. But overall, governments exercise strong control on tradable systems. They usually define the goals and keep high discretionary powers.

Though, it must be said that there is a recent tendency for governmental authorities to devolve managerial responsibilities in some ITQ fisheries. Nowadays, the implementation of quota systems shows that both public and private actors are implicated, as the latter are often given a role in governance. Hence, the traditional dichotomy between public and private is blurred. More generally, the opposition of public and private in modern resource governance is criticized by Sikor (2008). Empowering participation of private actors in governance has redefined the role of public authorities, thereby shaping new imbricated institutional arrangements for resource management.

Because ITQ management faces generally high costs, particularly for monitoring and enforcement activities, governmental authorities may be willing to cede parts of its regulatory power. The objective of empowering resource users is to improve the efficiency of ITQ management, notably by increasing compliance with the regulations. Then, instead of commanding and monitoring directly the rights and rules, governmental authorities are trying to encourage active participation of fishing industries through *self-governance* initiatives.

2.4.2.2 Self-Governance in ITQs

Recently, there has been an emergence of self-governance initiatives in ITQ fisheries across the world (Townsend et al., 2008). Self-governance in resource management means that some responsibilities, instead of being beared by the government, are carried out by resource users themselves. In ITQ systems, the principle is that a resource authority should delegate areas of governance in which the users are better incited and capable of exercising responsibilities. Regarded as an alternative to centralized command and control regulation, the objective is to operationalize the incentives for harvesters to maximize the value derived from the resource. For example, the proposal of reform for European fisheries falls precisely within this scope. The European Union sees the involvement of private fishers into resource governance as a major objective for the design of the proposed ITQ system.

In Canada, self-governance has increased economic rents in fisheries that were already under ITQ regime before devolution of responsibilities to the industries. The geoduck and horse-clam fisheries in British Columbia have witnessed an increase in value, a decline in fishing effort, and an improvement in industry-funded monitoring and enforcement (James, 2008). Another example of fruitful self-governance is the devolution of power to fishermen in the Southern Scallop fishery in New Zealand (Mincher, 2008). While the fishery collapsed in the late 1970s as a result of overfishing, the recovery programme has successfully devolved responsibilities to a company created by commercial fishers. The company, which was established for quota management activities, was even given further control over functions such as research or water quality. Still in New Zealand, self-governance by stakeholders contributes to improve the performance of the Bluff oyster fishery (Yang et al., 2010).

Since self-governance has emerged only recently and still concerns relatively few of the world's fisheries, it may be premature to draw a global assessment of its achievements and to foresee whether such initiatives will generalize or not, though this approach seems promising. Yet, self-governance faces also limitations in its applications. Some cases highlight the difficulties to decentralize resource governance in ITQ regimes. In New Zealand fisheries, the efforts made by the government to transfer some management responsibilities were dampened by high transaction costs faced by the industry to organize self-governance (Townsend, 2010). Because the costs faced by the fishing industry to organize itself were greater than its expected benefits, participation in management was tepid.

Although self-governance is defined as a delegation of power from the state to the resource users, it would be a misconception to consider self-governed ITQ fisheries as fully decentralized, bottom-up resource management. The fact that self-governance appeared only in recent years shows that ITQ system were hitherto primarily devised in a top-down manner, without seriously considering the involvement of resource users. But more importantly, rather than being an initiative of resource users, devolution of management responsibilities is usually initiated by the authority in charge of fishery management.

According to Townsend and Shotton (2008), self-governance must be enabled and empowered by the government, which have sovereign authority to define the institutions that support it. In other words, in order to happen, self-governance requires the implication of the state in resource management as an absolute necessary condition. Hence, government regulations cannot be spontaneously replaced by self-governance. Canadian fisheries offer an example of why even ITQ systems which integrate self-governance responsibilities may still be considered, albeit it is simplifying, as a kind of top-down resource management. Despite the devolution of power to the industry, the Minister responsible of fisheries still retains great discretion to manage fisheries (Wilson, 2008). According to his sole desires, the Minister can revoke existing rights or issue new rights. Thus, although this power has been used to implement policies based on the participation of fishermen, it has also brought an inherent limitation to their responsibilities, impeding further evolution of self-governance.

2.4.3 Achievements and Limitations of ITQs

The economic and environmental consequences of ITQs are still highly discussed (see Yandle and Dewees (2008) for a review of this debate). On one hand, ITQs have been praised to stop the trends toward worldwide collapse of commercial fisheries. By compiling statistics covering 11,135 fisheries from 1950 to 2003, Costello et al. (2008) found that implementation of ITQs significantly improved the situation of global fisheries. More precisely, ITQs have apparently improved economic efficiency and increased returns of fishers in Australia, Canada and New Zealand (Grafton, 1996). In Icelandic fisheries, while direct effort controls by the state failed to prevent increasing fleet size and fishing effort, the implementation of ITQs has indeed brought the fisheries toward greater efficiency (Runolfsson, 1999; Arnason, 2005). Personal interviews conducted in New Zealand and British Columbia confirms the positive appreciation on ITQs (Dewees, 1998).

On the other hand, while agreeing that New Zealand and Canada are cases of success, Hannesson (2004) considers the introduction of ITQs in Chile and Norway as cases of failure. At a global scale, Chu (2009) found that worldwide implementation of ITQs over the last thirty years does not translate into consistent changes in stock biomass in marine fisheries. According to her study, fisheries managed through ITQs that have witnessed continuous decline in their fish stock would need better enforcement and monitoring, though other measures are also required. Others like Pinkerton and Edwards (2009) dispute the positive assessment on ITQs by revealing some overlooked hidden costs. Challenging the usually positive assessments, the British Columbia halibut fishery would nevertheless suffer from quota leasing activities, which would reduce significantly the economic benefits to society and fishermen. Overall, despite persistent critics, ITQ management seems to receive favorable attention from scholars and policy-makers, though there are still serious shortcomings to be addressed.

Because ITQ regimes are based on the principles of the market, they are potentially subject to market failures. Among the criteria that are particularly important for ITQ management to succeed, the number of resource users is of great importance. Indeed, an ITQ market will function efficiently solely if its size is large enough. If only a few participants operate in an ITQ market, the number of transactions would stay at a low level. The problem is that markets with infrequent transactions are usually characterized by high price volatility, as well as high transaction costs. Hence, significant fluctuations in quota prices can discourage long term investments, thereby diminishing efficiency of ITQ systems plagued by insufficient quota trade (Squires et al., 1995). Stavins (1995) also argued that markets of tradable permits can be hampered by high transaction costs and thus low trading levels, thereby reducing costeffectiveneness of these schemes.

Another serious concern for ITQ markets is the potential persistence of externalities. Designed for eliminating appropriation externalities, tradable quota markets can still face negative externalities. For example, suppose a fishery where one species is covered by an ITQ scheme, while another species is not. If the cover species is protected, fishers, by switching their activities to the capture of the uncovered species, could increase the pressure on the latter. Beyond this example of leakage effect, there exists other kinds of side effects that may degradate the ecosystem, such as highgrading (discarding low-valued fish thrown back into the ocean to fill the quota with higher value fish) or bycatch (fish caught unintentionally while intending to catch other fish).

Also, to be effective, a property right must be recognized by others, and as such it has to be enforced in some way. The problem of how to secure harvesting rights is fundamental in ITQ management, as inefficient enforcement and monitoring would inevitably lead to resource overexploitation. The fact that individual quotas entail rights on harvest, rather than to the resource system, renders the question of enforcement even more troublesome. Because in ITQs the resource system is still common property, private individuals may still have incentives to harvest over the quota levels. Hence, higher efforts for enforcement may be required in ITQ systems compared with regimes where property rights are provided over territorial zones. Since achieving cost-effective enforcement and monitoring is a major concern for the design of any ITQ regime, one solution may be to involve resource users in self-enforcement activities. Given that an harvesting quota represents a share of the total allowable catch, which is itself reduced when the resource stock is in decline, harvesters should have an interest in the enforcement of ITQs. In the future, the issue of monitoring and enforcement may find a credible solution in the initiatives of self-governance described above.

Given the benefits and shortcomings of ITQ management, Grafton and McIlgorm (2009) propose a framework aimed at determining whether ITQs should be introduced or not. Using data from Australian fisheries, they undertake a cost-benefit analysis of ITQ programmes. Several criteria are identified to assess the costs and benefits of implementing ITQs, such as the gross value of the fishery, the number of participants, and others. For example, if the gross value is not large enough, the benefits expected from the introduction of ITQs will be too low regarding to the cost of implementing a quota system. Hence, this result suggests that ITQs are clearly unadapted for small-scale fisheries. Beyond the purely economic issue of ITQs, Sumaila (2010) also draws some strategies that need to be part of ITQ programmes to achieve also ecologically and socially desirable outcomes.

Overall, despite its advantages, resource management based on ITQs cannot represent a universal solution which can be applied generally and uniformly in any situation. ITQ management is expected to work properly only under specific conditions on the resource characteristics and the social environment in which exploiters interact. Because of the various conditions required for ITQs to operate correctly, market-based regimes cannot be implemented everywhere. In worldwide fisheries, ITQ systems can constitute an effective solution for tackling overfishing in various situations, though it is not a panacea for all fishing grounds, especially where small-scale fisheries are prevalent. Due to the high costs of implementation and maintenance, the benefits must be high enough to justify such programmes (Libecap, 1994). Hence, only resources of sufficiently high-scale can pretend to yield enough economic benefits for being supported by trading quota regimes. Besides, transferable quota systems have been also implemented successfully in other situations than fisheries, such as pollution control or water management. However, for forest lands, pastures, and others, the introduction of ITQs seems to be limited, if not hypothetical, for now. In the United States of America, tradable grazing permits have been introduced by the federal government in rangelands, but their effectiveness is still debated (Wiebe and Meinzen-Dick, 1998). When government control and market-based management are unadapted for coping with resource overuse, other solutions have to be found.

2.5 Bottom-up Resource Management

According to Ostrom (2005b), the presumption that an external agency has to take direct control of common resources is a consequence of a theoretical framework unadapted to deal with social dilemmas. Precisely, she criticized the role of the traditional rational choice theory. Developed in the field of market institutions, rational choice has been also applied to nonmarket situations, such as common-pool resources dilemmas. However, this theory has been of little help to explain successful – and also unsuccessful – experiences from individuals to engage themselves into collective actions aimed to cope with resource overuse. For Ostrom, without understanding how humans are able to develop behavioral norms in order to govern their use of resources, typical recommendations for overcoming issues of overexploitation and misuse will continue to take the form of centralized, *Leviathan-like* remedies.

We saw that, in many instances, government appropriation of the commons did not represent a consistent solution to the problem of resource misuse. The general failure of top-down approaches to promote sound exploitation has therefore encouraged research of alternative solutions. Where top-down resource management failed, both common ownership and private ownership have a potential to ameliorate governance. Because of the inherent nature of common resources, full privatization through the introduction of complete property rights over resource systems can hardly represent a credible solution, apart in some specific situations. However, extensive evidence have demonstrated that communities of local actors are able to organize systems of norms and rules to preserve their commons. Institutions created by communities have enabled successful systems of governance in various kind of natural resources worldwide. Hence, it is widely accepted that better governance of natural resources must rest upon common property institutions created and administered by, or at least with, local communities. The current shift of paradigm, from centralized to localized resource management, is covering the whole variety of the commons worldwide. Tendencies toward decentralization concern fisheries (Nasuchon and Charles, 2010), forestries (Ostrom, 2005a), water resources (Pahl-Wostl et al., 2008), and so forth.

2.5.1 Community-Based Resource Management

The growing awareness of successful community-level management has led policy makers to seek involvement of local users to preserve the commons. In contrast to centrally driven resource policies that give local people very limited power of control over the commons, a real decentralization of power creates opportunities to engage them in resource management by establishing their own institutions. The idea that local actors must be integrated into resource management is now accepted by public authorities worldwide. Generally, the participation of local populations to the design of resource management is aimed at fulfilling two main objectives: i) promoting sound exploitation in order to guarantee the sustainability of the resource, ii) securing and ameliorating livelihood of local communities. Then, initiatives of delegation of power from the central state to lower jurisdictions should encourage both efficiency in decision making and fairness over resource use.

For a long time, the commons were mostly considered as being accessible to all, without any limitation on entry. Apart situations where common-pool resources are managed under state property, the commons were usually viewed as devoid of any institution and ownership structure. However, instead of being open to all, or being ruled under state property as previously thought, most of common resources are managed under common property regimes by local communities. Ostrom (1990), Baland and Platteau (1996), Wade (1987) and many authors showed that local people living near – and from – their commons have developed common property institutions for coping with overuse problems. Although this aspect has been overlooked until recently, community resource management has in reality existed for centuries or even for thousands of years, immeasurably long before the takeover by external authorities.

During the last twenty years, a vast number of studies have documented the importance of communities in resource conservation, often highlighting successes, sometimes shortcomings. Beyond the scope of resource exploitation, the role of communities, thought to be in declined during the 1970s and the 1980s, has in fact taken an increasing importance before the early 1990s to shape the structure of economic interactions and to promote local development (Doucet and Favreau, 1991). In the perspective of ecotourism, there is also a growing acceptance of the idea that development projects must integrate the two dimensions of sustainability of the resource and participation of local communities (Lequin, 2001).

2.5.1.1 Portraying Communities

Because of the large diversity of resource characteristics and human institutions, communities can take various forms in reality. Hence, describing the notion of community in a single definition is not straightforward. Also, according to the interests and objectives of scientists, a single community can be defined in different ways. Agrawal and Gibson (1999) identified three manner of defining communities in the literature on the commons: as a small spatial unit, as a homogeneous social structure, or a set of shared norms and common interests. Communities are generally described from one of these conceptions, or from combinations that articulate several of these features.

In natural resource use, a community can be seen as a spatially localized group of individuals sharing common interests and similar values. This definition aims to encompass the main features that characterize communities in common resources use, though it does not have the pretension to portray the entire variety of communities. A fundamental aspect is that a community is a spatial unit which is territorially attached to the resource. The commons are indeed essentially governed by communities of people belonging to the nearest geographical environment. This is why the adjective *local* is sometimes attached to the term community. The notion of territorial attachment suggests that communities are small in both area and number of individuals. In the empirical literature, small group size has been indeed identified as a condition that favors effective governance (Wade, 1989). However, smallness is still a relative concept, as groups of local resource users can cover wide areas and can easily count in their rank several hundreds or thousands of members, without endangering soundness of resource governance.

Successful governance of the commons is facilitated by the homogeneity of identities and interests, as well as shared *social norms* (Baland and Platteau, 1996). High degree of homogeneity in kinship, ethnicity, or religion is for example important to achieve sound exploitation in many Asian fisheries (Pomeroy et al., 2001), as well as in Indian forestries (Ray and Bhattacharya, 2011). Besides, experimental studies also suggest that group homogeneity favours communication and cooperation (Ostrom, 2006). In an experimental study realized in India, Bouma et al. (2008) found that trust and cooperation in CBRM is positively linked with social homogeneity (based on caste membership). Hackett et al. (1994) shows that group homogeneity in size encourages communication, thereby improving resource appropriation.

Though group homogeneity is not a critical condition, it is nevertheless a factor that favors establishment of social norms. Social norms can be seen as informal behavioral rules that guide individual actions toward desirable outcomes from a collective standpoint. When individuals voluntarily agree to restrict their own exploitation level, when they decide to sanction those who destroy the resource, they are following social norms. As indicated by many case studies, such internalized norms are the result of processes of learning through repeated interactions between community members. The empirical literature on the commons suggests that the development of social norms is more likely when resource users share common beliefs and interact over long periods of time. Besides, as they usually share identical origin and similar culture, and because they all depend on their resources, community members should be also able to engage more easily in more formal collective decision-making than external people who have disparate interests.

Most of communities fit the definition of localized groups of people that share common interests and values. But many other features that characterize communities may influence the outcome of community management of natural resources. Along with the comprehension of external factors, understanding the intrinsic elements of communities that underpin successful governance is one of the main objective of the literature on the commons (see Agrawal and Ostrom (2001) or Agrawal (2002) for a summary of the empirical literature aimed at identifying these conditions).

By saying that communities are composed of agents who share similar values and interests, one could imagine that these individuals are identical in all respects. In fact, the conventional view has indeed treated communities as sets of homogeneous people. However, this vision has been contested by Agrawal and Gibson (1999). Instead of being clones, individuals in communities differ in their preferences, political power, and other aspects of their life. Therefore, the most important for resource conservation is not necessarily to have strictly homogeneous people. Rather, it is that communities have the capacity to develop efficient *institutional arrangements* respected by all – or at least most of – resource users.

Throughout history, communities, instead of letting their members exploiting their commons freely, have developed institutional arrangements to prevent resource overuse. The way people create and articulate formal and informal institutions have received particular attention from legal scholars (see for example Ostrom (2005b)). Institutional arrangements can be defined as the set of rules and norms, either formal or informal, that shape how humans behave and interact with each other and the environment (North, 1990). As defined by Crawford and Ostrom (1995), norms are prescriptions held by an individual that an action, or an outcome, may be permitted or not. Their function is to constrain activities that are considered as harmful, while allowing or encouraging appropriate conducts.

In this sense, institutions are not synonym of organization. Institutions can be viewed as regularized patterns of behavior between individuals and groups (Leach et al., 1999). This definition suggests that norms and behavioral rules are the foundations of institutions. Rather than just being formal structures, institutions are before all behaviors which are deeply rooted and shared among individuals. Because institutions are shaped by every day interactions among community members, they are subject to change. Through this view, institutions can be seen as temporary agreements depending on particular circumstances of time and place. Hence, for achieving desirable outcomes, institutions must be designed to be properly adapted to local circumstances.

It is widely recognized in the literature on CBRM that, to achieve efficient governance, communal authorities should command rules which define resource use practices. Ostrom et al. (1994) defined three levels of rules, from the lower to the higher, which are relevant in common resources, operational rules, collective-choice rules, and constitutional rules. *Operational rules* concern daily decisions made by the participants. They affect activities such as the intensity of harvesting, methods of cultivating, and so forth. *Collective-*

choice rules are determining who is able to define operational rules and under which conditions. As for *constitutional rules*, they specify the terms and the general structure of governance, by determining who is eligible to craft the set of collective-choice rules. When resources are managed without interference from the government, communities are in charge of setting all these kind of rules.

An important aspect is that communities should be able to enforce these rules. Self-enforcement through monitoring and sanctions executed by resource users themselves is a crucial element for sustainable resource conservation. Besides, local authority over operational rules also involve the right to let individuals directly in charge of the rules without any degree of formal coordination. Concretely, actions in line with sound exploitation do not only stem from rules imposed at the collective-level. From repeated day-to-day interactions, users are likely to develop behavioral norms that are consistent with sustainable use. In these cases, some management responsibilities are realized through informal norms shared among resource users. Such norms are the result of evolutionary processes of learning, rather than the outcome of governance structures. It represents the most extreme level of decentralization, where conservative outcomes are determined by the process of interactions between individuals, without the help of any decisional body. Therefore, community management of the commons can range from total reliance on norms, to more centralized decision-making at the collective level. But even in the last case, extensive evidence highlighted the fundamental role of norms to achieve successful resource governance.

Thus, either through decisions taken at a collective level, or as a result of the decentralized interactions between them, communities have created formal and informal rules and norms over time. Local institutions usually include management rules designed at the collective level, as well as individual rights that stem from both collective decisions and social interactions between resource users. An important issue for successful CBRM is the design of appropriate institutional arrangements, or in other terms, the efficient nesting of the set of rules and norms.

2.5.1.2 Strength of Community Management

Achievements of CBRM have been documented from a large number of case studies worldwide. A salient example of success is given by community forest management in Mexico. While in Latin America most of forest areas are state property, Mexico is an exception with the majority of forests held in common property by communities. Contrary to the situation in other countries in the region, the Mexican model of community forest management has brought sustainable use and biodiversity protection (Bray et al., 2003). In Asian countries, community-based management has proved to be successful in terms of conservation of forests, water, grazing lands (Andersen, 2011), as well as fisheries (Ruddle, 1998; Nasuchon and Charles, 2010). In India and West Africa, indigenous communities have also shown real capacities to manage their common property resources (Beck Cathy, 2001). These are only few examples among many others.

CBRM is granted with numerous potential merits in the literature. Basically, CBRM can achieve satisfying outcomes because local users can have both the capacity and the willingness to engage themselves in sound management. We argue hereafter that the capacity to manage common resources may be significantly determined by the knowledge held by local people. As for the willingness to preserve the commons, it stems essentially from long term dependence on resource use.

A major reason that advocates for management by local people is that, because they hold particular knowledge about their environment, they have strong capacities to govern their commons. The wide diversity of common-pool resources in their biological characteristics, as well as the social environment defining human interactions, suggests that actors close to the field have the most appropriate knowledge. In this line, we suggested previously that governmental officials could fail to collect and use properly the knowledge of the particular circumstances of time and place, as defined by Hayek (1945). On the contrary, local resource users are those who possess the closest and the deepest experience of the field. Because they have usually used the resource for a long time, they hold specific knowledge about its biological characteristics. But even more important to design conservation programmes, locals have the innermost understanding of the social environment in which they interact (see Houde (2007) for a description of traditional ecological knowledge in communities). Thus, because they detain appropriate knowledge, actors close to the field should be in the best position to create institutions that would ensure a high level of compliance from resource users. Also, since local individuals interact and use the resource on an everyday basis, their knowledge of the field is flexible and adaptive to change. In environments characterized by high variability, like are many commons, holding adaptive knowledge may represent an important advantage to keep sustainable and efficient institutions for resource conservation.

Traditional ecological knowledge is the support of a large variety of essential management practices in CBRM (Berkes et al., 2000). Complementing scientific knowledge with traditional forms of knowing is crucial to achieve a sustainable adaptive management. In Canada and New-Zealand, the combination of local knowledge and science can improve the control of wildlife populations by indigenous people (Moller et al., 2004). Another example of the relevance of local knowledge is the communal exploitation of forest land in South and South-East Asia. While national and international forest management programmes led to rapid deforestation, traditional knowledge have proved far more environmentally appropriate than initially supposed by outsiders (Colchester, 1994).

Still, there is a difference between the manner that the knowledge is used in a large society like a country, and in a localized common resource area. For Hayek, the processing of information in a society is realized throughout the price system. In the commons, the local knowledge is used by communities to develop norms and rules that are partially decided at the collective level. The price system, which only determines the revenues and the incentives to sell the products derived from resource exploitation, has therefore no real role in the way the knowledge is utilized. Yet, if the advantage of the price system to allocate scarce resources in society lies in its flexibility, the advantage of social norms for common resource governance is also its flexibility. Indeed, many institutions in CBRM are informal norms which consist in the regularized practices of people. As such, they are also dynamic, changing over time as individuals adapt their behavior to suit new circumstances (Leach et al., 1999). On the contrary, formal organizations, such as external state agencies or non-governmental organizations, may lack this flexibility.

Besides the question of capacities of governance, an other reason for letting responsibilities to communities is that locals, because they are dependent on their natural resources for their livelihood, should be willing to adopt sustainable management practices. Since communities usually lived upon their commons for a long time, and are going to rely on them in the future, they have strong incentives to engage themselves in sustainable use. Provided a stable policy environment, they can benefit from exploitation returns over very long periods of time. Thus, the discount rate of exploitation should remain lower for local users than for outsiders. Indigenous people may also attach particular cultural and social value to their commons, thereby increasing the willingness to preserve them. Instead of public officials, who are often confined into short time horizons due to their limited time in office, or outside companies that can find opportunities elsewhere if the resource is depleted, local resource users should have an intrinsic motivation for sustainable use in the long run. This argument to involve communities in resource management can also be seen in reverse angle. If communities are not involved in resource management, or if they do not benefit from the resource, there is a risk that they will lost long term vision, and engage themselves into destructive use.

The capacity and the willingness for communities to undertake responsibilities in resource governance can be illustrated by the issue of the enforcement of rules. A critical argument in favor of CBRM is that the enforcement of exploitation rules can be more efficient when realized by local actors. Whatever the system of governance, it is widely accepted that having effective monitoring and enforcement is always crucial for resource conservation. When these activities are executed by local users, enforcement is expected to be cost-effective. Because of their presence and their knowledge of the field, resource users should be able to detect rule-breakers. Moreover, since poaching affects them, they should be also incited to make sure that rules are respected. Hence, local actors should have both the capacity and the willingness to monitor and enforce rules which define resource use. For example, the experience of successful forestry communities in Mexico shows that social norms can provide cheap monitoring and discourage free-riding (Klooster, 2000). Self-enforcement through monitoring and sanctions will be analyzed further in chapter 5.

2.5.1.3 Limits of CBRM initiatives

As for state control and the tradable permit approach, CBRM should not be viewed as a magic bullet for resource management and conservation. Besides many success stories, Ostrom (1990) also identifies examples of failures in in-shore fisheries (Turkey), in groundwater basins (California), or in irrigation systems (Sri Lanka). The promotion and imposition of CBRM from outside by national governments or non-governmental organizations have led to disappointing results (Blaikie, 2006). Devolution of responsibilities in common forests in many developing countries has often given poor outcomes regarding the welfare of local communities (Larson and Soto, 2008). Failures of external interventions which resulted in resource degradation could be partly caused by the lack of recognition of local institutions. State interventions in resource regulation can create a crowding-out effect, in the sense that well-functioning social norms may be supplanted by the imposition of external rules (Ostmann, 1998).

Often idealized, local communities are in reality more complex and diverse than the usual theoretical conceptualizations. Rather than a small and clearly defined spatial unit, a homogeneous social structure and a system of shared norms, Agrawal and Gibson (1999) suggest that a community is a set of actors having multiple interests. Then, the informal arrangements that structure the interactions between individuals matter. This complexity, added to the wide variety of common-pool situations, makes it hard for policy-makers to design and implement effective rules at the local level. Despite undeniable progress during the last twenty years, the question of the determination of the environmental and human factors under which communities will successfully manage their resources remains largely unresolved (Agrawal, 2001).

Although decentralization initiatives are publicly favored by many governments, they are far from being always effective in reality. Because relations within government officials and interactions between different governmental bodies are often complicated, involving conflicts of interests, it may be hard for the state to accomplish a concrete transfer of power from officials to local people. An other reason could be that the alleged relinquishing of power is just a trompe l'oeil intended to improve the public image of the state. Displaying a willingness to delegate decision-making allows to appear as a fair and modern institution, careful of the desires of its citizens. In the forestry sector of Senegal, Uganda, Nepal, Indonesia, Bolivia, and Nicaragua, central governments greatly attenuated the powers of local actors by limiting the transfers of power and by choosing local institutions serving their own interests at the expense of those of local communities (Ribot et al., 2006). Other initiatives of community forest management that are promoted by external interventions showed modest success and serious difficulties of implementation (Sikor, 2006). In Southeast Asia's upland regions, rather than reducing state interference in local affairs, CBRM initiatives resulted on an intensification of government control over natural resources and livelihoods of rural populations (Li, 2002). In the end, efforts to decentralize control over natural resources to local communities depend essentially on institutional factors. CBRM initiatives for wildlife management in Sub-Saharan Africa have been effective in countries where public institutions are strong and corruption is limited, while turning to "patronage" in more corrupted countries (Nelson and Agrawal, 2008).

Beside, having real decentralization of power is not always sufficient to ensure sound community management. CBRM needs to rely on strong local institutions to succeed, but for many reasons, local institutions developed by communities may not be solid enough to deal with the challenges of resource governance. In the developing world, decentralization programmes have suffered from a lack of enforcement of common property ownership, thereby rendering communities unable to fully exercise their management responsibilities (Engel and Palmer, 2011). Another problem is that, in many countries, decades of state control over natural resources have in some measure disintegrated traditional institutions. If, after a long period of nationalization, ancient common institutions were destroyed, communities may not have the managerial competence and enough compliance culture to design new appropriate institutions. Building new institutions from scratch is generally much more difficult than from existing, even though imperfect, structures. For example, in some Indian fisheries, community-based management was short-lived because, after a period of state control, most of the community fishers' organizations were new and did not possess adequate managerial skills (Thomson and Gray, 2009).

2.5.2 Resource Co-Management

Although CBRM practitioners often view governments in an external role that should be as limited as possible, CBRM does not necessarily exclude totally any interference of the state. As stressed by Baland and Platteau (1996) and showed by overwhelming evidence, the dichotomy "state versus community" is an overly simplification, since in reality both governmental and communal institutions are often imbricated in complex arrangements, making a large range of mixed options available. CBRM is often described in simplified terms, suggesting that public authorities give up all initiatives, thereby leaving local actors to deal alone with resource governance. However, if CBRM programmes involve significant renunciation of power from the state, it is in some cases more a redefinition of the role of public agencies rather than a complete withdrawal.

Strong involvement of the public authorities in CBRM that takes the form of partnership arrangements between the government and local communities has been termed cooperative management, or *co-management* (Berkes et al., 1991). Co-management can be defined as an arrangement where governance is shared between communities and the government (Nielsen et al., 2004). Hence, it can be seen as a set of rules which defines the cooperation between public authorities and communities. Nevertheless, if the principle of shared responsibilities is easy to understand, cooperative systems of governance are of complex nature. Then, defining precisely what co-management really is in reality is challenging, thereby leading to different conceptualizations in the literature (see Carlsson and Berkes (2005) or Berkes (2009) for a discussion of the concept of co-management).

Basically, the conceptual origin of co-management is the same as for CBRM. Rather than centralized command-and-control interventionism, governance that relies on local people is more likely to succeed. It is expected that efficiency will increase if decisions are taken at the local level. Though, CBRM and co-management are not synonyms. Resource management can be considered as community-based only if the center of gravity of decision-making stays on the community side, with little interference of the government. On the contrary, co-management confers a greater role of public authorities, as governance responsibilities are shared on the principle of joint venture.

One may ask for what reason the government should be included in resource governance along communities, rater than letting the latter exercise control by themselves. In fact, there is room for state interventions when management by communities is facing challenging difficulties. In developing countries, the integration of local markets into larger trading areas, population growth, and other factors can add great pressures on management systems. While CBRM have generally proved to be adaptive to changing circumstances, these new pressures may create great problems where community governance is weak. Therefore, co-management can represent an attractive solution whenever CBRM faces risks of failure, without returning to command-and-control style of resource management.

The definition of co-management looks also similar to the concept of self-governance discussed previously. Sometimes, these terms are indeed used interchangeably to designate resource management systems. However, Townsend and Shotton (2008) make a distinction between self-governance and co-management. In their view, self-governance implies that the devolution of power expands upon existing formal institutions. We already stated that it is usually the case for resource management under systems of individual transferable quotas, where the initiatives that involve fishers stem from the government. On the contrary, co-management is fundamentally established as a partnership that fully includes community-based institutions. Rather than delegating new rights inside an already build external structure, co-management differs from self-governance in ITQs by its focus on partnerships with governance institutions at the community-level. In the theoretical conception of co-management, the rights of users arise basically from their own collective institutions, and not only from a delegation of power from the government to local administrative bodies. Therefore, because local institutions represent a crucial basis of co-management, this form of resource management is more decentralized than ITQ self-management. This is the reason why resource co-management can be reasonably classified as a bottom-up approach, even though in reality governments can retain essential control of the resource instead of considering communities as equal partners.

Joint governance initiatives have been credited with several positive effects. Co-management is now viewed as an adaptive institutional response to complex and changing social-ecological systems (Armitage et al., 2008). Bringing together different actors, from local to higher levels, can generate and mobilize knowledge at different scales. Then, cooperation between partners would enhance processing of new knowledge to deal with problems of governance (Berkes, 2009). Besides, co-management is expected to decrease transaction costs, especially for monitoring and enforcement. The case of Japanese coastal fisheries provides an example of low-cost joint governance (Makino and Matsuda, 2005).

In various fisheries, implementation of co-management has been useful to reduce conflicts and to promote resource conservation (Singleton, 1998; Viswanathan, 2003). In Chilean artisanal fisheries, attitudes toward conservation and environmental awareness tended to increase as a result of engagement in co-management (Gelcich et al., 2008). Other types of common resources have benefited from joint management initiatives. For instance, collective management have improved forest conservation in Tanzania and Central America (Hayes and Persha, 2010), while arrangements between community representatives and government appointees seemed to improve control of wildlife population in Canada (Thompson, 2011).

Co-management has certainly the potential to bring benefits where CBRM or direct state control fails to accomplish sound resource governance. Yet, due to the complexity of shared arrangements between the state and communities, its successful implementation still depends on many conditions. For example, effective monitoring of co-management systems requires access to long-term funding for decision-making and reliable information about both resources and legal issues (Cundill and Fabricius, 2010). In Indian forestries, heterogeneity in co-management institutions raises transaction costs, thereby influencing negatively the outcomes in terms of both equity and efficiency (Ray and Bhattacharya, 2011). Pomeroy et al. (2001, 2011) identified sets of conditions related to the physical, economic, social and political environment, which promote successful co-management in fisheries.

Co-management implies a deeper involvement of the state than in traditional CBRM. Despite the theoretical conception of co-management as an equal partnership between communities and the state, there is a tendency for the latter to keep most of control over natural resources. So, due to the potential takeover of the government, there is a danger for local communities to lose significant responsibilities in resource management. In fact, many co-management projects indeed failed because they were conceptualized under top-down approaches that keep aside real community participation. This opinion is shared by Nielsen et al. (2004), who consider that when co-management is introduced for conservation concerns in fisheries, results are not better than top-down management. The lack of effective empowerment of fishing communities creates frustrations that have negative impacts on resource conservation since local users are less willing to comply with management rules. In fisheries programmes carried out in Malawi, Mozambique and Zambia, joint governance that is less responsive to communities is also less efficient (Wilson et al., 2010). In Chilean fisheries, management innovations are hampered by highly centralized decision-making and concentration of power in government (Marín and Berkes, 2010). In Sri Lankan forests, Nuggehalli and Prokopy (2009) see top-down decision-making as an obstacle in co-management.

Therefore, without true recognition of resource users, co-management may simply come down to disguised state management. Yet, the risk of lack of participation by communities may be reduced when government structures are already decentralized. For example, in Southeast Asia fisheries, that witnessed a shift from CBRM to co-management in the 1990s, the participation of communities in resource governance was guaranteed by concomitant decentralization of power (Thomson and Gray, 2009). In these cases, co-management has not really replaced, but rather absorbed CBRM in composite arrangements.

2.6 Conclusion

In this chapter, we proposed a review of the different solutions that have been advocated and employed for coping with tragedies of the commons. Our classification is based on a dichotomy between top-down and bottom-up approaches. On one extreme, centralized resource control at the level of the state can be fully considered as top-down regulation. On the other side, resource governance that is uniquely based on local actors can be seen as a genuine bottom-up solution. As for intermediate approaches, where both local users and officials from higher level jurisdictions are involved in resource management, categorizing them is more arduous, especially since governance programmes can differ in rethorics and in their real applications.

Market-based systems of tradable quotas are often considered as a decentralized approach, compared with direct state control. Indeed, resource exploitation is regulated through the price system, and such systems seem to integrate some self-governance responsibilities, especially in fisheries. However, the global design of transferable quota systems usually remains in the hand of the government, which detains ultimate discretional power to modify constitutional rules. In this sense, the tradable permit approach can be fairly seen as top-down in its foundations. As for initiatives of co-management, it represents the most intermediary approach between the role of the state and local actors. Co-management is defined as a joint system of governance based on relations of partnership between the government and local people. Though in some cases the center of gravity lies on the side of the central government, co-management systems generally devolve real and significant power to local people. Hence, this institutional solution can be fairly viewed as a decentralized approach.

Our presentation of the solutions for coping with resource overuse should not be regarded as a rigid categorization that is relevant for covering all single empirical situations. Due to several factors, solutions that are decentralized in their spirit and theoretical conception can de facto be centralized when applied in reality. Depending on the effective degree of involvement of local actors, and of the degree of centralization of governmental institutions, the nature of resource governance can vary significantly. However, the synthesis proposed in this chapter is aimed at highlighting, beyond the particularities of each individual case, the general tendencies at work in the commons.

The global trend in the governance of common resources, which has been extensively documented during the last twenty years, is toward greater decentralization of power. Although we pointed out some limitations to the devolution of responsibilities from the government to local actors, the description provided in this chapter is fundamentally in accordance with this vision. Precisely, decentralized resource management signifies that local communities have an important, even central, role in governance. A fundamental feature that favours sound resource use by communities is the social norms developed by local actors. Many times, by following and enforcing norms of behavior which are compatible with sustainable exploitation, local users have proved to be successful in preserving their common resources. The ability for individuals to comply with social norms is crucial to achieve sound resource use and to promote better conservation of the commons in the future.

As we will argue in the following chapter, a social norm can be explained as the outcome of an evolutionary process. By following behavioral rules that differ from the standard hypothesis of maximization, individuals are able to adopt norms through repeated interactions over long periods of time. In this light, the evolutionary game theory represents a useful framework to analyze how people behave in respect of norms that define sustainable resource use.

Chapter 3

Evolutionary Thinking and the Commons

Contents

3.1 Introduction

Thirty years ago, the principles of the theory of evolution re-emerged in the field of economics. Since then, applications of evolutionary theories have spread to various domains of social sciences and economics. Though it still represents a minor approach in economics, evolutionism has developed significantly in some areas, especially in the studies related to the notions of innovation or knowledge.

Historically, theories of evolution were essentially created and applied in the field of biology. Given their prevalence in biology, we may expect that principles of evolutions would spread principally to areas related to biology. In this light, environmental and resource economics should be well placed to accept evolutionary theories. Environmental economics is indeed related to the field of biology in the sense that they both analyze the biological environment in which humans live. However, though evolutionism has some significance in the multidisciplinary field of ecological economics, applications are still rather limited in environmental economics (Van den Bergh, 2007).

Most of evolutionary applications in environmental economics are formalized through the theory of games. The analysis of common resource exploitation has also received some attention through the use of evolutionary game theory. A few models have described how resource users exploit their commons and how they manage to cope with overuse. As well as presenting the concepts of evolution and reviewing the evolutionary literature on the commons, the aim of this part is to discuss whether evolutionary game theory has a real appeal to model interactions taking place in the commons.

The plan of this chapter is the following. Section 3.2 gives a brief overview of evolutionism in economics, including evolutionary game theory. Section 3.3 presents in a literal form the core elements constituting evolutionary games. The evolutionary literature on the commons is reviewed in section 3.4, which also discusses the advantages of EGT to model interactions in common-pool resources. The last section concludes.

3.2 Evolutionary Theorizing in Economics

In economics, evolutionary thinking has a long history. Often considered as a theory essentially used by biologists, principles of evolution are nevertheless deeply rooted in the history of economic science. Even Alfred Marshall, who is generally regarded as a prominent figure of neoclassical economics, advocated the usefulness of evolutionary thinking to explain economic phenomena (Marshall, 1961). Though its evolutionary thinking was not integrated in a developed formal theory, he tried notably to apply the principle of natural selection to explain the outcome of a competitive industry in the long run.

Basically, the difference between neoclassical economics and evolutionism lies in the way humans take their decisions. In particular, under the assumptions of the standard theory, agents are "rational" in the sense that they are able to compute actions permitting them to reach the highest possible utility, whatever the volume of knowledge and information they have to treat. The ability for individuals to derive their optimal actions in a world characterized by uncertainty has been severely criticized by Alchian (1950), and many scholars afterwards, while Simon (1955) has proposed a thorough revision of the traditional assumptions regarding the behavior of economic agents.

In the evolutionary theory, in contrast with the neoclassical view, individuals are provided with "limited rationality". Since the human brain has only a limited ability to treat information, while the capacities of memorization are also constrained, real people are devoid of the huge cognitive capacities that are usually required for optimizing in standard models. Taking into account the fact that humans cannot apprehend a complex environment in its totality, evolutionary economics postulate that individuals adapt their behavior to it. Rather than computing their optimal choices through elaborated calculations, they progressively adjust their behavior through a process of learning over time. Therefore, it is expected that in many situations, rather than using uniquely their abilities to compute optimal actions, individuals will tend to rely on other behavioral rules of conduct to adjust their behavior to the environment in which they interact.

Alchian (1950) made an opposition between the logic of rational profit maximization on one side, and adaptive, imitative, and trial-and-error behavior on the other side. In an uncertain environment, profit maximization would be meaningless to guide behavior toward specifiable actions, while behavior based on adaptation would represent a realistic and efficient way to reach positive profits. Despite this strong opposition, a common view about evolutionary selection process was that competition would weed out firms or individuals who are not rational profit maximizers. Economic agents would behave in the same way and get an identical outcome in the long run whenever they maximize their profits under the standard assumptions of rationality, or when their behaviors are selected through the logic of the survival of the fittest. For some neoclassical economists, such as Friedman (1953), there is a fundamental accordance between the classical hypothesis of maximization and the evolutionary principle of natural selection. Put it simply, in an evolutionary process, individuals would behave *as if* they were optimizing rationally. For example, a firm that maximizes its returns will prosper and survive, while a firm that deviates from rational maximization will tend to lose resource, thereby ultimately disappearing. Therefore, rational optimization is thought to summarize appropriately the conditions of the survival of the fittest. In this case, one may think there is no special need for further developments in the evolutionary theory, since it boils down to the same thing as the standard theory. Yet, if it is indeed possible to specify some conditions under which the outcomes of natural selection will match neoclassical predictions, this concordance does not hold every time. According to Nelson and Winter (2002), the list of conditions is quite demanding, and their articulation delicate.

Though the evolutionary theory has been kept aside for a long time after the Second World War, evolutionary arguments have been recently reintegrated into economics, especially through the book of Nelson and Winter (1982) on the evolutionary explanations of economic change. The resurgence of evolutionary thinking in economics may be explained by the difficulties of the neoclassical theory to model competition as a truly dynamic process, while the principles of evolution are naturally dynamic. Excessive focus on the concept of equilibrium and its conditions derived from profit optimization would have led to neglect questions about economic progress. The equilibrium analysis treated the issues of where the economy was located rather than where the economy was tending. On the contrary, the evolutionary side is much more interested in deviations from equilibrium. Then, for Nelson and Winter (2002), the interest in evolutionary economics would be the result of an incapacity for the standard neoclassical framework to deal with disequilibrium dynamics, in opposition to the theories of evolution that would constitute a natural approach for disequilibrium analysis.

Actually, when speaking about the evolutionary theory, the term theory should be put into the plural. Indeed, evolutionary economics must not be considered as a unique theory, a single framework accepted unanimously. Rather, this field should be viewed as a set of theories that are sharing some common fundamental features, notably the principle of selection, but also differ in substantial ways, for example on how this principle should be applied. Therefore, different families of theories based on a diversity of tools still coexist today (Arena and Lazaric, 2003; Safarzyńska and van den Bergh, 2010). There is no single canonic framework, no unified microeconomic model that would allow to bring together the differing approaches for now. The prominently theory of economic change proposed by Nelson and Winter, based on Scumpeterian and

Simonian traditions, is essentially build upon the concept of *routine*. A routine is an organizational or individual competence acquired through learning from past experiences. Those which are more adapted to the environment will survive (according to the logic of natural selection), while some new routines will break through at times (according to the principle of mutation). Together, the principles of natural selection and of mutation, that is the appearance of novelty for the latter, give rise to a learning process characterized by constant adaptation over long periods of time.

The evolutionary approach of Nelson and Winter has been developed in frontal opposition to neoclassical economics. In particular, as mentioned above, their approach has tended to reject the concept of equilibrium on which standard economics is build upon. Yet, knowing that recent evolutionary thinking has been, at least for a significant part, constructed onto a critic of the equilibrium analysis, it would be somewhat surprising that a theory of evolution could integrate the notion of equilibrium as a core element in its foundation. However, there does exist an evolutionary theory that is precisely funded on the concept of equilibrium. This theory, which has the advantage to present a certain degree of formal unification, is known as the *evolutionary game theory* (EGT).

EGT can be viewed as the implementation of the principles of game theory to the evolution of populations. Or equivalently, it can be seen as the application of the principles of evolution into the game theoretical framework. EGT offers the opportunity to analyze formally the evolution of behavior in populations as a result of a dynamic process of learning. This theory, which will be described below, is useful to determine how individuals behave in the long run when they adapt their strategies through time. EGT has developed at the same time as the revival of evolutionary economics in the 1980s, though its first applications concerned the field of biology (Smith, 1982). This theory is now largely used in economics.

EGT has been criticized for giving too much focus on the conditions of equilibria instead of studying disequilibrium analysis. In fact, there is, in numerous cases, concordance between the outcome of evolutionary processes and the standard outcome of noncooperative games, that is the Nash Equilibrium (NE) (see Friedman (1991)). In this sense, EGT would not be a genuine evolutionary theory, just a mere patch aimed to mend some of the failures of neoclassical economics. However, in our point of view, the full implementation of the notion of equilibrium inside evolutionism can also represent an advantage. What is appealing in the evolutionary theory is not the fact that it permits to break with the equilibrium analysis; rather, it is the possibility to reach equilibria without having to rely on strong assumptions on rationality. An equilibrium means a state of stability in a system, where most individuals do not change their actions. In game theory, the main difference between an evolutionary equilibrium and a classical equilibrium lies in the way of reaching it. Because learning through adaptation takes time, evolutionary equilibria are only relevant when considering interactions that are repeated many times, that over long periods of time rather than the short run.

In our view, another argument in favor of the notion of equilibrium is that, contrary to a common intuition, evolution does not mean constant and unceasing change. The essence of an evolutionary system is not only to be always on the move and to evolve constantly, either chaotically or by gradual change. In many economic situations, we believe that the process of repeated interactions ends to states characterized by a high degree of stability, which can be sustained for a while. Of course, these periods of stability can be interrupted by periods of change, otherwise there would be no evolution anymore. This vision is in line with the notion *punctuated equilibrium* proposed by paleontologists Eldredge and Gould (1972). Instead of being gradual, evolution of species are characterized by long periods of relative stability, which are sometimes interrupted by times of rapid change. Although the time period considered is of course much more compressed for human interactions, many situations seem to follow this kind of pattern. For example, long periods of stability are particularly visible in the domain of conventions, such as whether to drive on the right or the left side of the road.

Adaptive behavior that stems from an evolutionary selection process is sometimes called social learning, as it is based on interactions with other individuals. More precisely, social learning relies fundamentally on observation and mimetism. Though imitation can take different forms, copying plays a central role in human interactions (Rendell et al., 2010). Imitating the others who are successful can be the best way to learn under imperfect information and uncertainty. Yet, while many economic models postulate that agents act as imitators, one may ask if people really behave as imitators in reality. In fact, studying imitative behavior is indeed interesting because of its real-life relevance. Recently, experimental evidence provide strong support for imitation (Apesteguia et al., 2007; Bigoni, 2008; Offerman and Schotter, 2009; Matthey, 2010). Aside economists, scholars from other disciplines also recognize the importance of imitation. Many psychologists estimate that imitation has a central place in the human mind. Meltzoff and Prinz (2002) proposes a collection of studies highlighting the cognitive and neural basis. According to Prim and Meltzoff (2002), human beings are even the most imitative creatures on the planet. Neurobiologists also demonstrate that mimetism is an ability fundamentally linked to human intelligence, as it is supported by a core circuitry in neural mechanisms (Iacoboni, 2005).

Besides, introspection suggests that mimetism is widely used for deciding appropriate actions. For example, suppose that the author wants to go for lunch at the canteen of the faculty. Either because he is too lazy for taking the time to read the menu, or because he does not know in which domain the chef is the best at, he has clearly no idea on what to choose for his lunch. Therefore, facing uncertainty, his best choice is simply to copy the choice of those who precede him in the queue, hoping that they have more experience than him. Another reason for imitating others is related to the time dimension. While computing optimal behavior is time consuming, on the contrary imitation allows faster decision-making. In this light, imitating represents a way to take relatively appropriate decisions in situations where time is constrained.

3.3 Population Games and Evolution

Before we draw up the usefulness of EGT for the study of the commons, the next section describes more generally the elements of the theory which will be used for the applications in the following chapters. Since the aim is only to draw out the principles on which EGT is build upon and to see whether these principles are adapted for the study of human interactions in the commons, the following presentation of evolutionary games is totally free of mathematical symbols. Besides, formalized descriptions of EGT are already given, among others, in the books of Vega-Redondo (1996); Weibull (1997); Sandholm (2010).

3.3.1 Normal Form Games

In standard games, the two usual approaches for modeling interactions are the *normal form* and the *extensive form*. Both the normal form and the extensive form allow for the representation of simultaneous interactions and sequential moves. In evolutionary games, the extensive form is barely, not to say never, in use.[1] On the contrary, the normal form has been widely used, especially in early developments when the principle of pairwise contests was prevalent (see a brief description below).

When building up a normal form game, one have to define the set of

[1] Friedman (1991) is one rare exception.

the players involved and to specify the payoffs that will be earned by each player given their respective strategy choices. The payoff obtained by an individual is determined not only by the strategy he is following, but also by the strategies played by the others. This feature defines the fundamental idea of game theory, the choice of each player is influenced by the choices made by every other participants. Since the payoff of an individual depends both on his own choice and the strategies chosen by the others, designing a normal game becomes laborious when there are more than a few players. While the payoff matrices may be easily defined for two or three players, the complexity increases rapidly with the number of participants.

In real economic interactions however, the number of agents is often quite large. These situations can hardly been modeled as normal form games, and this is a difficulty of evolutionary games. Indeed, the evolutionary theory deals with situations where agents interact with each other in large populations. Fundamentally, the evolutionary analysis focus on the structure of the distribution of strategies, named the *social state*, in a single or several populations. Thus, the normal form framework seems to be intractable to deal with dozens, hundreds or thousands of agents.

However, using an evolutionary framework, the biologist Maynard Smith successfully adapted the normal form to situations where interactions are taking place between large numbers of players. The trick, which relies on the principle of *pairwise matching*, is the following. Assume that, from a population composed of numerous players, two of them are randomly taken out for a confrontation. Hence, during this period, the game involves only two players. The others are considered as totally passive when the matching is realized. Once the outcome of the confrontation achieved, players decide to revise, or not, their strategies. The manner in which the players make their revisions is determined by a *revision protocol*, which defines how agents adapt their choices given the relative success of their strategies. According to the long term logic of evolution, this matching process is repeated over and over again until reaching an interesting outcome. Generally, the outcome of the matching process is an equilibrium state where the distribution of strategies in the population remains constant.

Although the principle of pairwise matching is intuitive, tractable, and extensively used in textbooks, it has still a crucial limitation. Maynard Smith himself recognized that pairwise matching is a rather special type of interaction in large populations. While Smith, as a biologist, was primarily interested in interactions between animal species, what is true for animals also holds for humans in this case. Most of time, the payoff of a player is not only determined from the strategy chosen by an opponent who is randomly picked in the population. Rather, it stems from the strategies played by all the others at that time. For example, when a car driver is on a highway, the expected time he would get stuck in a traffic jam does not depend on the probability to be matched with another driver who is taking the same route. His waiting time would be determined from the congestion created by all the drivers who have chosen to use the same route as him, at the same time.

From a mathematical standpoint, in the random matching process, payoffs are always linear in the state of the population. In other words, the expected individual payoff varies proportionally with the evolution of the shares of the different strategies. Unfortunately, this assumption is highly inconsistent with most economic applications, especially when we introduce the phenomenon of positive or negative externalities. By taking again the preceding example, if only a few drivers are taking the motorway, an additional one would have a negligible congestion effect only. The negative effect on the utility of the other drivers would be insignificant. However, when the motorway is already overcrowded, an additional driver would worsen the traffic jam. His effect on total congestion may be modest, but not insignificant. Hence, the negative externality would be proportionally much higher in this case. In this example, payoffs do not depend linearly on the population state.

For the same reason provided just above, in common-pool resource games, the payoffs are not linearly related to the population state. When the pressure exerted on the resource by extraction activities is low, adding a unit of harvesting effort is not dramatic. Now, if the resource is already subject to overexploitation, the appropriation externality created by an additional unit of harvesting effort would be much higher. The negative side effect of appropriation is increasing in the aggregate level of exploitation. In other words, the more the resource is exploited, the more the appropriation externality is high. Then, if we want to analyze properly the problem of negative externalities generated by resource use, we must move to a nonlinear approach where payoffs depend on the whole population state, that is the *population games*, which are presented in the next section.

3.3.2 Population Games

Formally, a game is defined by three elements: the set of players, the set of available strategies, and the payoffs associated with the strategies. Further, a population game exhibits the following fundamental properties:

1) *The number of players is large, and each of them is small.* That means the behavior of an agent has only a marginal effect on the others' payoffs.

2) *Players interact anonymously.* Precisely, payoffs depend on the behavior of others uniquely through the distribution of the strategies in the population.

In contrast to normal form games, population games are adapted to model interactions that take place among large numbers of agents. This feature is appealing because many economic situations are characterized by rather important numbers of interacting actors. In population games, individuals in a given population are assumed to be identical in respect to the strategies available to them, as well as their preferences and their payoff function. Sandholm

(2010) calls *society* the collection of all individuals in the populations. In our analysis of resource exploitation, the notion of society simply corresponds to the total number of resource users.

In population games, the participants can be either divided in several distinct populations (multi-population games), or simply stay together in one population. In most economic models, societies are usually composed of one single population. Our applications in following chapters will not depart from that. Yet, one may think: if we consider only a single population where agents have the same preferences, the outcome would logically be a situation where everyone behaves in the same way. But beware that this is not necessarily the case. Preferences are defined by a payoff function which itself depends on the strategy chosen and the distribution on the strategies in the population. Thus, depending on the distribution of strategies, the value of strategies can vary. A strategy that yields a high payoff in a given distribution may provide lower returns for an other state of the distribution. Hence, when the distribution of strategies is changing, the payoffs of the different strategies are changing too. Therefore, it is possible that different strategies allow to get the same payoff at some point(s) of the distribution. Such situation corresponds to what is usually called a *steady state*.

The structure of the distribution of strategies in a game, which corresponds to the aggregate behavior of the community of players, is a *social state*, or put it simply a *state*.[2] Fundamentally, determining the composition of social states is what population games are about. The main questions which are of interest in the study of these games are the following. How strategies are distributed

[2]Technically speaking, for a finite number of populations and a finite strategy set, the set of social states is a polytope, that is a geometric object with flat sides. In our applications, because we will consider only a single population and a few strategies, the sets of social states will take the simple forms of a line (two strategies), a triangle (three strategies), or a tetrahedron (four strategies).

in the population, as a result of individual interactions ? How the incentive structure of the game can lead to a particular social state, or on the contrary alter it?

Let us take a simple example to illustrate these questions. Consider a community of individuals where everyone has to choose between two pure strategies. The first strategy is to behave as good person, who is generous and liberal with others. The second strategy is the opposite, individuals can choose to be vicious and petty-minded. In this case, the interesting question is: what is the proportion of good persons relative to the bad ones ? In other words, we would like to determine the composition of the population, that is the distribution of these behaviors in the society. Is everyone behaving well, like in a wonderland? Or does this community turn to a dreadful society entirely dominated by thugs? Or maybe, the outcome can also consist in a mixture of both kind of people. Besides, if one would like to seek how to promote good behavior, or simply understand why people behave in a particular way, the other point of interest lies in the incentive structure where interactions take place. More precisely, we may ask what are the elements and parameters that drive people to behave in a good or in a bad manner, and how to modify them in order to achieve a desired outcome.

In economics, as well as in biology, most studies using population games follow the logic expressed in the above example. In many cases, strategies in population games are about the concepts of cooperation and free-riding[3]. Agents have the choice to cooperate, in the sense that they agree or conform to a behavioral norm that is considered as desirable in some way. Besides, they have also the opportunity to free-ride (i.e. to defect), by refusing to comply with the *norm*. In the case of the exploitation of renewable natural

[3]The word cooperation may be confusing. Here, cooperation has nothing to do with the class of *cooperative games*. We will only study cooperation in the framework of non-cooperative games.

resources, cooperation means that individuals adapt their harvest to a level that is compatible with the preservation of the resource over the long run. The choice for resource users to harvest on a sustainable level, instead of overexploiting the resource, is precisely what constitutes a social norm in our analyzes.

3.3.3 Evolutionary Stable Strategies

Up to now, we pointed out that the analysis of population games relies fundamentally on the characteristics of social states. However, we did not say anything about the specific states that should retain our attention. For large populations, the number of distributions of strategies can be huge, so the set of social states is usually composed of a great number of states. If we assume that the population is continuous, the number of social states is even infinite.

Because it would be nonsense to study every single social states, theoreticians have developed criteria to select only the states that are likely to be played by the agents. These states are called *equilibria*. In game theory, the most famous and popular type of equilibrium is the *Nash Equilibrium*, followed by many of its refinements. Among the refinements of the Nash Equilibrium, one concept has been adapted to fit the principles of evolution, the *Evolutionary stable Strategy* (ESS hereafter). Suppose that initially all agents in the population share a unique, mixed or pure strategy. Now, assume that a small number of individuals decide to switch from the incumbent strategy to a new one. The incumbent strategy is said to be evolutionary stable if there exists a positive invasion barrier such that it provides a higher payoff than the "mutant" strategy (Smith, 1982; Weibull, 1997). In other words, an ESS is a strategy that is robust to evolutionary pressures. If any small group of individuals experiment another strategy, they will perform badly compared with those who stick to the incumbent behavior. Thus, once reached, the ESS offers stability against invasion of alternative strategies.

In its original formulation, the concept of evolutionary stable strategy is defined for symmetric pairwise interactions. Situations where all agents interact simultaneously where not considered. Hence, we will not use the standard formulation of the ESS for the applications in the next chapters. Rather, in chapter 4, we will use another version of the ESS which is adapted to define evolutionary stability in situations where all players act simultaneously as imitators. By copying, at each single round, those who get the higher payoff, agents are engaging a process of selection of strategies that can ultimately lead to a state of equilibrium. To distinguish it from the standard definition of evolutionary stability, we will call such equilibrium an *imitation evolutionary stable strategy* (IESS).

Because it is defined as a situation of robustness against the invasion of alternative strategies, the concept of evolutionary equilibrium focus essentially on the principle of mutation (i.e. experimentation). Apart the mechanism of experimentation, the other basic element of evolutionary processes is the process of selection, which describes how the different strategies are selected or discarded by players. The selection mechanism creates a dynamics that may ultimately lead to a situation of equilibrium. In many applications, evolutionary stability is defined under the concept of the *replicator dynamics*. This evolutionary selection process, that will be used in chapters 5 and 6, is presented in the next section.

3.3.4 Evolutionary Dynamics

The objective of evolutionary dynamics is to describe how, in a population game, participants choose and revise their actions. In economics, the evolutionary principle of selection is applied directly on the different strategies that are played by the participants, and not on the people themselves as it is usually the case in biology. Generally, it is assumed that agents, by using myopic rules of behavior, adjust progressively their strategies in response to their environment. It is often said that agents have only "limited rationality" in the sense that instead of computing their optimal behavior, they usually choose predetermined strategies. The strategies are selected by individuals according to their respective performances in terms of payoff. Adaptive behavior also means that players revise their actions only in an occasional way. Delays in adjustment represent the imperfect diffusion of information or the limited ability for humans to deal instantaneously with the flow of information. Besides, no coordination of players' beliefs is needed in evolutionary processes of learning.

In the family of evolutionary dynamics, the replicator dynamics is a widely used concept to describe evolutionary processes of selection, both in biology and in economics. The basic assumption behind the replicator is that agents select their strategies by looking at the choices made by each others, thereby imitating the strategies that yield high payoffs. Hence, the replicator belongs to the family of *imitative dynamics*. In its continuous form, that will be used in chapter 5 and 6, it is formalized as a system of ordinary differential equations (Taylor and Jonker, 1978).

The logic of the replicator dynamics is following. Consider a strategy that is played by one or several agents in the population. The replicator dynamics for this strategy describes the evolution of its share compared with the other strategies played in the population. More precisely, the replicator states that a strategy will gain momentum in the population if it yields a higher payoff than the weighted average payoff in the whole population. Conversely, a strategy that performs badly compared to the average will lose ground. For the sake of completeness, we can add that under the replicator the growth rate of a strategy is proportional to its current share in the population. Hence, a marginal strategy will take more time to spread to the entire population than a strategy that is already played by a larger fraction of the participants.

Instead of evolutionary dynamics based on the logic of best response, imitative dynamics, including the replicator dynamics, accept rest points that are not Nash equilibria (Sandholm, 2010). Put it simply, a state which is evolutionary stable under the replicator is not necessarily a Nash equilibrium. This is the reason why imitation behavior is interesting, it can explain outcomes that do not correspond to Nash equilibria. Contrarily to the argument of Friedman (1953), processes of evolutionary selection may not result in similar outcomes than the standard maximizing behavior.

3.4 Evolutionary Thinking in the Commons

Evolutionary economics has mainly developed on the ground of a growing dissatisfaction with neoclassical mainstream. As mentioned previously, proponents of evolutionism have often considered its introduction in economics in frontal opposition with the standard approach. It is often seen as an alternative which is fundamentally incompatible with the "rational" theory. In our view, the role of the evolutionary theory is to provide answers to questions that are not satisfactorily addressed with the standard framework, and not to dismiss achievements made with the traditional approach. In this light, evolutionary and neoclassical theories can be viewed, instead of substitutes, as complements. The connexion between neoclassical and evolutionary economics is particularly advanced in the theory of games, as these two approaches share a common basis, and are linked together around the notion of equilibrium.

Traditionally, the field of environmental and resource economics has developed within the line of neoclassical mainstream, that is quite independently from evolutionary economics. Nevertheless, environmental economics and evolutionary economics share important features, thereby making it possible to combine these two fields in a fruitful manner (see Van den Bergh (2007) for arguments in favor of an evolutionary approach of environmental economics). As in other fields of economics, evolutionary economics has gained some importance in environmental economics. Faber and Frenken (2009) considers evolutionary economics have a high potential in environmental policy-making in several areas, such as technological transitions or consumer demand. Evolutionary games are used for analyzing processes through which countries join international environmental agreements (Breton et al., 2010; McGinty, 2010). Applications have emerged regarding, among others, farm management (Darnhofer et al., 2010), industrial waste pollution (Kronenberg and Winkler, 2009), or environmental innovation (Oltra, 2008; Brouillat, 2009). In common resource dilemmas, as we will see further, several studies combining economic evolution and resource use have been proposed during recent years, though they are relatively few. In this section, the relevance of EGT to analyze interactions that take place in common resource is discussed.

3.4.1 Rational Choice Theory: Insights and Limits

Standard game theory is confronted with two major problems, one of theoretical nature, and one more empirical. The theoretical problem is the presence of multiple equilibra in some games. For example, in a coordination game with two players and two strategies, there are two Nash equilibria. Both agents can coordinate their actions either on one strategy, or on the other strategy. In such case, the basic formulation of the Nash equilibrium is insufficient for predicting the outcome of the game, since there is no way to determine which equilibrium will be played by the agents. The multiplicity of equilibria is the reason why game theorists have developed refinements of the Nash equilibrium. Stronger specifications for stability are needed to determine which equilibrium will be played.

Initially, the development of EGT was driven by the objective of finding a new selection criteria of Nash equilibrium (Samuelson, 1998). The evolutionary stable strategy can indeed be viewed as one of the refinements of Nash equilibrium. Under some specifications, an ESS corresponds to a Nash equilibrium (while the reverse is not necessarily true). More precisely, for pairwise contests, the ESS is defined as a Nash equilibrium, plus an additional condition guaranteeing stability against invasion by alternative strategies. Therefore, the evolutionary equilibrium can be used as a tool to select between Nash equilibria when the outcome is unclear under the standard framework.[4]

The second problem with the Nash prediction is the question of its validity in real-life situations. Many experiments performed on varieties of games have shown that individuals do not always behave in the way predicted in theory. In common-pool resource games too, results are not always consistent with the predictions stemming from rational choice models. Experimental studies have found that resource overuse can be more intense than Nash (Walker et al., 1990; Walker and Gardner, 1992; Maldonado and Moreno-Sanchez, 2008). The use of common land in villages of Côte d'Ivoire shows a similar pattern, confirming the possibility for deviations toward higher exploitation than Nash (Lopez, 1998). In the next chapter, we attempt to explain why resource users can engage in more destructive use than the Nash prediction.

On the other side, it has been widely documented that individuals can avoid or limit harmful races to the resource. Experimental and empirical

[4] Though the ESS is more demanding than the Nash equilibrium, it is possible that several strategies fulfill the conditions for evolutionary stability, thus limiting the utility of EGT as a solution to select outcomes. For example, in the coordination game, the two Nash equilibria are evolutionary stable. Sometimes, it is considered that the genuine evolutionary outcome is the ESS having the larger basin of attraction, since in the long run most of the time will be spent in this equilibrium. However, this logic relies on the assumption that interactions takes place over very long periods of time, which can be excessive to describe real economic situations.

examples of deviations toward more efficient outcomes than the standard Nash equilibrium are plentiful. Ostrom (1990) and Ostrom et al. (1994) used some elements of classical game theory to show that exploiters have an incentive to comply with social norms for limiting resource use. However, such analyzes do not provide any explanation on the process through which norms are generated or enforced by resource users. The difficulty with the standard approach is that it is essentially norm-free, since it does not understand behavioral norms as a result of processes of learning.

3.4.2 The Role of Norms

As stated in the introduction, it was originally thought that evolutionary processes of learning would lead individuals to conform to the rational maximizing behavior. Without having to compute the best strategies under the standard assumptions of rationality, just by imitating and experimenting, agents would be driven to discover how to behave rationally in the long run. However, we know now that the coincidence between evolutionary and standard behavior holds only under specific circumstances. In other words, the outcome of interactions can differ sensibly under the standard hypothesis of perfect rationality on one hand, and the evolutionary assumption of limited rationality on the other hand.

One of the fundamental difference between evolutionary game theory and the standard theory of games is that the former can include behavioral norms, while the latter is norm-free. Mainstream resource economics, by focusing on perfectly rational agents, has consequently overlooked the role of norms that arise through local interactions of users. Yet, knowing that a norm is a particular behavior individuals may – or must – follow, as stated in the previous chapter, one may ask what it really means under a formal representation. In fact, the questions of how to define a norm and how to represent it into a formal model have no definitive answers. Sometimes, norms are used as an ex post explanation to explain why an observed behavior is not consistent with the prediction derived from the usual assumptions of game theory. Observing that individuals did not conform to the predicted outcome, it is tempting to say that they must have used some norms of reciprocity or something else, without entering into further details.

An explanation of how behavioral norms can survive in competitive environments is proposed by the *indirect* evolutionary approach (see Güth (1995)). The fundamental intuition of this approach is that following a norm would increase the utility level of the individual through feelings of pride or higher esteem, while breaking it would decrease utility by generating a feeling of shame. In the indirect approach, instead of assuming exogenously the preferences held by players, they are explained endogenously by a selection process. Predetermined preference parameters are submitted to an evolutionary process aimed at exploring which preferences will evolve and survive. Usually, the intrinsic value for a particular action is based on other-regarding preferences. In this sense a norm corresponds to an other-regarding preference or a set of such preferences that have proved to be stable under evolutionary dynamics.

The inclusion of norms in formal models can be rather simple. Letting aside the problematic of the indirect evolutionary approach which tries to determine which preferences are selected, norms can be represented formally by including one or several parameters representing the intrinsic value of obeying some ethical prescriptions. As suggested Crawford and Ostrom (1995), adding in the payoff function some parameters which would represent the internal valuation that individuals place on the requested behavior is a simple and efficient manner to introduce norms into formal models. Yet, without rejecting the idea that human behavior is partially driven by intrinsic other-regarding preferences, adding a symbol into the payoff function will not be our method to represent norms in the following chapter. In fact, most of evolutionary models of common property resources have tried to explain cooperation through self-centered preferences. Similarly, in our study of cooperation in the commons, resource users will start cooperating because it is through cooperation that they will achieve higher monetary returns from resource exploitation, not because they would feel happy for their kindness toward others. Thus, without having to refer to intrinsic other-regarding preferences, cooperation will be explained in an environment in which individuals are driven by their self-regarding motivations.

A norm can be defined as an action or a behavior that, contrary to the classical outcome of non-cooperative dilemmas, leads to an efficient outcome from the point of view of the society of resource users and the sustainability of the resource. Also, a norm is a behavior developed through repeated interactions and sustained over significant periods of time. Hence, to become a norm, a behavior must offer some stability to deviations. This definition of norms does not postulate any condition on the kind of preferences people are following. Consequently, individuals can potentially follow norms even if they have no consideration for the well-being of others. The most important question is not to determine if individuals are fundamentally altruists or egoists, but to see how they are able to cooperate in order to cope with the problem of overuse, thereby guaranteeing the sustainability of their resources and rents.

3.4.3 Applications of EGT

While applications of EGT to common-pool resource interactions are still rare, several studies have used the principles of evolution to analyze how users can overcome the problem of overexploitation. Osés-Eraso and Viladrich-Grau (2007) showed that resource users can develop behavioral norms through other-regarding preferences. Using continuous time replicator dynamics, they found that harvesters can voluntarily restrict their exploitation level when they are socially rewarded for doing so. Social approval between cooperating agents can work as a mechanism to increase compliance in common resource exploitation.

While other-regarding preferences can explain why people cooperate, many case studies have highlighted the fundamental role of informal sanctions to enforce social norms. Given the importance of endogenous sanctions for successful community-based resource management, applications of EGT have initially integrated self-enforcement activities as a means to explain cooperation. Sethi and Somanathan (1996) introduced the possibility for harvesters to sanction those who do not comply with social norms in common resource use. They showed that, by sanctioning harvesters who overexploit beyond a certain level (i.e. the norm), resource users can effectively enforce harvesting restrictions. Hence, in their model, the norm is enforced endogenously through the actions of local users, without any need of external enforcement.

Several recent evolutionary models of common-pool resource have followed this path. Bischi et al. (2004) find that self-enforcement based on endogenous sanctions can work as a means to promote cooperation when considering discrete time dynamics as well. Noailly et al. (2007) show that compliance with social norms is possible when agents, spatially located on a circle, can only observe and sanction their direct neighbors. Contrary to Sethi and Somanathan (1996) where the only possible outcomes are full cooperation or full defection, they find a large variety of equilibria to be the outcome of the game, including ones where both strategies coexist. This result is not qualitatively affected when agents are situated on a torus and follow a more simple imitative rule by copying the best performing neighbor (Noailly et al., 2009). In all these applications, resource users are able, under some conditions, to comply with a rule aimed at limiting individual harvesting. Sanctions are supposed to be exercised by individuals who cooperate, while free-riders have not the possibility to sanction. In chapter 5, we will propose a model that falls within the scope of self-enforcement. However, we will authorize violators to sanction as well, and study the consequence of such behavior for common resource management. Besides, Xepapadeas (2005) also states that monitoring and sanctions can increase compliance in common-pool resources. However, his approach differs since harvesting rules, instead of being self-enforced by local users, are enforced exogenously by an external regulator.

Blanco et al. (2009) extend the analysis of common-pool interactions to the tourism sector. They show that firms using common natural resources to provide recreational activities can undertake voluntary abatements in order to limit congestion and degradation. Here, the source of compliance lies in the price premium that can be charged when the environmental quality is increased. Firms have an individual interest to reduce the pressure on the commons when they can benefit privately from the price premium, that is if the price premium can be at least partly privatized.

All the pre-cited evolutionary models share common features. Instead of computing their optimal level of harvesting effort, exploiters make the choice to follow one of the several predetermined strategies at their disposal. Among these strategies, the following two are always present. Individuals can choose to cooperate, that is to agree with harvesting rules, or to free-ride by overexploiting the resource. Limiting the choice to only a few simple strategies may seem restrictive. However, individuals do indeed make choices between a few alternatives only in real-world interactions, including the commons (Noailly et al., 2003). Moreover, all these model use the replicator dynamics to design how people adapt and select their strategies through time. Hence, agents are supposed to learn gradually their best choices by imitating those who succeed.

3.4.4 On the Relevance of EGT

The literature combining common resource exploitation and evolutionary games has put forward several justifications to use the principles of evolution. However, these justifications are rather limited, as they mostly refer to general descriptions of EGT aimed at highlighting its relevance to describe human behavior in social science and in economics, but that are not specific to natural resource settings. In our view, the suitability of EGT to analyze real common-pool interactions is not enough questioned, and the links between the characteristics of the models and real systems of resource management should be developed further. Here, we point up some of the advantages of EGT regarding the study of the commons.

The most appealing reason to introduce EGT into the analysis of the commons is the prevalence of social norms in resource governance. As stated in the previous chapter, social norms are fundamental for successful management, particularly when it is based on the participation of local communities. Evidence gathered worldwide has shown that behavioral norms emerge and evolve as a result of long time interactions between resource users. EGT is well-adapted to study the evolution of such kind of norms, as it represents them as the result of processes of learning over long periods of time. Adaptive dynamics in evolutionary games is mainly based upon imitative dynamics. While it is difficult to check directly how people make their individual decisions when interacting, imitation is relevant in widespread situations. Mimetism has received a large support by social scientists to describe correctly how individuals improve their actions, in particular in situations characterized by uncertainty. Limited rationality, uncertainty, and imperfect information are the main factors that favor the use of imitative heuristics. These factors defines most areas of economic interactions, including the commons.

Contrary to standard economics, EGT is uniquely focused on interactions repeated over long periods of time. Because selection processes assume adaptive adjustments, states of equilibrium can take time to be reached. In fact, assuming that interactions between resource users are repeated on the long run is suited to describe real situations in the commons, in particular for management by communities. In many cases, exploitation of common resources is a family tradition. In fisheries, it is common for the occupation to be transmitted from father to son. Among the example of long-enduring self-governed commons, communal tenure of grazing lands in Switzerland, irrigation water in Spain, or common meadows and forest lands in Japan are all cases of sustainable governance that lasted several centuries, and still exist today (Ostrom, 1990). Yamamoto (1995) describes traditional fishery management in Japan over the last 250 years. Although all systems of management are not that old, resource use usually takes place on sufficiently long periods for individuals to have the opportunity to develop social norms and rules of governance.

Last but not least, the question of the number of individuals involved in resource exploitation is fundamental. Most of evolutionary models, including those based on the replicator dynamics, rely on the assumption that individual agents cannot affect significantly the distribution of strategies. To guarantee that isolated individual behavior has only a marginal effect on the aggregate outcome, interactions must take place among a large number of people. Therefore, evolutionary models based on the replicator dynamics are not adapted to study interactions between a few participants, such as oligopoly situations. In general, the issue of the population size is seldom addressed in application of EGT. For example, this can be problematic in the model of Blanco et al. (2009), where the replicator is used to analyze the behavior of firms providing tourism activities in a common-pool resource. One may ask if, in the case of recreational activities, common resources are really exploited by large numbers of companies in reality. Maybe it is, but this is not so obvious at a first glance.

Fortunately, in common resource use, the number of participants is most of the time rather high, especially for local communities which are often characterized by small actors. According to Ostrom (1990), the fishery of Alanya in Turkey, which counts around one hundred, represents a case where the number of fishers is small. In other Turkish fisheries, their numbers can easily grow up from several hundreds to thousands. The number of appropriators in Californian groundwater basins also adds up to several hundreds. In the region of Valencia in Spain, irrigation water can be shared between more than ten thousand farmers. These examples are not a selection of extreme cases, and a collection of many others would show similar patterns. Rather, they give a quite fair order of magnitude of the number of exploiters involved in common natural resource used by communities. Thus, the assumption of large population made in most evolutionary games is clearly not constraining. On the contrary, it seems to fit well the range of empirical examples of resource use by local communities.

While local communities are generally composed of numerous individuals users, the number of participants is not as high when the resource industry is more industrialized. For example, in Norwegian modern fisheries, the number of vessel owners has dramatically decreased as a result of economic and technical progress (Béné et al., 2010). Other situations, such as timber forests, are characterized by limited numbers of companies sharing exploitation. In these cases, the replicator dynamics is unadapted for modeling how firms behave. However, there exists some specific formulations of EGT which are less used, but that are compatible with smallness in the number of players. The application proposed in the next chapter belongs to this family.

By summing up, community-based exploitation is characterized by widespread presence of social norms, repeated interactions over long periods, and large number of harvesters. For these reasons, EGT represents an appropriate approach to analyze interactions in the commons, particularly when they are governed by local communities.

3.5 Conclusion

Evolutionary thinking has been introduced in economics on a fundamental reject of neoclassical economics (Nelson and Winter, 1982). However, the case of EGT is rather special in the family of evolutionary theories. Although it represents an alternative approach to model economic interactions, EGT should not be considered as totally opposed to classical theory of games. Rather, EGT should be viewed as an extension of the standard framework, aimed at complementing some shortcomings of game theoretical analysis. It can be seen as an intermediate approach between neoclassical economics on one side and evolutionary economics on the other.

While environmental and resource economists, by studying the impact on human activities on the environment, are rather close to the preoccupations of biologists, relatively few applications of evolutionism have emerged in environmental economics. Yet, evolutionary game theory has been used for modeling economic interactions in environmental setting, including the commons. In the case of common resource exploitation, the objective shared by the majority of evolutionary models is to highlight the role of social norms aimed at coping with the problem of overuse. As a result, it has been demonstrated that individual harvesters, through self-enforcement activities or other mechanisms, are able to sustain behavioral rules compatible with sound resource use.

Recognizing the fundamental role of social norms in common resource exploitation is important for policy-making. Any external intervention aimed at regulating resource use can potentially "crow-out" social norms. Substituting internalized norms by imposed formal rules can lead individuals to behave in a destructive way for the resource. Hence, external interventions should be designed carefully to avoid the potential destruction of well-functioning norms. The recognition of social norms as a decentralized form of resource management should prevent inappropriate or excessive interventions from the government. Yet, there may be some room for proper interventions. By taking correctly into account the role of norms, an intervention that works on the conditions which favor the emergence and the sustainability of efficient behavioral rules can be useful. Identifying the conditions that enable the use of norms is the principal objective of both the empirical and the evolutionary literature on the commons.

The introduction of evolutionary principles to describe economic interactions has been motivated by several reasons. In this chapter, we also discussed why evolutionary game theory is adapted to model interactions in common resource dilemmas. The empirical literature on the commons identified regularities that cover a large range of cases. Common resources exploitation is usually characterized by the presence of large numbers of participants, repeated interactions over long periods of time, and widespread development of self-enforced social norms. We argued that these features correspond precisely to the essence of evolutionary games. As a consequence, EGT represents a relevant approach to analyze the outcomes of interactions and to identify the conditions that promote sound resource use. In this line, the next chapters will propose three applications of EGT to the problem of the commons.

Chapter 4

Imitation, Perfect Competition, and Pure Tragedy

Contents

4.1 Introduction

Initially coined by the biologist Hardin (1968), the expression "tragedy of the commons", which refers to the problem of exploitation of common resources, has been largely adopted in the economic literature. The logic behind the overuse of common resources, which was described in chapter 2, has been mathematically formalized, notably through the use of game theory. In the standard framework, the fundamental result is that the best-response behavior leads to an inefficient outcome, the Nash equilibrium, in which the resource is overexploited.

Numerous experimental and field studies tend to confirm the fact that common resources face severe exploitation pressures. In this way, the standard game-theoretical framework seems to be the right tool to describe how resource users tend to extract more than what would be required at the collective optimum. In other words, the Nash outcome would be a precise prediction to assess the degree to which resources are overexploited.

However, if laboratory experiments and empirical studies have corroborated the phenomenon of resource overuse, some of them found that the outcome may differ from Nash. It can differ in a positive manner when resource users manage to cooperate by reducing their pressure on the resource, but on the contrary the outcome can be also worse than what the Nash equilibrium predicts. It is the latter point that will interest us in this chapter. How is it possible that resource users exploit more than Nash? What is the economic rationale for exploitation beyond Nash, since the actors involved in extraction have a payoff incentive to reduce their effort to the Nash level, according to the standard analysis?

Using an evolutionary game, our objective is to see how actors can be trapped in an interaction situation that lead to the worst possible outcome, where resources are exploited up to the point where all rents are dissipated. When resource users follow a behavioral rule based on imitation, more precisely when they decide to imitate the best performing harvester, then the result is a higher level of dissipation of the resource than the Nash equilibrium (proposition 1). The idea is that when a resource user increases the effort he puts in harvesting, the profits of others are reduced since the returns in the industry are diminished. Thus, by reducing the payoffs of his counterparts, an individual who decides to increase his investment in resource extraction gets an advantage over them. If everyone adopt this strategy through imitation, the result is an intense competition, more intense than Nash.

The chapter is organized as follows. In section 4.2, we discuss the literature related to our problem. Section 4.3 presents and examine the characteristics of a usual common-pool resource model. Sections 4.4 and 4.5 determine the outcome of the evolutionary stable state. The last section concludes.

4.2 Background

From a theoretical standpoint, conflicts related to the commons have received much attention, especially from analyses based on the principles of game theory. The basic prediction from non-cooperative game theory is that rational players will exploit more than the level corresponding to the collective optimum. The income maximizing Nash equilibrium of the common-pool resource game leads to overexploitation because agents do not take into account that an increase in individual harvesting effort creates a negative externality which decreases the returns for all individuals. At their own expense, individuals play Nash rather than the Pareto-optimal strategy that would correspond to the exploitation level of a single actor. As a result, the exploitation level of the resource exceeds the Pareto-optimal level, where the marginal revenue from exploitation equals the marginal cost, that maximizes the total profit of the industry.

In this logic, the degree of overexploitation depends positively on the number of appropriators. If the number of resource users is limited, as it is the case in a common property structure, overextraction is more or less contained and the resource rent remains positive (if the resource is not destroyed by overuse). On the contrary, in a situation of open-access, where everyone has unlimited access to the resource, the tragedy is exacerbated to a further extend. In this case, harmful competition force harvesters to extract at the maximum level, where the average returns equal the marginal appropriation cost, so that the rent generated by the resource is totally dissipated. Thus, the Nash equilibrium lies between optimal rent and complete rent dissipation, depending on the number of players. From this standard theoretical point of view, the range of the tragedies faced by the commons are explained by the number of resource users involved in exploitation, as an increase in the population of harvesters would drive the Nash level of exploitation toward the open-access level, while conversely a reduction of the population would lower the pressure of extraction.

This somewhat intuitive result has led scholars to question the impact that the widespread increase of human populations have over natural common resources. Understandably, overpopulation has been incriminated as the main threat for the commons by Garett Hardin. However, population pressure is not always a major cause for resource depletion. In Costa Rica for example, deforestation during the 1970s and 1980s was not primarily caused by the increasing number of squatters. Rather, the depletion of forests was a direct consequence of profit-seeking strategies adopted by logging companies (Lutz and Herman, 1991). It is also important to recall that most of common resources are exploited under situations of limited-access rather than in open access (Ostrom, 1990), so that other factors than population pressures are needed to explain the extend of severe tragedies. These factors can be of technical nature, such as the physical characteristics of the resource and the technology used for exploitation, but also of human nature, which include the specificities of the behavior adopted by individuals while interacting.

Yet, if the logic of Nash behavior provides a fundamental insight on the systematic tendencies of resource overuse faced by the commons, numerous experimental and field studies have challenged the outcome predicted by the Nash equilibrium. In general, their purpose is to show that overexploitation is not always that severe since resource users may cooperate to reduce their extraction levels. And it is true that a huge amount of evidence collected by economists and legal scholars have shown that individuals successfully cope with resource overuse, usually through local institutional arrangements and by conforming to social behavioral norms.

Unfortunately, this bright side is only a part of the whole story of the commons. Even though the empirical literature has mostly tested the potential gains of cooperation rather than studying to what extent the resources are overexploited, we should not forget that environmental disasters involving common resources are still plentiful. One striking example is the dramatic collapse of fish stocks in many parts of the world. Even though pure open-access fisheries tend to become rare, halieutic resources still face rapid depletion. According to the Food and Agriculture Organization (FAO), the percentage of marine fish stocks that are underexploitated or moderately exploited declined from 40 percent in the mid-1970s to 15 percent only in 2008[1]. Conversely, fully exploited stocks (58 percent in 2008) and overexploited stocks (32 percent in 2008) are on the rise, as well as depleted and recovering stocks. This negative trend suggests that limiting entry at an international level through exclusive economic zones (EEZ) failed to cope with overfishing problems. On the solid ground, communal forests in several African and Asian countries are also endangered, partly because of population pressures, but not only. In many parts of the world, excessive pumping of underground water is causing rapid depletion of aquifers. Falling water tables create shortages of drinking water and sources for irrigation, and may also lead to contamination by mineral poisons and saltwater intrusion.

Of course, we cannot draw any conclusion on this very brief overview of degradation of common resources, since each single tragedy has its share of own characteristics that need specific investigation. However, the widespread experiences of resource depletion like those mentioned above gives us the intu-

[1]FAO, The State of World Fisheries and Aquaculture, Fisheries Department, Food and Agriculture Organization of the United Nations, Rome, 2010.

ition that overexploitation may be sometimes worse than the Nash equilibrium would predict. Thus, it is legitimate to ask whether deviations from the Nash equilibrium occur toward even more overexploitation, rather than the Pareto-optimality outcome. As pointed out by Ito et al. (1995), empirical evidence and experimental results indeed suggest that, even though the number of appropriators is limited, the degradation of common resources may exceed the Nash outcome.

The degree to which common-pool resources are overused has not received much attention in the empirical literature. One exception is McWhinnie (2009) who has estimated the magnitude of overfishing in internationally shared fisheries, finding that they are indeed prone to overfishing. Concerning the problem of land use, Lopez (1998) showed that village farmers in Côte d'Ivoire are facing large losses of income due to excess of cultivation of land under common property. Agricultural productivity is declining as the reduction of fallow periods diminishes the natural vegetation, whereas excessive cultivation of communal land reduces the forest areas. Thus, farming reduces the natural biomass, thereby causing soil degradation. This negative impact on soil fertility is not taken into account by individual cultivators in their harvesting decisions. In this case, rural communities have failed to build up a system of incentives that would induce a sustainable use of their common lands, even though the common property is clearly delimited, with access restricted to local villagers only. For our analysis, the interesting feature of this study is that, in an essentially closed-access form of land use, villagers exploit the biomass resource almost up to the open-access level, resulting in losses much more important than estimated with the conventional approach.

Besides, some laboratory experiments also support the idea of rent exhaustion in the presence of a limited number of players. Walker et al. (1990) performed several experiments designed to test the prediction of suboptimal rents in a limited-access common-pool resource. Their results confirm the severity of the problem in a non-cooperative environment, with investments in resource extraction far beyond optimum. Moreover, when players were provided a sufficiently high level of endowment to invest in extraction effort, such that they were not significantly constrained in their investment activities, the level of rents fell far below the Nash equilibrium, and sometimes even below the open-access level. In an another experiment which includes a probability of resource destruction if players put excessive effort in harvesting, Walker and Gardner (1992) found that players do not follow the Nash equilibrium, even if it is safe and yield positive rents. They systematically destroy the resource, and in most cases rather quickly.

The two preceding experiments were performed with university students. One may ask whether the same kind of worrisome results can be obtained with individuals used to interact in common-pool dilemmas. More recently, an experiment conducted by Maldonado and Moreno-Sanchez (2008) also tested the extend of resource overuse, but this time with fishing communities from Columbian Caribbean. They find that players extract more than Nash, particularly when the resource is scarce, thereby exacerbating the tragedy of the commons. Then, although the Nash equilibrium is inefficient, it represents in these experiments an excessively optimistic prediction about resource overuse. The tragedy of the commons is not only confirmed in these cases, but even worse than usually thought according to the usual theoretical predictions.

On the side of the theory of the commons, almost all studies have focused on how to achieve deviations from Nash behavior to Pareto-optimality. The reverse have received very little attention from scholars. One exception is Cornes and Sandler (1983), who stated, using a static game, that an individual will not conform with Nash behavior when anticipations about how others exploiters react to his own harvesting effort. If a resource user make conjectures about what will be the effect of his behavior on the efforts of the others, he will either overextract or underextract, depending on the kind of anticipation he is following. For negative conjectures, that is when a harvester expects others to reduce their efforts when increasing its own investment level, resource use is intensified regarding to the usual Nash solution. With their formulation of anticipations, Cornes and Sandler conclude that the rent is even entirely dissipated whatever the number of harvesters is, from two to infinity.

The intuition behind this result is the following. If one expects its increased harvesting effort induces a reduction in the effort of others, his expected returns are higher due to the reduction of aggregate effort. Thus, he is willing to increase his input level. If everyone is acting according to the same logic, increasing individual and thereby aggregate effort level, the extraction level will eventually rise up to the open access situation where all rents are dissipated. This idea provides an interesting explanation to the question of rent dissipation and resource overuse in restricted-access commons. Nevertheless, the reason why resource users come to elaborate such negative conjectures is not obvious, and left unanswered. Maybe the intuition lying behind this kind of anticipation is that a user, by increasing his effort, expects the others would start to reduce their inputs in order to avoid harmful competition. This could make sense in the short period, which is in the spirit of their static model. However, is it the case if we consider repeated interactions over the long run, which clearly typifies the commons? Sooner or later, players may realize that their conjectures, instead of decreasing the level of effort in the industry, reinforce the rush on the resource. Then, it is possible to imagine that all individuals would not want to keep their anticipations unaltered.

The objective of this chapter is to explain how interactions between resource users can lead to tragedies of the commons intensified compared with Nash prediction, as suggested by empirical and experimental evidence. However, unlike Cornes and Sandler (1983), we will move away from the standard game theory which assumes strong assumptions concerning information available to the players and their computational abilities to determine optimal strategies. Rather, we will use the principles of evolutionary theory to model the way individuals behave in their interaction environment.

Although most of recent evolutionary analyzes attempt to prove the existence of cooperation and altruism in games, competition based on mimetism also deserves attention because it provides a theoretical explanation of the severe dissipation of common resources caused only by a few actors. One may still wonder if individuals really behave as imitators. Do they look at what the others do and mimic the strategies that seem to work well? As discussed in the preceding chapter 3, the answer is that imitation is indeed a fundamental driver of human behavior, especially since the world is characterized by imperfect information and uncertainty, which is also the case for interactions in the commons.

The model presented in this chapter is similar to Vega-Redondo (1997)'s Cournot Oligopoly where firms imitate those who earned the higher profit in the earlier period. The result of this *imitate the best* behavior rule is a convergence toward the walrasian outcome, instead of the Cournot-Nash equilibrium. The imitation dynamics describes a logic of *relative* profit maximization, leading to the perfect competition equilibrium. This competitive behavior has been extended to the class of submodular and quasi-submodular games (Schipper, 2004; Alós-Ferrer and Ania, 2005; Leininger, 2006), and since the CPR game is submodular, as a result, the dissipation of common resources under the imitation-experimentation dynamics exceeds the Nash equilibrium. Proposition 1 states that under the rule of *imitate the best*, all rents are completely dissipated due to excessive extracting activities.

Finally, the framework used here differs from other CPR evolutionary models in several ways. On the contrary to Sethi and Somanathan (1996), Noailly et al. (2007), and Osés-Eraso and Viladrich-Grau (2007), as well as those of the following chapters, where cooperative behavior guided by social norms or reward/punishment may be a stable outcome, there is no possibility of sanction or cooperation between agents. These models share the same objective: to show how resource users can cooperate to deviate from the Nash strategy toward Pareto-optimality. Our objective is just the reverse, since we want to see how actors deviate from Nash to the competitive equilibrium. A second fundamental difference is that the following analysis relies primarily on the equilibrium concept of evolutionary stable strategy, rather than the selection process generally represented by the replicator dynamics. Also, unlike Noailly et al. (2007), here agents interact exclusively globally and have full information about the strategies and payoffs of all other agents.

4.3 The Common-Pool Resource Game

Although all common-pool games are not defined exactly in the same way, they share common features. First, the profit function always includes an harvesting function and a related cost function, both depending on the harvesting effort level. Second, as long as the aggregate extraction level increases, harvesting faces decreasing returns since it becomes more and more difficult to exploit the resource efficiently. The decreasing returns can be modeled through a convex increasing cost function, or a concave increasing extraction function. Widely used in the literature, the second formulation is also adopted hereafter.

The common-pool resource game is a tuple $\Gamma = (n, E_i, \pi)$ where $n \geq 2$ is the number of players, $E_i \in \mathbb{R}_+$ is the strategy set common to all players, and π the payoff function. Each player chooses a level of effort (input) $e_i \in E_i$ in order to extract the resource. $E = \sum_{i=1}^{n} e_i$ is the sum of all the individual efforts. The extraction process is represented by a strictly concave and twice differentiable production function $f(E)$ with $f(0) = 0$. Each player receives a part of the total output in proportion of his individual effort. We assume the game to be symmetric, so that the payoff of agent i is given for all $\tilde{e} = (e_1, ..., e_n) \in E_i, i = (1, ..., n)$, by

$$\pi_i(e_i, E) = \frac{e_i}{E} f(E) - ce_i \tag{4.1}$$

where $c > 0$ is the cost of the individual effort, for example the wage rate. The individual payoff depends both on the player's strategy and the aggregate of all strategies chosen. Precisely, individual payoffs decrease when the aggregate effort increases.

The next section defines the concept of evolutionary stability that will be used to determine the outcome of the game.

4.4 Evolutionary Stable Behavior

The main purpose of evolutionary game theory is to describe the outcome resulting from the long run behavior adopted by players. If models of common-pool games rely generally on the replicator dynamics to describe how individuals react to their interacting environment, our analysis is based on the equilibrium concept of *evolutionary stable strategy* (ESS). Here we define the ESS in the case of a finite population, and show that it corresponds to the long run behavior under the imitation-experimentation dynamics.

4.4.1 Imitation Evolutionary Stable Strategy

Smith (1982) defined the concept of an evolutionary stable strategy to characterize the long run equilibrium in evolutionary games. A strategy is said to be evolutionary stable if a population using this strategy cannot be invaded by a small group of mutants using another strategy. In other words, there exists an invasion barrier such that the ESS yields higher payoffs than the other strategies.

Maynard Smith's formal definition holds for pairwise contests where two players are repeatedly chosen at random in an infinite population. But in many economic situations, including the common-pool extraction game, it is more realistic to assume that players take part simultaneously to the game and that the number of players, even large, is limited. Instead of the standard formulation, we will use the definition of Schaffer (1988) adapted for finite populations of agents who compete simultaneously, and call it the *imitation evolutionary stable strategy* (IESS).

Definition 1. *Let* $\Gamma = (n, E_i, \pi)$ *be a symmetric game. The strategy* e^* *is an IESS if,* $\forall\, e \in E_i$, $e \neq e^*$ *and* $i = 2, \ldots, n$,

$$\pi_1(e_1^*, \ldots, e_{i-1}^*, e_i, e_{i+1}^*, \ldots, e_n^*) \geq \pi_1(e_1, e_2^*, \ldots, e_n^*) \tag{4.2}$$

This definition means that in the IESS, a single mutant performs badly compared to the other players. When a resource user tries to deviate from the strategy corresponding to an IESS, he lowers his payoff level. Thus, he has a clear incentive to go back to his previous strategy, which is the guarantee that this strategy is stable under the IESS formulation. Yet, if this strategy is stable once it is reached, does the imitation and experimentation process really lead to the IESS? The next section address this issue, and the answer is clearly yes.

4.4.2 Stochastic Stability

Assume that all players adopt the *imitate the best* behavioral rule, excepted for a few experimenters. For each discrete time period, any individual will imitate, with a probability close to one, the strategy that gave the highest payoff in the previous period among all participants. Hence, the agents need to know the individual strategies played by all the participants in the previous period, as well as the associated payoffs. However, no specific information is required about the payoff function. The knowledge or not of the extraction function has no influence on the outcome of the imitation process.[2]

With a small probability, instead of imitating the others, the player will try a new strategy randomly chosen in the strategy set. This experimentation behavior is fundamental to drive the imitation dynamics toward the IESS, because without experimentation it would be impossible to reach this state if it was not played by anyone at the beginning. Besides, assuming the initial state is symmetric (i.e. all individuals play the same strategy), it would correspond to the long run outcome even if the state is unstable in the sense that a single deviation would be sufficient to leave it. Then, there is absolutely no interest to define an imitating rule without allowing also that some players act differently by experimenting other strategies.

The combination of imitation and experimentation describes a learning process, the imitation-experimentation dynamics. In fact, this process is particularly interesting because it converges toward the IESS, as shown in the next paragraph.

By definition the IESS resists to the appearance of one mutant at a time. If it holds out against any groups of mutants of any size inferior to n, then it is said to be globally stable. Leininger (2006) established that in a strictly submodular aggregative game any IESS is strictly globally stable (theorem 1, corollary 2), thus the IESS cannot be invaded by any number of mutants. Moreover, Alós-Ferrer and Ania (2005) showed that the strictly globally stable IESS corresponds to the unique stochastically stable state of the imitation-experimentation learning process (proposition 4). Thus, since the common-pool resource game fits the definition of submodularity, we know that in the long run every agent will adopt the IESS.

[2]The significance of the rule of imitating the best is supported by experiments of Bigoni (2008) and Offerman and Schotter (2009), where it appears to be a robust description of behavior used in oligopolies and other problems.

4.5 Evolutionary Stability Versus Nash Equilibrium

It is well known that the Nash equilibrium leads to an overutilization of common resources compared with the Pareto-optimal outcome. The next proposition states that the degradation is even worse when individuals adopt the *imitate the best* behavioral rule.

Proposition 1. *In the CPR game, the condition defining the IESS is* $f(E^*)/E^* = c$ *with* $E^* = ne^*$*. As a result, the IESS optimal effort exceeds Nash equilibrium effort. The resource is exploited in the IESS to the point where rents are totally dissipated.*

Proof. The definition of an IESS states that

$$e^* \in arg \max_e [\pi_1(e_1, e_2^*, \ldots, e_n^*) - \pi_1(e_1^*, \ldots, e_{i-1}^*, e_i, e_{i+1}^*, \ldots, e_n^*)],\ i = 2, \ldots, n.$$

If e^* is the candidate strategy for an IESS and e is the mutant strategy,

$$\begin{aligned} &\pi_1(e_1, e_2^*, \ldots, e_n^*) - \pi_1(e_1^*, \ldots, e_{i-1}^*, e_i, e_{i+1}^*, \ldots, e_n^*) \\ &= \frac{e - e^*}{e + (n-1)e^*} f(e + (n-1)e^*) - c(e - e^*) \end{aligned}$$

the first order condition is given by

$$\frac{e + (n-1)e^* - (e - e^*)}{(e + (n-1)e^*)^2} f(e + (n-1)e^*) + \frac{(e - e^*)}{e + (n-1)e^*} f'(e + (n-1)e^*) = c$$

We set $e = e^*$ because we look for a symmetric state where all agents play the same strategy. Then the second term cancels and the IESS condition becomes,

$$\frac{f(E^*)}{E^*} = c \quad \text{with} \quad E^* = ne^* \tag{4.3}$$

Now, we show that IESS effort level is necessarily higher than Nash.

The Nash equilibrium's aggregate effort follows from

$$\sum_{i=1}^{n} \frac{\partial \pi_i(e_1^N, \ldots, e_n^N)}{\partial e^N} = (n-1)\frac{f(E^N)}{E^N} + f'(E^N) - nc = 0 \qquad (4.4)$$

Replacing c by $f(E^*)/E^*$ gives

$$(n-1)\frac{f(E^N)}{E^N} + f'(E^N) = n\frac{f(E^*)}{E^*} \qquad (4.5)$$

$$\text{Then} \quad \frac{f(E^N)}{E^N} > \frac{f(E^*)}{E^*} \quad \text{if} \quad \frac{f(E^N)}{E^N} > f'(E^N)$$

which holds by concavity of f. Therefore, $E^* > E^N$ and $f(E^*) > f(E^N)$, the effort and exploitation levels are higher in the evolutionary equilibrium than in the Nash equilibrium.

□

The IESS competitive outcome results from two negative externalities. The first is the usual Nash externality: an increase in individual effort raises the total effort, which affects negatively the individual payoffs. The second externality, which explains the difference between the IESS and Nash equilibrium, derives from relative maximization behavior. Since an increase in individual effort decreases the payoffs of all others, the player is incited to increase his extraction activity to get a higher payoff than his counterparts. In this case, the imitation rule will force them to push up their effort levels, thereby reducing individual payoffs.[3]

In fact, this process will go on until all opportunities of profit disappear. Since the average revenue $f(E^*)/E^*$ equals the marginal cost c, this condition

[3]Of course, this logic is true when profits are still positive in the industry. In a situation where the exploiters would face losses, the imitation dynamics would drive down their harvesting contributions.

implies profits are equal to zero in the IESS, $\pi_i(e_i^*, E^*) = e_i^*(f(E^*)/E^* - c) = 0$. If $\frac{f(E)}{E} > (<) c$, profits are positive (negative), so reaching the IESS requires the players to increase (decrease) their effort level. At IESS equilibrium, agents increase their efforts until all profits vanished, leading to the situation of complete rent dissipation, like in the *open-access* Nash equilibrium.[4] The main difference with the standard game theoretical analysis is that *perfect* competition takes place even in a situation of limited entry.

Fundamentally, the imitation process described above relies on the fact that someone gets a benefit by reducing the payoffs of others. In biology, the literature has denominated this behavior as *spiteful*, while economists tend to speak about *relative maximization*, opposed to classical maximization where the absolute level of profit is looked for. Yet, if these terms are appealing and are largely used in the related literature, we have avoided to use them here for the following reason. If it is true that an individual increases his payoff at the expense of others when raising his effort level, the imitate-the-best rule stipulate that individuals follow the strategy that yields the highest payoff in the industry. Thus, it means they also optimize the absolute profit level, like in the standard theory. It is the way of maximizing, through imitation rather than computing the optimal strategies that leads to a different outcome, and not the willingness to get more than the others. This is why the term *relative maximization*, though convenient, is nevertheless confusing. In our view, like common resources, this expression is sometimes overused. As for the word *spiteful*, which contains some judgment value, we skipped it for the same reason.

[4]This result is similar to Vega-Redondo's Cournot oligopoly (1997) where the imitation-experimentation dynamics leads to the perfectly competitive outcome.

4.6 Discussion

Although most of evolutionary common-pool resource games focus on the emergence and the stability of cooperation and altruism, we should not forget that competition for scarce resources is also relevant and is not the privilege of non-evolutionary theory. Assuming that agents follow the imitate-the-best behavioral rule in a restricted-access situation, the tragedy of the commons is not only confirmed, but even exacerbated compared with the Nash equilibrium outcome. The logic of imitation helps to understand the existence of *tragedies* characterized by three features: severe resource overuse, limited entry and unprofitability in the long run.

Two negative externalities explain the convergence toward the competitive outcome in the evolutionary game presented in this chapter: 1) the Nash externality that an increase in individual effort and thus total effort reduces the individual payoffs; 2) the relative maximization externality that an increase in individual effort reduces the payoffs of all others, and thus also individual payoffs. The sum of these two negative effects leads to the worst possible outcome, *perfect* competition in the sense that all rents are dissipated. Instead of the standard framework where such outcome is the result of atomistic competition caused by unlimited entry, here the competition is intense whatever the number of resource users involved in exploitation, as previously mentioned.

Usually in economics, the more there is competition, the more efficient is the allocation of resources. Competition guarantees that the social profit is maximized at the benefit of the consumer. If this is true for most of private good markets, the story for common resources is unfortunately different. Even without speaking about the probability of resource destruction, which was not analyzed here since the resource stock is exogenous, the decreasing returns of extraction activities induce overcapitalization by the users. Generally, a high degree of competition is not a good thing, or a bad one, in itself. It depends on what competition is applied. In common-pool resources, perfect competition leads to *pure tragedies*. The logic of the so called relative maximization, which creates overuse beyond Nash, stems from the fact that resource users compare their respective profits and imitate those who obtain the higher yield.

Ostrom (2005b) established a distinction between behavior based on social norms and behavior resulting from neoclassical maximization, the latter being norm-free. According to this logic, any behavior that differs from rational optimization can be considered as a norm. In this sense, competition driven by imitation as described above may also be seen as a behavioral norm, since the outcome deviates from the Standard Nash prediction. However, instead of being social, this so-called norm is anti-social and destructive. Because imitation-based competition is extremely harmful for harvesters' profits, it would be better to prevent them from adopting it. Compared with imitation-based competition, the Nash behavior can be viewed as a second-best outcome. Moving from total rent dissipation to the Nash situation would already represent an improvement before reaching more desirable outcomes.

If we consider situations involving large numbers of resource exploiters, the outcome of competition under standard and imitation behavior is the same: full rent destruction. As mentioned in the previous chapter, the number of participants where resource are exploited by local communities is usually rather large. In such cases, the prediction of evolutionary competition would not differ from standard analysis. Hence, since the evolutionary outcome diverges from Nash as the number of individuals is decreasing, the framework proposed in this chapter is more interesting when small-scale interactions are considered. Situations characterized by small population size can be of various kind. For example, communities can be divided into small sub-groups of exploiters that operates in closed access form at a very localized level. Other situations involve a few companies which claim, legally or de facto, a monopoly on resource exploitation.

Many common resources are still facing severe overexploitation pressures nowadays. In this chapter, we stated that resource overuse can be even worse than expected. However, solutions for coping with problems of overuse exist. As stated in chapter 2, under some circumstances, resource users can develop social norms for overcoming common-pool dilemmas. The presence of social norms has been also highlighted in several experiments. For example, by facilitating communication between resource users, they could be able to agree on conservative harvesting rules (Ostrom and Walker, 1991; Hackett et al., 1994). Sanctioning is also seen as a fundamental mechanism to enforce rules promoting sound resource use (Ostrom et al., 1992; Casari and Plott, 2003; Falk et al., 2005). In this line, the next chapter will examine how cooperative outcomes can be self-enforced through the use of sanctions.

Chapter 5

Cooperating through Sanctioning

Contents

5.1 Introduction

To achieve sustainable use of natural resources, the development of effective institutional arrangements is needed in any management system. Institutional arrangements, as defined in chapter 2, are constituted by both formal rules and informal social norms that shape human behavior. Either they are informal or collectively-decided, operational rules should be designed in a way that leads users to exploit their resources reasonably. A large body of literature on the commons is aimed at identifying the conditions that favor the design of well-functioning institutional arrangements. In particular, the conditions under which local communities are able to develop informal social norms, as well as rules decided at the collective level, have been extensively documented.

Devising an appropriate set of rules and norms is necessary to guide users' behavior toward a more conservative exploitation. However, the development of sound harvesting rules is usually not sufficient in itself to reach sound resource exploitation. Indeed, rules are useless if they are not respected. The problem is that, in a common-pool dilemma, there is always a temptation for breaking the rules in order to increase individual payoffs. Therefore, a mechanism of enforcement is usually needed to guarantee compliance with rules and norms, thereby making institutional arrangements effective.

Generally, the enforcement of harvesting rules is realized through two related activities: monitoring and sanctioning. Monitoring can be defined as the observation of the common-pool environment and the behavior of appropriators. A monitor can be an agent employed by the authority in charge of resource management for this specific purpose. For example, it is usually the case of guards in national parks. In such case, the monitor is accountable to the authority. On the contrary, in community resource management, monitors are not external agents specifically employed for this purpose. Rather, monitoring activities are undertaken by the resource users themselves. As for sanctioning activities, they intervene after violations of operational rules are detected. Sanctions are aimed at forcing violators to start cooperating, thereby increasing compliance with rules. Like monitoring, sanctions can be undertaken by external authorities, or by the participants themselves.

The general pattern of monitoring and sanctioning is the following. When systems of resource management are of top-down nature, these activities are taken up by an authority external to the collectivity of exploiters. On the contrary, when management is more decentralized, local actors may be more likely to engage themselves into self-enforcement activities. Self-enforcement generally happens in community-based management, in co-management initiatives, and also in other situations where self-governance responsibilities are introduced, such as in systems of transferable quota. Recognizing the rights of local people over their resources may favor self-enforcement initiatives over external self-enforcement. Hence, the recent tendency toward decentralization of resource management will probably result in a reinforcement of the role of local sanctioning in the future. The empirical study of Coleman and Steed (2009), covering a large range of community forestries, supports the idea that increasing the rights of local actors lead them to undertake more actions of self-enforcement. Among other factors, they find that, when local community members have rights to harvest within forests, self-enforcement is more likely to occur, while the likelihood of external monitoring is instead negatively affected.

The presence of local monitoring and sanctions has been identified as a major condition to achieve successful community management (Ostrom, 1990; Baland and Platteau, 1996). Many case studies highlight the central role of internal self-enforcement in many natural commons resources. In Thailand, local people undertake self-enforcement in a better way than government agents in mangrove areas, as living and working nearby gives them a comparative advantage (Sudtongkong and Webb, 2008). Local participation in monitoring in Madagascar increased respect for fishing conventions in wetlands (Andrianandrasana et al., 2005). At a worldwide scale, Gibson et al. (2005); Pagdee et al. (2006) demonstrate that monitoring and sanctioning by locals are important factors for successful governance in community forestries. These are only a few examples among many others. Overall, most of field studies regarding local resource management mention the presence of self-enforcement mechanisms.

In community-based management, sanctions can cover a large range of options, from monetary to other kind of non-monetary sanctions. For example, in traditional fishery management in Vietnam, either social or economic sanctions are applied. Economic sanctions consist in the payment of a tax or the seizure of catch, whereas social punishments for rule-breaking can take the form of public criticism or even banishment (Ruddle, 1998).

In many self-enforcement settings, local appropriators are undertaking both monitoring and sanctioning responsibilities. This is quite understandable in terms of cost-effectiveness as these activities are closely related. According to numerous evidence, local actors are indeed often involved in both activities. However, in other cases, they are separated. An example is given by cultivation of oyster in the bassin d'Arcachon in France. To our personal knowledge, oyster farmers have developed self-monitoring activities as a response to the incapacity of the national police to detect thieves who operate at night. Some oyster cultivators, at their own cost, have decided to take their boat to go on observation tours. When an illegal activity is detected, evidence are transmitted to the legal judicial system to bring violators to the courts. In this case, farmers monitor the behavior of each other, but sanctions are externalized through the legal system.

Whatever self-enforcement is realized from both monitoring and sanctioning, or monitoring only, the analytical question is the same. Why would resource users undertake self-enforcement actions at their own individual cost, while the benefits are shared among everyone? The individual incentives that motivate this behavior are not obvious. The interest of every single user would be to let the others sanction while keeping aside, thereby benefiting from increased compliance without participating in enforcement. This problem can be seen as a second-order dilemma that takes place inside the common-pool dilemma. Solving this enforcement dilemma is important, as it can represent a solution to solve the first-order dilemma, that is the problem of resource overuse.

Experimental studies in common-pool dilemmas have also confirmed that cooperation on efficient outcome is possible when sanctions are introduced. When participants are given the opportunity to punish those who overexploit the resource, cooperation is likely to be higher compared with situations where players can free-ride without being sanctioned (Ostrom et al., 1992, 1994; Fehr and Gächter, 2002; Casari and Plott, 2003)).

On the theoretical side, as argued in chapter 3, evolutionary game theory is particularly useful to explain the internalization of social norms by economics agents. Most of applications concerning common resource exploitation are indeed aimed at explaining how harvesters comply with norms through self-monitoring and sanctioning. Sethi and Somanathan (1996) (S&S hereafter) propose an evolutionary model based on continuous time replicator dynamics where harvesters face two primary choices: to cooperate on a low harvest strategy or to defect by overexploiting the resource. Moreover, those who comply also choose whether or not to punish (individually and at their own cost) the defectors. Two extreme equilibria are candidate for stability in their setting, full cooperation or total defection. Boyd et al. (2003) find that, even for large groups of harvesters, enforcement of cooperative behavior is possible under one-time, anonymous interactions. Bischi et al. (2004) show that cooperation is also possible in discrete time dynamics. Noailly et al. (2007) and Noailly et al. (2009) state, respectively in local interactions and a combination of local and global interactions, how the evolution of harvesting behavior leads to cooperation, too. These models have in common the fact that they account for cooperation in the presence of three types of agents: *cooperators*, *defectors*, and *punishers*. Cooperators comply with a restrictive harvesting level (i.e. the social norms), while defectors free-ride by overexploiting. The punishers, as cooperators, comply with the norm, but contrary to the latter, they also perform sanctions against defectors.

However, even if sanctions mostly come from cooperators, defectors also punish in common-pool experiments (Ostrom et al., 1992). Falk et al. (2005) find in a prisoner's dilemma experimentation that some defectors, in a "surprisingly" high proportion, sanction other defectors too. Several justifications may answer these observations. Ostrom et al. (1992) advance the idea that defectors would be resentful of being sanctioned and so they retaliate (this logic is called "blind" revenge). Falk et al. (2005) point out the role of spiteful motivation. Punished individuals would have the desire to increase the payoff difference with the other agents by decreasing their payoffs, even at the expense of their own absolute level of profit. Both explanations, based on emotional factors and malevolent behavior, ignore potential economic incentives that would drive defectors to punish.

In a public good experiment conducted by Masclet et al. (2009) where threats and sanctions improve the level of contribution, some noncooperators do also sanction other defectors. Asked in the questionnaire why they behaved that way, several of them answered that by sanctioning defectors, they forced them to cooperate. As a result, these punishing noncooperators enjoyed the benefits of a higher level of contribution (Villeval, 2010). Thus, the motivation behind noncooperative sanctioning in this case relies clearly on economic incentives, rather than emotional factors.

Even if this aspect has hitherto been largely overlooked in economics, the idea that noncooperators may sanction other ones appeared in the Prisonners' Dilemma game of Sethi (1996). As rational optimizers, noncooperator-punishers can integrate into a stable state in his model. This idea also recently emerged in theoretical biology (Nakamaru and Iwasa, 2006). Eldakar and Wilson (2008) explicitly identify how noncooperator-punishers can coexist with cooperators in a model which emulates an experimental public goods game, and hope to stimulate interest in human and nonhuman species. Engaged in the human part, our objective is to apply the concept of noncooperative punishment in the field of resource economics. However, because we aim to show that some users who overexploit a common resource may contribute to its sustainability, we will depart from the usual terminology by naming them *overexploiters* rather than noncooperators.

To analyze the presence and the role of punishing overexploiters in common-pool resource use, we propose an evolutionary model based on S&S which includes behavioral assumptions made in Eldakar and Wilson (2008). Then, instead of assuming that cooperators punish overexploiters, we assume that overexploiters can sanction other ones (we will simply call them *punishers* hereafter)[1]. The intuition is the following. If sanctions raise the proportion of cooperators, aggregate harvest diminishes and then average product of extraction effort increases. This means that harvesting is less input intensive, thereby increasing the profitability of resource extraction.

As a result, we demonstrate the existence of a stable equilibrium where both cooperators and punishers survive (Propositions 3 and 4). Moreover, since full cooperation cannot be a stable outcome, our main conclusion is that the presence of these particular punishing agents may be useful (and even necessary here) to support cooperation. The analysis is structured as follows. Section 5.2 states the static common-pool resource model, while the population dynamics is studied in section 5.3. The concluding section (5.4) provides a discussion about the potential implication for resource management.

5.2 The static Common-Pool Resource game

Consider a common property situation where a fixed number of players n have an unrestricted access to a pool of resource. Each player i chooses a harvesting effort level e_i in order to extract the resource. $E = \sum_{i=1}^{n} e_i$ is the sum of all individual efforts. We assume the resource stock is exogenously given, therefore the extraction process is represented by a strictly concave and twice differentiable harvesting function $f(E)$ with $f(0) = 0$. Each player receives a part of the total output exactly proportional to his individual effort. Defining

[1] Eldakar and Wilson (2008), following the usual terminology employed in the biological literature (and sometimes also in economics), call the noncooperators who punish *selfish altruists*. In fact, cooperating individuals are often considered as altruists, while those who free-ride are selfish. However, in our view, speaking about altruism is unappropriated. It is misleading because both in most of evolutionary models, individuals only cooperate and punish if it is in their own material interest. In this sense, they always act selfishly, whatever outcomes are cooperative or not. Hence, rather than using the words selfishness and altruism, we will stay with the terms cooperation and defection.

$c > 0$ as the marginal cost of individual harvesting effort and normalizing the price of the resource to one, the individual payoff is

$$\pi_i(e_i, E) = \frac{e_i}{E} f(E) - ce_i \tag{5.1}$$

and hence the aggregate payoff is

$$\Pi(E) = \sum_{i=1}^{n} \pi_i = f(E) - cE \tag{5.2}$$

Maximization of $\Pi(E)$ gives the condition for the aggregate Pareto-efficient level of exploitation. Denote the aggregate Pareto effort level by E_{po} (and e_{po} the individual Pareto effort), optimality implies that

$$f'(E_{po}) = c \tag{5.3}$$

the marginal product equals the cost. Note that in the static model, with fixed costs and a strictly concave harvesting function, agents always prefer to harvest over staying of the field. Besides, it is a well-known result that under the assumption of perfectly rational agents, the Nash equilibrium involves overexploitation of the resource. Even if rents are positive when the number of players is limited, the outcome is inefficient because an increase in individual catch creates a negative externality on harvesting returns of all agents. Formally, we have the individual Nash equilibrium effort $e_N > e_{po}$ and the aggregate Nash effort $E_N = n \cdot e_N$. The average products of effort (i.e. catch-to-effort ratios) are ordered as follows: $f(E_{po})/E_{po} > f(E_N)/E_N > c$.

As S&S, instead of allowing the agents to choose any effort level, we simplify the analysis by supposing agents face only two effort levels, e_l (low) and e_h (high), such that

$$e_N \geq e_h > e_l \geq e_{po} \tag{5.4}$$

The agents are confronted with a coordination problem. It is in the interest of all to adopt a low effort level e_l, close or equal to Pareto-optimality, to maximize resource rents. But each individual has an incentive to free-ride by taking advantage of the intensive harvesting strategy e_h, close to the Nash equilibrium. This strategy individually overperforms the low intensive one, but at the cost of imposing a negative externality on the whole community through the decreasing returns to scale of the harvesting function. Agents who follow the low effort e_l are named *cooperators* and those who choose the intensive e_h are the *noncooperators* (or *overexploiters*).

Our objective is to see whether cooperation on low effort levels may be a long run outcome or not when we consider the following three types of players: *cooperators*, *defectors* and *punishers*. Here, cooperators are simply agents who restrict their harvesting effort to e_l, whereas both defectors and punishers are assumed to be individuals who overexploit by choosing e_h. Besides the choice of effort level, we also set that the overexploiters have the opportunity to inflict sanctions toward others who do not comply. Thus, unlike S&S, where only cooperators can punish the free-riders, here only overexploiters are able to punish. Among overexploiters, those who practice sanctions are called *punishers*, whereas *defectors* do not impose any punishment. Besides, punishers are allowed to sanction all noncooperators, that is to say defectors as well as other punishers (except themselves of course)[2].

The idea that overexploiters punish other agents because they do not cooperate either seems to be cynical. But it makes sense in economic and evolu-

[2]This situation where punishers sanction each other could represent a situation of feud. In a public good experiment, Nikiforakis and Engelmann (2011) showed that when free-riders have the possibility to retaliate, cooperators are discouraged to sanction, thereby decreasing cooperation. On the contrary, because sanctions are performed by noncooperators, it may have a positive effect on cooperation here since the costs related to sanctioning activities are borne by the former.

tionary terms because overexploiters have an incentive to sanction other ones by taking advantage of an increase of the proportion of cooperators in the population. More cooperation indeed reduces aggregate harvest and raises resource rents, which is ultimately to the benefit to the punishers through an increase in the average product of effort $f(E)/E$.

Hence, there are three types of agents: cooperators, defectors and punishers. Denote the respective shares of the whole population by s_1, s_2 and s_3. Since cooperators exert low effort e_l and both defectors and punishers share high effort e_h, aggregate resource extraction is

$$E = s_1 e_l n + (s_2 + s_3) e_h n \tag{5.5}$$

with $E_N \geq E \geq E_{po}$.

Unlike S&S, we do not consider that each punisher (*enforcers* in their article) sanctions each defector exactly once. We make the less stringent assumption that defectors risk the sanction at a probability equal to the share of punishers present in the population. The profit functions are expressed in terms of average (or expected) profits. Let γ be the cost borne by a punisher to sanction defectors and punishers, and σ the level of the sanction, both exogenously given. Rewriting the average product of effort as $A(E) = f(E)/E$, average profits to each strategy type are π_1 for cooperators, π_2 for defectors and π_3 for punishers:

$$\pi_1 = e_l(A(E) - c) \tag{5.6}$$

$$\pi_2 = e_h(A(E) - c) - s_3\sigma \tag{5.7}$$

$$\pi_3 = e_h(A(E) - c) - (s_3 - 1/n)\sigma - (s_2 + s_3 - 1/n)\gamma \tag{5.8}$$

The next section describes the evolution of the shares of strategies in the population, in order to determine which states are potentially stable in the long run.

5.3 Population Dynamics

Let us assume that players adapt their strategies to the payoff differentials via the *replicator dynamics* equation (Taylor and Jonker, 1978). As stated in chapter 3, the logic is that individuals tend to imitate those who perform better than the average. Hence, the share of strategies which yield high payoffs increases at the expense of dominated strategies. Contrarily to the classical assumption of full rationality in standard game theory, the imitation behavior only confers a simple rule of conduct on the agents. They do not have to know the composition of the profit function, that is the harvesting function or the punishment technology. Harvesters will react only on the basis of the difference between their payoff level and the average payoff of the whole population. Then, an implicit assumption is that the agents are able, in some way, to compare their own payoff with the payoffs of others. Defined for each strategy, the replicator gives the following three-dimensional system:

$$\dot{s_i} = s_i(\pi_i - \bar{\pi}), i = 1, 2, 3, \tag{5.9}$$

where $\bar{\pi} = s_1\pi_1 + s_2\pi_2 + s_3\pi_3$ represents the average payoff in the population. For a strategy, the growth rate of the share of the corresponding population is proportional to the payoff difference between this strategy and the average payoff in the whole population. Because the population shares are required to sum to unity, we replace s_3 by $1 - s_1 - s_2$ to transform (5.9) into a two-dimensional system,

$$\begin{cases} \dot{s_1} = s_1(\pi_1 - \bar{\pi}) \\ \dot{s_2} = s_2(\pi_2 - \bar{\pi}) \end{cases} \tag{5.10}$$

with $\bar{\pi} = s_1\pi_1 + s_2\pi_2 + (1 - s_1 - s_2)\pi_3$. Substituting s_3 into the payoff functions gives

$$\pi_1 = e_l(A(E) - c) \tag{5.11}$$

$$\pi_2 = e_h(A(E) - c) - (1 - s_1 - s_2)\sigma \tag{5.12}$$

$$\pi_3 = e_h(A(E) - c) - (1 - s_1 - s_2 - 1/n)\sigma - (1 - s_1 - 1/n)\gamma \tag{5.13}$$

Evolutionary modeling allows us to determine the long run behavior resulting from the population dynamics. The stable equilibrium points of the system reveal which strategies survive under the selection process. More specifically here, we would like to know if the presence of punishers is susceptible to reduce overexploitation of the resource, and if so under which conditions.

Let the vector $S = (s_1, s_2, s_3)$ defines a state of the replicator system. The system is in equilibrium if the shares of the three strategies remain unchanged, that is $\dot{s_i} = 0$. Seven qualitatively different states can be listed. For readability, they are divided into two groups, noncooperative states where $s_1 = 0$ and cooperative states where $s_1 > 0$. The three noncooperative states are $S_D = (0, 1, 0)$, $S_P = (0, 0, 1)$, and $S_{DP} = (0, s_2^*, s_3^*)$, where the subscripts $_D$ and $_P$ assign to the presence of defectors and punishers respectively. The four remaining cooperative states are $S_C = (1, 0, 0)$, $S_{CD} = (s_1^*, s_2^*, 0)$, $S_{CP} = (s_1^*, 0, s_3^*)$, and $S_{CDP} = (s_1^*, s_2^*, s_3^*)$, where the subscript $_C$ denotes the existence of cooperators. Stability of each state is checked in Proposition 2 (for noncooperative states) and Proposition 3 (for cooperative states). The main result, stated in Proposition 3, is that the state composed only of cooperators and punishers may be locally asymptotically stable. All proofs are relegated to the appendix.

Proposition 2. *Stability of **noncooperative** states of system (5.10) and payoff equations (5.11) - (5.13).*

Two states are locally asymptotically stable under conditions:

- The state where only defectors survive, $S_D = (0, 1, 0)$, when $\gamma(n-1) > \sigma$.

- The state composed only of punishers, $S_P = (0, 0, 1)$, if $(e_h - e_l)(A(E) - c) > (\sigma + \gamma)(1 - \frac{1}{n})$ and $\gamma(n-1) < \sigma$.

As for S_{DP}, this state is a nonhyperbolic point. Considering the strict condition $\sigma = (n-1)\gamma$ to equalize defector and punisher's payoffs, stability is unlikely to occur.

If punishments are sufficiently low relative to the cost of sanctioning, that is if the *punishment technology* designed by σ/γ is not efficient enough, the population dynamics converges to defector's hegemony (S_D) where resource exploitation is maximum. To the contrary, with an efficient sanction technology, only punishers survive when the profit gap between cooperators and overexploiters is high enough. This state, S_P, is the worst possible situation since resource extraction is also maximum, and furthermore agents inflict costs to each other through punishment. An equilibrium with coexistence of defectors and punishers cannot be stable. If local stability would be determined with nonlinear techniques, such a state would just be an intermediate situation between the bad (S_D) and the worst (S_P). It is not of further interest here, especially since the strong necessary condition ($\sigma = (n-1)\gamma$) equalizing the punishment technology and the number of players (minus one) has no concrete justification.

We define cooperative states as states where the cooperation level s_1^* is strictly positive. The following proposition checks whether such a state may be stable or not.

Proposition 3. *Stability of **cooperative** states of system (5.10) and payoff equations (5.11) - (5.13).*

The equilibrium formed only with cooperators and punishers, $S_{CP} = (s_1^*, 0, s_3^*)$*, is locally asymptotically stable when* $\frac{\sigma}{\gamma} > n\frac{(e_h - e_l)(A(E)-c)}{(\sigma+\gamma)}$.

The three remaining states $S_C = (1, 0, 0)$*,* $S_{CD} = (s_1^*, s_2^*, 0)$*, and* $S_{CDP} = (s_1^*, s_2^*, s_3^*)$*, are always unstable.*

Regarding the unstable states, we remark that S_{CDP}, where the three types of agents coexist, never constitutes a stable solution. So is S_C, which exclusively contains cooperators, because an overexploiter would overperform cooperators in a state where all agents behave on low extraction level. Then, total conformity to the socially efficient norm is not attainable. For the same reason it is impossible to reach an equilibrium composed of cooperators and defectors (S_{CD}).

Last but not least, the state S_{CP} is candidate for stability. Made up of cooperators and punishers, it is the only possibility to reach partial cooperation. Then, since cooperators cannot survive alone, the presence of punishers is unambiguously a necessary condition for cooperation. Even if they themselves overharvest, they may help to avoid overexploitation of the resource by sanctioning other overexploiters.

The intuition behind this result is that the overharvesters do not get higher payoffs than those who exercise restraint because they are bearing the costs of punishing and being punished. Provided these costs are increasing in their population share, the punishers' payoffs fall to the level of the cooperators once their number climbs high enough. For example, under the stability condition for S_{CP}, if a cooperator tries to become a punisher, the net average returns $(A(E) - c)$ diminishes while the costs related to sanctioning activities rise. Both elements lead to a lowering of punishers' payoffs greater than those of cooperators. Thus, there is an incentive for a punisher to start cooperating, and we go back to the initial equilibrium. The same reasoning holds when a punisher is willing to cooperate. The profit of punishers would increase in a greater measure, thereby leading to a move from cooperation to punishing. The balance between the two strategies is automatically restored.

Because cooperators and punishers earn the same profit level in the state S_{CP}, no one has an incentive to change his behavior regarding these two strategies. But what happens if an individual tries now to defect? In fact, he would lower his payoff. Indeed, punishers can survive in a state without defectors because the former have a slight advantage since a punisher will never sanction himself (see the term $1/n$ in equation 5.13). When this advantage offsets the cost related to sanctioning activities, a defector gets a lower payoff than a punisher or a cooperator. The stability condition for S_{CP} is therefore highly dependent on the number of resource users and, as we admit, may seem non-relevant, especially when the population becomes large. This problem will be overcome further in proposition 4.

Obviously, we can verify that S_{CP} and S_P cannot be simultaneously stable (see appendix, at the end of S_{CP} case). Thus, the presence or not of cooperators next to punishers depends on the range of parameters. One could ask how, from an initial situation where all harvesters are identical (for example all defectors), diversity is likely to emerge, thus leading to a heterogeneous equilibrium. Evolutionary theory is build upon two fundamental concepts, the *selection* (modeled by the replicator equation) and the *mutation* processes. Although it is not explicitly formalized, the mutation principle enables individuals to occasionally experiment new strategies instead of following the imitation rule. Since the state S_{CP} is locally stable when the stability condition is fulfilled, whereas other states are unstable, a single mutation is sufficient to leave any other state and to eventually reach it. No new experimentations, in other words perturbations of the dynamics, can destabilize the equilibrium under these parameter restrictions. Hence, evolutionary theory explains how new behaviors emerge and diffuse among a population from individual interactions, without the need of an external intervention.

Further comments are needed about the stability condition for S_{CP}, that is $\frac{\sigma}{\gamma} > n\frac{(e_h-e_l)(A(E)-c)}{(\sigma+\gamma)}$. Firstly, the harvesting technology $f(E)$ influences stability through the net returns of resource extraction $(A(E)-c)$, hence a more efficient technology may affect negatively the norm's robustness. Secondly, if the price were not normalized, it would simply appear along with $A(E)$. Thus, an increase in the market price may also destabilize this equilibrium. Finally, the sanction level must be sufficiently high regarding to the cost of punishing to ensure stability of S_{CP}. In other words, the punishment technology σ/γ must be efficient enough. Moreover, the dynamics is more likely to move toward total noncooperation when the number of harvesters increases.

The number of appropriators n also influences to a large extent the stability of S_{CP}. An increase in the size of the population of harvesters can affect negatively this equilibrium. For high numbers of exploiters, it is unlikely for the stability condition to be fulfilled. In the light of evidence from the ground, it can constitute a weakness of S_{CP}. Indeed, as mentioned in chapter 3, in many cases of common resource exploitation the number of appropriators is usually quite large, varying from at least few dozens to several thousands of participants. Then, as the population size raises, the punishment technology must become incredibly efficient for S_{CP} to be stable, which may be unrealistic. We show below that this problem can be overcome by assuming that punishers, instead of sanctioning other punishers at the same level as defectors, sanction them less.

Imagine now that punishers only sanction defectors, and no other agents of their kind anymore. Is it possible to obtain a stable state S_{CP} in this case? We would intuitively think that wiping off defectors, and so reaching the S_{CP} equilibrium, will be easier. However, one can show the system would not converge to S_{CP} because if punishers are never sanctioned, they earn more than cooperators and the system moves away from cooperation. In other words, S_{CP} is candidate for stability when punishers sanction all overexploiters, but is unstable when they only punish defectors.

Let us assume now that punishers impose sanctions on others from the same group, but to a lower extent regarding to defectors. Such an assumption makes sense in reality if we think punishers as members of an implicit "coalition" whose priority is to deal with defectors first. Or one could imagine that punishers, because it is less dangerous, are more willing to attack the "pacific" defectors than other "aggressive" punishers. Formally, we introduce a parameter $\lambda \in (0, 1)$ in the defector's average profit function (5.13). With a linear punishment technology, we get the following average payoffs,

$$\pi_1 = e_l(A(E) - c) \tag{5.14}$$

$$\pi_2 = e_h(A(E) - c) - (1 - s_1 - s_2)\sigma \tag{5.15}$$

$$\pi_3 = e_h(A(E) - c) - s_2\gamma - \lambda(1 - s_1 - s_2 - 1/n)(\sigma + \gamma) \tag{5.16}$$

The presence of λ means that punishers sanction defectors with a higher probability than other punishers, or equivalently that sanctions faced by defectors are more severe than those for punishers. The following proposition states the new condition for asymptotic stability of the cooperator-punisher equilibrium.

Proposition 4. *Under system (5.10) and payoff equations (5.14) - (5.16), the state composed of cooperators and punishers* S_{CP} *is locally asymptotically stable under condition* $[(1 - \lambda)(e_h - e_l)(A(E) - c) + \lambda(\sigma + \gamma)/n]\sigma > \lambda(e_h - e_l)(A(E) - c)\gamma$. *For a large population* ($n \to \infty$)*, asymptotic stability is verified if* $(1 - \lambda)\sigma > \lambda\gamma$.

Proposition 4 reveals that when punishers inflict higher sanctions toward defectors than other punishers, the stability condition for S_{CP} is clearly less stringent on n compared to Proposition 3. Moreover, in a situation where many individuals are involved in resource extraction, stability does not rely significantly on n anymore. For example, if average sanctions against defectors are twice as much as for punishers, S_{CP} stability is ensured as long as the punishment σ exceeds the sanctioning cost γ.

Propositions 3 and 4 highlight the role of punishers through the stability of the state formed by cooperators and themselves. By sanctioning noncooperators, they force some of them to adopt a more reasonable harvesting rule. Then, aggregate extraction decreases, thereby raising marginal and average product of effort (because of concavity of the harvesting function). The idea is that punishers act this way if the benefit of increased returns is superior to the cost of sanctioning. As a result, overexploitation is reduced, which is good for resource sustainability.

If the punishing behavior is beneficial for resource conservation, what can be said from a purely economic standpoint? Since we can imagine the costs due to sanctions may counterbalance gains from increased returns, are harvesters really better off regarding a situation characterized by total defection? Globally and individually, the answer is yes. The decreasing returns of the harvesting function imply that average returns are higher when agents are more cooperative. Then, the aggregate profit of the community is increasing in the share of cooperators. And so is the individual profit in the state S_{CP} since at equilibrium everybody gets the same revenue. Thus, whatever the sanctioning level is, the profits of all harvesters are necessarily higher in such state than it would be if everyone defects. Now, we consider the effect of a change in some parameters on the cooperation level in the state S_{CP} defined in proposition 4.

Claim 1. *In the state S_{CP} defined in proposition 4, the cooperation level s_1^* raises when the parameters c,σ,γ or λ increase. The effects of the number of harvesters n on cooperation is undetermined.*

If the marginal extraction cost c raises, net returns and so incentives to free-ride $(e_h - e_l)(A(E) - c)$ diminish, thereby increasing the level of cooperation. The punishment level σ and the cost of sanctioning γ affect negatively punisher's payoffs, then an increase of these parameters fosters cooperation. λ has a similar effect that σ and γ. By raising sanctions inside the group of punishers, a higher λ generates more cooperation. As for the influence of the number of harvesters, an increase of n can either strengthen or weaken cooperation. Although having a relatively small number of appropriators is often considered as a factor that positively influences cooperation, this ambiguous result is not necessarily unrealistic. Several situations of successful exploitation involve a large number of harvesters, whereas some small-scale situations are characterized by severe overextraction (Ostrom 1990).

Of course, reality is much more complex than the behavioral assumptions made in this model. Experiments show that cooperators sanction as well, and usually at a higher level than defectors. Hence, it would have been more realistic to allow cooperators to sanction, like in other evolutionary models. However, because our objective is to identify specifically what are the motivations and the consequences that lie behind sanctioning from overexploiters in a tractable framework, we kept aside cooperative sanctioning.

However, for sake of completeness, let also allow cooperators the right to punish overexploiters. By adding this fourth class of agents called cooperators-punishers on payoffs equations (5.6) - (5.8), we get the new following profits:

$$\pi_1 = e_l(A(E) - c) \tag{5.17}$$

$$\pi_2 = e_h(A(E) - c) - (s_3 + s_4)\sigma \tag{5.18}$$

$$\pi_3 = e_h(A(E) - c) - (s_3 + s_4 - 1/n)\sigma - (s_2 + s_3 - 1/n)\gamma \tag{5.19}$$

$$\pi_4 = e_l(A(E) - c) - (s_2 + s_3)\gamma \tag{5.20}$$

This formulation corresponds to a generalization of S&S's model. Using the same methodology as before, one could show that, under replicator dynamics, stability of the dual state S_{CP} composed of nonpunishing-cooperators and punishing-overexploiters requires exactly the same condition as in Proposition 3 (or Proposition 4 if we assume that punishers sanction themselves to a lower degree than defectors). The intuition behind this result is the following, since cooperators who sanction perform less than those who never punish, they are swept aside from the game. However, if it is obvious that a punishing cooperator would have a lower payoff than a non-punishing cooperator, it remains possible his payoff to be higher than the one of the defector-punishers. The reason is that the latter individuals would be punished by one more person and their payoffs would be lower than they were in the state S_{CP}. Thus, a punishing cooperator could earn more than a punishing overexploiter and even more than the average payoff in the whole population, so their share in the population would increase. Hence, we could think that an intrusion of punishing cooperators may render the state S_{CP} unstable.

In fact, a successful intrusion of punishing cooperators is only possible in the short run, and may not destabilize durably the S_{CP} state. Formally, starting at S_{CP}, the payoff difference between the punishers and the punishing cooperators would be $\pi_3 - \pi_4 = (e_h - e_l)(A(E) - c) - (s_3 + s_4)\sigma + (\sigma + \gamma)/n$. Because the move toward cooperation increases the average returns, the first term would increase if the share s_3 of defector-punishers reduces. As for the second negative term, the share of the punitive agents $s_3 + s_4$ would decrease because some of - and even most of - the defector-punishers who switch to cooperation will not punish anymore. Eventually, the payoffs of defector-punishers would outperform those of cooperators, and since the punishing ones earn less than the other cooperators, we would then go back to the initial state S_{CP}.

5.4 Discussion

Numerous studies have demonstrated that cooperation is likely to occur in social dilemmas, including common-pool situation, when agents have the opportunity to sanction noncooperators. If theoretical models usually assume the punishers are cooperative agents regarding to harvesting effort, laboratory observations show that those who overharvest sanction as well. Whereas Ostrom et al. (1992) explain the sanctions coming from overexploiters by emotional factors such as revenge in a common-pool experiment, Masclet et al. (2009) find that overexploiters also sanction for economic reasons in the closely related public good situation.

Using an evolutionary model, we propose an economic justification to account for situations where punishments are undertaken by overexploiters. Apart from resentment and immoral motives, punishers may also act according to egoistic payoff optimization, even if this behavior may seem hypocritical. By forcing harvesters to cooperate, the punishers allow cooperators to sustain in the population. Hence, challenging the usual negative view about the presence of this type of agents, we showed how they can help reducing resource overexploitation. Our model stated that both cooperation on a norm that limits harvesting, and overexploitation while sanctioning, can be viable at the same time.

In terms of resource management, what are the implications of the fact that free-riders have an economic incentive to sanction? Imagine that an authority in charge of resource management wants to promote local enforcement of harvesting rules. This authority can be an external governmental agency or a collective body representing the interests of the community of exploiters. When crafting the operational rules, the idea is that the authority may deliberately authorize users who accept sanctioning defectors to harvest more than allowed by the norm. *Authorized overexploitation* would compensate the punishers for the costs of sanctioning, thereby providing incentives for individuals to engage in self-enforcement activities.

This solution may be attractive for the authority since enforcement would be undertaken at no cost under such institutional arrangement. In developing countries in particular, external authorities are often reluctant to bear the costs of enforcement. As for the communities of local people, their collective institutions can also face shortages of funds to finance enforcement activities. Thus, allowing higher level of harvest for individuals who participate in enforcement could represent a relatively efficient arrangement, especially in situations where other retributions to undertake sanctions are not sufficient enough.

Besides, the persons in charge of resource management can also act on the level of the sanctions. First, by setting the level of sanctions, they can make sure that defecting is not paying off, thus stabilizing the cooperative outcome. Further, the level of fines implemented by the regulatory body can also affect the degree of cooperation in the partially cooperative equilibrium. That is, the management authority can choose the sanctioning level to influence the aggregate harvest and the rents of resource users.

In fact, the scheme described above can alternatively be viewed as a situation where resource users who undertake sanctions at their own cost would be compensated with a higher share of harvest. On the contrary, those who are not willing to sanction must restrict their harvest to the level defined by the norm, or face the risk of being punished. In this manner, overharvesting by individuals who sanction may be seen as fair and acceptable by the community of harvesters, which can be important to get them involved in sound resource use. An institutional arrangement of this kind, correctly adapted to specific local circumstances, may provide the right incentives to enforce sustainable harvesting rules.

Chapter 6

Private and Common Property Rights

Contents

6.1 Introduction

Since the seminal work of Demsetz (1967) on the economic raison d'être of individual property, private ownership has been seen as a solution to prevent the overexploitation of natural resources. If an individual has a secure right to harvest a delimited amount of a resource, the incentive to rush on the resource at the expense of others is eliminated.

The case of the seas and the oceans is of particular interest. On the contrary to a forest land, a pasture, or another solid ground location, one would hardly imagine that an individual could be allowed to buy a formal title of ownership over a maritime area. However, it is not because formal title given by an authority are totally absent that there is no such things as property rights. In fact, economists and anthropologists have highlighted the existence of territorial rights and other forms of individual possession since the prehistoric times, prior to the existence of any governmental institutions. Biologists also discover that these kinds of rights are shared among many animal species. Using an evolutionary game, Gintis (2007) has recently explained the emergence and sustainability of individual property through the endowment effect, deeply rooted in humans and animals behaviors. Hence, property rights are not originally an external creation stemming from an authority in a top-down manner. They are rather the result of the intrinsic characteristics of individuals who interact with each other in a decentralized way.

The emergence and the sustainability of individual property within human populations have been analyzed in an evolutionary perspective. Private property can be explained as a result of repeated decentralized interactions among individuals over long periods of time (Gintis, 2007; Krier, 2009). However, if these studies expose how a common resource may become a private property, they usually do not consider the institutional arrangements that characterize the management of the resource. In many field studies on natural resources, private property is always defined within a common property structure, which means that the rules governing the usage are crafted at a collective level. Hence, the traditional opposition between common property and private property is misleading. Collective actions taken in a common property regime do not necessarily exclude individual rights. On the contrary, communal property may be a necessary condition to support the implementation of private rights.

On the side of studies based on the principles of evolution, several models have highlighted the sustainability of social norms in common resources (see chapter 3). However, the question of property rights has not been considered for now in this perspective. We attempt to fill this gap by proposing an evolutionary model that combines private property with common property. Our approach tries to account for the sustainability of informal systems of property rights in common property resources.

The logic of our analysis is the following: if the introduction of individual property rights indeed reduces resource overuse and thereby increases resource rents, then there may exist an incentive for local actors to invest and devote some resources in the enforcement of a system of harvesting rights. Our model assumes two types of resource users: 1) those who invest in the enforcement of property rights and then comply with limited harvesting (i.e. cooperators), 2) those who overharvest the resource (i.e. defectors). They will choose between the two strategies according to the payoff difference between them, that is they will tend to imitate the strategy that yields the higher payoff. We show that resource users who devote their endowments to enforce a system of individual harvesting rights may be better off, or at least earn the same payoffs than those who free-ride by exploiting the resource in open-access. Under some conditions, individual property restricts the exploitation of harvesting zones, and thus reduces the resource stock that remains in open-access. In the end, the global level of exploitation can be reduced in the cooperative state. On the contrary, an outcome characterized by defection is also possible, as the noncooperative state can be asymptotically stable as well.

Our approach significantly differs from existing models based on more traditional approaches in economics where the question of private property regimes have been introduced in natural resource settings. Croutzet and

Lasserre (2010) already proposed a game-theoretic model where a benevolent government externally enforce property rights in a common resource. As a result, resource overexploitation can be reduced. However, there are two major differences with our approach. The first is the nature of the interaction between harvesters. They postulate the standard behavioral assumptions whereas we assume that actors tend to imitate the strategies of those who perform well. The second fundamental difference concerns the way property rights are enforced. An external government has the charge to enforce property at his own cost in their model, when the cost of enforcement rely solely on the local actors here. Besides, in their study of the impact of international trade, Copeland and Taylor (2009) link property regimes with renewable common resources. At a global level, in order to check the effect of trade and other parameters, they distinguish between different types of countries for their degree of enforcement of property rights. Property regimes are simply defined as the capacity of governments to enforce better resource use at a country level. In contrast to our approach, their model does not consider the kind of property rights that are designed at the local level.

Before proposing the model, the next section (6.2) discusses the notion of property right in the commons. In particular, it challenges the classical opposition between private and common property rights. The model combining individual and collective property is presented in section 6.3, whereas the result and the stability conditions of the evolutionary equilibria are exposed in section 6.4. The last section (6.5) concludes the discussion.

6.2 Property Rights in the Commons

Because there is a lot of confusion about the definitions and meanings of property rights, we start by making two clarifications.[1] First, we must distinguish the resource system and the flow of resource units. For natural resources, property often refers to the ownership of a parcel of land (for example a forest land, or a fishing area). However, regarding to the use of these resources, the definition of property rights is possibly far more large and complex. Bromley (1991) defines property not as an object such a land, but rather as a right to a benefit stream, which is secure only if all others respect the protection of that stream.[2] Then, individual property does not necessarily imply that the owner possesses the resource system, such as the harvesting territory. According to this definition, property rights could thus apply either to a territory (land, fishing area) or the flow of units generated by it (timber, fish). In the case of fisheries, the systems of Individual Transferable Quotas implemented nowadays by formal authorities give a right over the units withdrawn solely. On the other way, many fisheries where informal rules are enforced by the fishermen themselves provide both examples of territorial-based property rights and individual withdrawal rights (see Durrenberger and Palsson (1987) for a review).

The second clarification is about the confusions surrounding the definition of property rights. The concept of right is closely related to the notion of rule. In chapter 2, we defined rules as prescriptions creating authorizations or placing restrictions on human behavior. Rights can be viewed as the positive side of rules. They are simply actions that are allowed by the rules. Schlager

[1] See Ostrom (2000b) for a thorough discussion and an extensive bibliography about private and common property rights.

[2] "Property is not an object such as land, but rather is a right to a benefit stream that is only as secure as the duty of all others to respect the conditions that protect that stream" (Bromley, 1991, p.247).

and Ostrom (1992) define property as a *bundle of rights*. They identify five attributes which are relevant for common resources: access, withdrawal, management, exclusion, and alienation. The first, *access*, is the right to enter a physical area. The second, *withdrawal*, is the right to catch and appropriate resource units. These two attributes are defined as *operational-level property*. As for the three other attributes, they form the collective-choice property. *Management* is the right to regulate the patterns of use at the operational level. *Exclusion* is a right to determine who have access to the resource. Finally, *alienation* is the right to transfer management and exclusion rights to another individual or group.

In common-property resources, individuals may hold rights which range from one to all of these attributes. In community-based resource management, operational rights of access and withdrawal are usually privatized, while management, exclusion and alienation rights are held at the collective level, as suggested by the term collective-choice property. However, the latter kind of rights are not always in the hands of communities of resource users. They are held by an external authority when the resource is governed by the state, or held privately when there is a sole owner. Even in community-based management, some management responsibilities are undertaken at the individual level. Thus, rather than defining management, exclusion, and alienation as collective-choice property rights, it may be better to refer to governance property rights.

According to the conventional view of economists, private property that do not contain all kinds of rights are considered as incomplete, thereby leading to inefficient outcomes. However, the presumption that private property must involve all attributes to achieve best resource use has been challenged. Larson Daniel and Bruce (1990) showed that giving full property rights to individual actors is not necessarily the optimal solution to promote sound resource use. Hence, it is a priori not clear which type of property is optimal to prevent resource degradation. In fact, the design of an optimal property-rights system depends on particular conditions about the physical attributes of the resource and the social and institutional environment in which actors are evolving.

Hence, private property rights do not only refer to absolute ownership of a resource system, but cover a large range of actions that individuals can take in relation to a system and the flow of the resource units generated by it over time. According to the definition of Bromley and the classification of Schlager and Ostrom, many working rules set up by local communities could be qualified as property rights. Indeed, numerous case studies around the world have shown that resource users have crafted diverse arrangements granting various forms of individual rights. In the next section, we will discuss the notion of "privatization" of the commons. Here, contrary to the authors who define privatization as the introduction of tradable permit systems, privatization is defined as the implementation of "full" (or "complete") private property, in the sense that such property confers the whole range of rights to its holder.

6.2.1 Privatization: a Panacea?

According to the microeconomic classification of goods, the conceptual difference between private goods and common goods is the cost of excluding others. If the cost of exclusion in a common resource goes down, whatever the reason, then it would make the barrier between private and common resources narrower. More precisely, a decrease in exclusion costs would at some point transforms some common resources into private resources. Therefore, if one makes the assumption that the cost of fencing common resources would inexorably decrease over time, for example through continuous technical progress, more and more Commons would gradually become private resources. Assuming that the splitting of Commons into privately-owned resources will happen at a great scale all over the world, the logic conclusion of the extinction of common resources is that there will be no tragedies of the Commons anymore. Under this hypothetical vision, current tragedies of the Commons could be viewed only as a transitional state before all resources are ultimately privatized, which would represent the definitive solution to cope with the problem overuse. Thus, the right answer in terms of policymaking would be to encourage the mutation from common resources to private ones, and to make sure that private rights are properly and effectively enforced, once for all.

Usually, economists tend to consider common property as an ancient, almost archaic, form of property. On the contrary, the emergence of private property, by replacing former communal forms of rights, have been identified as a decisive factor to explain the growth of modern societies. Historically, the emergence of private property as described by Demsetz (1967) seems to confirm the intuition that, through the forces of modernity, common resources are dying away, transformed little by little into private resources. Demsetz explained the advent of private property as an outcome of a bottom-up response to changes in economic and social forces. He used the example of communities of American Indians hunters to determine why a land where all members could hunt fur-bearing animals freely finally turned into private territories. Originally, Indians in Quebec were able to hunt without restriction over the land, which was then subject of the tragedy of the Commons, that is overhunting. However, due to some factors, the price of fur had increased significantly. Since the value generated by the fur increased, the negative externality created by overexploitation pressures had become more costly. Hence, because it was worth the effort to reduce overhunting externalities, the Indians were incited to change the land from common to private hunting territories.

Demsetz pointed out that the increasing value generated by the resource, in other words the resource rent, is the driving force toward private property. Before, we suggested that it is the decreasing cost of exclusion that would represent this driving force. Actually, they are just opposite sides of the same coin. The cost of exclusion can be viewed as the *cost* of switching from a common property regime to private properties, while the level of resource rent represents indirectly the *benefit* of such change. Therefore, the best property system between common and private options depends on a cost-benefit relation. On one side, common property saves the cost of exclusion, but reduces resource rent by inducing overharvesting. On the other side, a private property structure is more costly to implement, but generates higher rents. If we follow the logic of Demsetz, there is a strong tendency toward the privatization of the Commons since natural resources are becoming more and more valuable with the growth of human populations and hence increasing demand for products and services from them. Then, whatever we consider the cost side or the benefit side, there seems to be heavy pressure for the decline of common resources and the generalization of private property.

However, assuming that the costs of implementing private property are indeed decreasing over time, while the value generated by the resources will continuously increase, is it right to predict the end of common property resources? A closely related question is: would it be always desirable for common resources to be turned into privately owned resources?

For natural resources, two major reasons suggest that full privatization is not a panacea to guarantee successful governance. First, if granting individual ownership over a resource system is effective to internalize the appropriation externality, all side effects are not eliminated. The use of a resource, though privately held, can still impose costs on the surrounding environment or the society at large. For example, the way an owner of a forest land uses his parcels can affect the quality of soil for agriculture in the vicinity, the diversity of vegetable species or wildlife, the quality of the air and the climate, the beauty of the landscape, and so forth. If the use of the resource is not constrained or guided in some manner toward the internalization of external costs and benefits, private ownership can also result on improper usage from a collective standpoint.

The second problem of introducing full private property concerns the interests of local, indigenous people. Since property is essentially a right to exclude others, the trend toward privatization of land is logically associated with a reduction in the number of people who can lay claim to the access and use. This is particularly problematic when other individuals depend on the resource for their livelihood. For local indigenous people, being excluded may be dramatic, thereby potentially creating serious conflicts between them and formal owners. The process of formalizing resource ownership in the hands of single owners can destroy the historical arrangements that previously granted access, use, and management rights to local communities.

Empirical examples also challenge the presumption that privatization is always the best solution. Gibson et al. (2002) compared biological data and social phenomena from five forests in Guatemala, two private and three communal. They found that holding forest lands in common can lead to better outcomes than under private property. In these communal forests, communities have crafted institutional arrangements that are more conservative-friendly than the exploitation incentives faced through private ownership. In the United States of America, where the majority of lands are privately held, the federal government tries to internalize the side effect of natural resource exploitation by offering financial incentives (Wiebe and Meinzen-Dick, 1998). However, since this solution requires high capacities of environmental assessment from the government and substantial funding, paying compensations to proprietors to promote environmental conservation is a scheme difficult to implement in developing countries.

6.2.2 Private and Common Property

The management of natural commons should not systematically view the question of property through the usual dichotomy between private and public (Sikor, 2008). Instead of considering it as substitutes, private and common property may be viewed as complements. The usual opposition between private and common property is an overly simplification. In reality, these two kinds of properties are often imbricated in various forms. If, as stated above, property is viewed as a bundle of rights, it becomes clear that ownership can be shared among several different actors. Relations between private and common property are therefore much more complex than a mere opposition.

According to Ostrom and Hess (2010), private property cannot emerge spontaneously from common property institutions. Private rights should be enforced by a set of rules defining who have the rights and which activities are authorized. Thus, the establishment of private property would be conditioned by the existence of a system of enforcement managed at the collective level. In this vision, the existence of common property institutions is a necessary condition for the development of private property. This assertion can be contested by examples showing the emergence of spontaneous forms of individual property, as well as studies highlighting the natural tendency for humans to develop private possession. However, arrangements in which private property is supported by common property institutions are indeed prevalent in common-pool resources.

Systems of individual transferable quota illustrate the possible combination between private and state property. As discussed in chapter 2, an individual quota is a private right over a quantity of harvest. By granting only access and withdrawal rights on the resource, it represents a minimal form of private property. Since the ownership of the resource system remains at governmental level, rights related to the design of the governance structure are not privatized.

However, individual rights of access and withdrawal have not only been introduced in a top-down manner, imposed by governmental authorities. For a long time, common property resources managed by local communities have also granted private rights to their members. Examples of situations where individual rights emerged and sustained at the community-level are abundant. For example, while the south-eastern coasts in Bangladesh have no state-allocated legal ownership of the fishing areas, there is a system of locally enforceable fishing rights within communities (Jentoft et al., 2010). These fishing entitlements, hereditary and transferable, are recognized and accepted by the members of communities, and thereby constitute a real property system even if they are not legally endorsed by public authorities. Numerous case studies show similar patterns of informal harvesting rights crafted by the users themselves. Such community-based resource management is particularly fundamental in developing countries since their formal institutions do not usually possess the capacity to enforce efficient management rules.

The consequence of defining property as a bundle of rights is that, in fact, any kind of individual right can be seen as a private property right. It is the case of harvesting rights taking the form of individual quotas, which are rights over the flow of resource units. As well, individual property can also concern the resource system. For example, communal fisheries where territorial rights are recognized by local fishermen do exist in many parts of the world. Field studies have shown the existence of such informal property in small scale fisheries in Nova Scotia (Davis, 1984), New-Zealand (Levine, 1984), Indonesia and New Guinea (Polunin, 1984), the Solomon Islands (Aswani, 1999, 2005). In Micronesia inshore fisheries, water is even treated the same way as land (Sudo, 1984). The fact that property systems often emerge in an essentially bottom-up manner is probably the very reason why territorial rights on sea zones are encountered mostly in locally managed fisheries, whereas individual rights granted by the government usually take the form of holdings on harvest only.

Local actors have then developed systems of property rights to overcome the problem of overexploitation caused by open access to the resource. By preventing the access to other harvesters, the objective is to promote resource conservation and then to protect resource rents. In terms of resource conservation, the implementation of informal property systems has been a success in coastal fisheries in Brazil (Cordell, 1978), in Nova Scotia (Davis, 1984), or in Latin American shellfisheries (Defeo and Castilla, 2005). On the other side, these systems can be endangered because of change in the external environment. For example, in Bangladesh fisheries the population pressure is creating tensions on indigenous property regimes as it becomes more and more difficult to exclude intruders. By and large, the common view is that customary property systems are in institutional decay due to exogenous political, social, and economic interference. However, this assessment is challenged by Aswani (1999). Because local property regimes have the capacity to evolve endogenously over time, they would be more resilient to changes in external environment than expected.

Interestingly, the inclusion of private and collective rights in a system of property is not only true for natural resource, but also for many other kinds of commons. For example, technology-dependent commons are also governed under mixtures of individual and common property. During the Cold War, the allocation of the frequency spectrum for broadcasting in Europe was established under a mixture of private property within national boundaries and a common property in the international arena (Henrich-Franke, 2011). In fact, even if we do not always realize it, arrangements of rights are present in the everyday life, usually under informal forms. Take the example of a lodging occupied by several persons. Some rooms like the kitchen or the living room may be shared, and ruled, in common. On the contrary, chambers are more likely to be privatized. But even in a private room, one must respect rules designed either explicitly or implicitly at the collective level, such as not making too much noise or other types of rules.

Another question that has been raised by legal scholars is whether informal *de facto* rights devised by local participants are superior or not to *de jure* rights created from outside. Ostrom and Hess (2010) argue that in many cases, resources that were governed effectively by local users under *de facto* common and private property faced disasters when they were converted to *de jure* government property. Satria et al. (2006, pp.228) state that locally devised property rights are likely to perform better than systems enforced by external authorities, because resource users define them in accordance to the specificities of their physical and social environment. The efficient design of a property right system ultimately depends on the particular situations considered. Given the importance of locally designed systems of property, the identification of the characteristics that influence the sustainability of informal arrangements and norms has been the main research area on resource conservation during the last twenty years. In the model presented hereafter, our attention is rather placed on the notion of *de facto* rights since the analysis focus essentially on locally devised systems of resource management.

6.3 A Model of Common Resource with Private Rights

Evolutionary models aimed at explaining the sustainability of private property have already been proposed (Gintis, 2007). Besides, private property regimes have been introduced in natural resource models based on neoclassical design (Croutzet and Lasserre, 2010). However, within common property structures, there is still no model to explain the existence of private property as an outcome of an evolutionary process where enforcement is realized through the contributions of the agents. Here, in line with the nature of community-based management, we attempt to introduce private rights endogenously determined inside an evolutionary game of common property resource.

6.3.1 General Definition

We consider a resource exploited by a community of local actors. The stock level of the resource, K, is defined in the following way. A share (λ) of K is protected by a regime of individual property rights, while the rest $(1-\lambda)$ remains in open access.[3] The protected part of the resource is further divided in two parts. The first part (θ) is harvested by the users under the property regime, whereas the second part $(1-\theta)$ is preserved from exploitation.

Formally, K is then defined by:

$$K = \lambda\theta K + \lambda(1-\theta)K + (1-\lambda)K \tag{6.1}$$

The first term represents the appropriated part of the stock, the second is the preserved stock, while the third represents the share harvested in open access.[4] We postulate λ as an endogenous parameter. The idea is that the share of the resource under the property regime will be the result of the voluntary contributions made by individual resource users.

The share of the protected resource that users can harvest, θ, is assumed to be exogenous. Thus, the decision about the share that can be harvested does not belong to harvesters on an individual basis. Rather, θ is assumed

[3] This formulation is similar to Croutzet and Lasserre (2010), where the resource is also divided into an open access and a protected part. However, a major difference is that these shares, exogenous in their model, will be endogenous hereafter.

[4] We will use the denomination “preserved” to designate the share which is not exploited. The term “protected” will represent both the preserved part of the stock and the share harvested under property rights.

to be set at the collective level by the authority in charge of the resource management.[5]. Field studies have shown that indigenous property rights are often accompanied by limitations on use defined at the collective level.

Hereafter, we define the payoffs of resource users. Assume that each agent has an initial endowment m he can invest in harvesting and resource management. This endowment can be seen as a monetary sum, but not only. Maybe more importantly, especially in poor rural regions, m can be viewed as the working time or effort an individual can put in its daily activities. We assume that a resource user can either put his effort in harvesting only, or participate in resource management. By resource management, we mean that, instead of competing the open access share of resource, the user can devote his money both to harvest under rights and to participate in the preservation of the stock. Then, the agent can spend a portion of his endowment (e_i) to harvest the resource under open access, and the other part (v_i) in the preservation and withdrawal under the property rights regime.

The individual payoff will depend on the selling price of the resource (p), assumed exogenous, the withdrawal rate $h_i(e_i, v_i)$, and the cost of the investment m (normalized to one). The general definition of individual profits is then,

$$\pi_i = ph_i(e_i, v_i) - m \tag{6.2}$$

with $e_i + v_i = m$.

The individual level of exploitation h_i, as well as its structure, depends on the sharing out of the endowment between the protection of the resource (v_i) and the effort devoted to exploit the open access share (e_i). However, h_i is also influenced by the choices taken by the others.

[5] Here, the authority in charge of resource management can be seen as a local institution representing the interests of resource users, rather than an external governmental agency

We assume that the protected share of the resource (λK) is an increasing function of the total effort made by the users to protect it, defined by $V = \sum v_i$. If this aggregate effort increases, more of the resource is protected. As for the share that remains in open access, the harvesting function will face decreasing returns as the global extraction effort increases, as is it always the case in common-pool dilemmas. By normalizing the selling price of the resource to the unity, the individual profit function becomes:

$$\pi_i = \beta(v_i)\lambda(V)\theta K + \psi(e_i, E)(1 - \lambda)K - m \tag{6.3}$$

The first term defines the stock level exploited under protection. $\beta_i(v_i)$ is the individual share of the protected stock which is available to the agent. We assume that β_i increases in v_i and that $\sum \beta_i = 1$. The second term refers to the share extracted in open access. The proportion withdrawn by the harvester, ψ_i, depends positively on the individual effort e_i, but negatively on the aggregate effort $E = \sum e_i$. The individual shares are assumed to sum up to one, $\sum \psi_i(e_i, E) = 1$.[6]

6.3.2 Resource Dynamics

We assume that the natural rate of renewal $G(K)$ is a logistic natural growth function:

$$G(K) = \rho K \left(1 - \frac{K}{\bar{K}}\right) \tag{6.4}$$

with ρ the intrinsic growth rate and $\bar{K}$ the maximum carrying capacity. We see that $G(K) > 0$ when $K < \bar{K}$ and $G(K) < 0$ when $K > \bar{K}$. Also,

[6] The extraction functions β and ψ are defined in the same way as in Croutzet and Lasserre (2010).

$G(K)$ increases in K for low levels of resource stock and decreases for higher levels.

Using a usual formulation, the resource dynamics, which depends on this aggregate harvest level and the natural rate of replenishment, is defined by

$$\dot{K} = G(K) - H(V, K) \tag{6.5}$$

where $H(V, K)$ is the total extraction, that is the amount of resource exploited under both the property regime and under the open access situation. Formally, $H(V, K) = [\lambda(s_c)\theta + (1 - \lambda(s_c))]K$. The resource stock evolves according to:

$$\dot{K} = \rho K(1 - K/\bar{K}) - [\lambda(s_c)\theta + (1 - \lambda(s_c))]K \tag{6.6}$$

6.3.3 Population Dynamics

For simplicity, we consider two types of resource users: 1) the *cooperators*, who devote their entire endowment in the enforcement of property rights and the exploitation of the resource under such a regime. For them, we have $m = v$; 2) the *defectors*, who spend their endowment in the harvesting under the open access regime only, $m = e$.

If we assume that the property is equally divided among cooperators, their average profit level is:

$$\pi_c = \frac{\lambda(s_c)\theta}{ns_c}K - m \tag{6.7}$$

s_c is the proportion of cooperators in the population. Because they uniquely harvest under a regime of property rights, their total effort is $V = ns_c m$. We assume that λ, which can be seen as the technology of protecting rights, is increasing in this effort level. Further, we suppose that $\lambda = 0$

when nobody is protecting the resource ($s_c = 0$), and $\lambda = 1$ when everybody cooperates ($s_c = 1$). Each member of this community receives a share $\beta = 1/ns_c$ of the protected resource. Obviously, this share depends negatively on the number of them, $\beta_{sc} < 0$.

Substituting the share captured by a defector $\psi = 1/n(1 - s_c)$, the profit of a defector is:

$$\pi_d = \frac{1 - \lambda(s_c)}{n(1 - s_c)} K - m \tag{6.8}$$

As in the previous chapter, we assume that players adapt their behavior according to the *replicator dynamics* equation. Individuals are supposed to imitate those who perform better than the average. Defined for the cooperative strategy, the replicator is:

$$\dot{s_c} = s_c(\pi_c - \bar{\pi}) \tag{6.9}$$

with $\bar{\pi} = s_c\pi_c + s_d\pi_d$ the average profit in the total population. The dynamics can be rewritten as:

$$\dot{s_c} = s_c(1 - s_c)(\pi_c - \pi_d) \tag{6.10}$$

Replacing π_c and π_d, we obtain:

$$\dot{s_c} = s_c(1 - s_c)\frac{K}{n}\left[\frac{\lambda(s_c)\theta}{s_c} - \frac{1 - \lambda(s_c)}{1 - s_c}\right] \tag{6.11}$$

This population dynamics combined with the resource dynamics defined previously will give us the evolution of the system. Thus, it is now possible to check the evolutionary stability of steady states in order to determine whether a community of cooperators may survive in the long run. A steady state corresponds to a situation where the number of cooperators - and then also the defectors - do not vary, formally $\dot{s_c} = 0$. We will verify if some of steady states characterized by the presence of cooperators are evolutionary stable. If so, a system of property rights would be sustainable.

6.4 Population and Resource System

The combination of resource dynamics and population dynamics leads to the following system:

$$\begin{cases} \dot{K} = \rho K(1 - K/\bar{K}) - [\lambda(s_c)\theta + (1 - \lambda(s_c))]K \\ \dot{s_c} = s_c(1 - s_c)K[\lambda(s_c)\theta/ns_c - (1 - \lambda(s_c))/n(1 - s_c)] \end{cases} \quad (6.12)$$

Qualitatively, three different types of states can be defined. One state formed only by cooperators, another composed only of defectors, and finally a mixture of both cooperators and defectors. The following proposition establish that the two potential asymptotically stable states are characterized by either full cooperation or total defection. Proofs are relegated in the appendix.

Proposition 5 (Stability of steady states)**.** *Two kinds of states can be asymptotically stable state under the population and resource dynamics: the state in which everyone cooperates, and the state where everyone defects. As for mixed states where cooperators and defectors coexist, trajectories are non-hyperbolic. Hence, no mixed state can be asymptotically stable.*

- The cooperative state, named $\mathbf{S_c}$*, is locally asymptotically stable if* $\theta > \lambda'(1)$.

- The noncooperative state $\mathbf{S_d}$ *is locally asymptotically stable if* $\rho > 1$ *and* $\theta\lambda'(0) < 1$.

Asymptotic stability is theoretically possible for the noncooperative outcome. Essentially, it depends on the intrinsic growth rate of the logistic function ρ. We know that this rate is positive, but do we have any idea of its amplitude? In fact, it is usually assumed to be much lower than the unity for natural resource.[7] Therefore, unless for the case of resources regenerating very rapidly, the $\mathbf{S_d}$ state is very unlikely to be stable. Yet, if we assume nevertheless that this condition is fulfilled, the second one states that θ and $\lambda'(0)$ should be kept at a relatively low level. It means that defecting is better than cooperating because a potential cooperator would only get a relatively slight proportion θ of a relatively low level of protected resource if $\lambda'(0)$ is low.

What happens in states between total defection and pure cooperation is quite complex. This is partly due to the fact that we did not make any specific assumption on the shape of the function λ (unless it is increasing in s_c). However, we know that in the range of intermediate state, no one can be asymptotically stable. If this does not rule out some potential forms of stability, these state are weaker than asymptotically stable ones. Thus, in the long run, the system is more likely to spend time in the latter type of states.

Since our primary interest is to study the conditions that allow individuals to cooperate, the cooperative outcome represents the most interesting case. For $\mathbf{S_c}$, the first condition concerns the relation between the share of the resource that can be harvested under property protection θ and the growth rate of the protection technology $\lambda'(1)$. $\theta > \lambda'(1)$ is the condition for ensuring that cooperation yields higher returns than defection. The fact that $\lambda'(1)$ should be kept relatively low is quite easy to interpret, it means that when deviations toward defection are happening, the protected share of the resource should not decline too much. As well, having a sufficiently high level of θ signifies that harvesters should be allowed to get enough benefits from their property, such that they are incited to cooperate.

Note that the resource stock would be necessarily higher with cooperation

[7] For example, in their numerical simulation Noailly et al. (2007) apply a rate of 0.2 to the intrinsic growth rate of the logistic function.

than under defection, since the share $(1-\theta)$ is preserved from exploitation when harvesters cooperate. The corresponding resource stock at the cooperative equilibrium $\mathbf{S_c}$ is $K^* = \bar{K}(1-\theta/\rho)$, which is decreasing in θ. The authority in charge of resource management might increase the equilibrium resource stock by lowering the share of the resource that can be harvested θ.

Of course, a lower θ would directly reduce cooperators payoffs $\pi_c = \theta K^*/n - m$. However, this negative effect would be at least partially offset by the increase of K^*. The profits could even increase if the condition $\theta > \rho/2$ is respected.[8] The optimal level of θ is ultimately a trade-off between resource conservation and the profits of harvesters.

6.5 Conclusion

Despite the commonly held opposition between private rights and common property, common ownership is often the support of private property in community-based resource management. All around the world, local communities of resource users have set up informal systems of norms to cope with overuse of common property resources. In fact, many of these systems rely on the enforcement of private property rights.

Although many field studies have proved the effectiveness of informal private rights in terms of resource conservation, economic modeling which accounts for the sustainability of property systems is lacking. We tried to fill this gap by setting up an evolutionary framework where resource users have the possibility to invest in the protection of the resource. In contrast to other models where the enforcement of rules is explicitly undertaken at the individual level (see the previous chapter), here resource users are involved in the definition and enforcement of rules at the collective level. While private rights are enforced through voluntary contributions made by individuals, these con-

[8] If we rewrite $\pi_c = \theta\bar{K}(1-\theta/\rho)/n - m$, then $\frac{\partial \pi_c}{\partial \theta} < 0$ when $\theta > \rho/2$.

tributions are channeled via collective institutions. Although the fact that resource users can devote a share of their activities to the functioning of their collective institutions has been overlooked in the theoretical literature, this aspect is nevertheless highly prevalent in community-based management.

Our model shows that, under some conditions, a system of private rights can be stable under the replicator dynamics. By devoting a share of their endowment to enforce a system of property at the collective level, individuals may be able to protect a share of their natural resources. An important condition to make sure the resource is preserved is that the institution in charge of resource management, by setting a share that cannot be exploited, should place a limit on the use of the individual property. This share should not be set to high, because the resource would face depletion, but not to low either, since harvesters would only cooperate if they get enough benefits from their property rights. At the collective level, decision-makers are facing a trade-off. They have to arbitrate between resource conservation and harvesting pressures.

For illustration, the principle of restricting the harvest under an individual property regime is used in the Tonlé Sap, a large lake and river system of primary importance in Cambodia. According to our personal knowledge, communities living in floating villages around the lake have granted territorial rights to their members. Covering fishing activities as well as wood collection in the adjacent forested banks, these individual rights are limited by rules enacted at the community-level. In order to preserve the regeneration capacities of these resources, individuals are only allowed to harvest a limited share of fish stocks and to cut tree-branches of specific sizes.

From a more philosophical standpoint, the idea that a private right of use of a renewable common resource should be restricted is in accordance with the Kantian approach of property rights. Indeed, Breitenbach (2005) determines that Kant's principles of justice are respected in common resources only if private property is restrained by a limit of use. Then, an *universalizable* property regime cannot include full ownership rights. It must inevitably contain management rights at a collective level to mark the boundaries of private rights. This corresponds precisely to our suggestion, which states that the share of the resource preserved from exploitation should be determined and enforced at the collective level.

The recognition of the existence and effectiveness of informal property systems is fundamental in the perspective of management policy. By considering common resources as a norm free environment where all individuals behave as free-riders who overexploit, governments and external agencies have often neglected local institutions. As a consequence, informal systems that were well-suited for resource conservation were sometimes wiped off and replaced with ineffective external control. When locally devised systems of property are working correctly, external authorities motivated by the desire to regulate resource use must be careful not to deter informal arrangements set up by local actors. In cases where informal systems of resource protection are effective, it may be preferable to avoid the potentially negative interferences created by external interventions. However, in cases where local institutions can be improved, the regulator may have a role to play in helping to enhance the capacities of local governance.

Chapter 7

Conclusion

Contents

7.1 Summary

Forty years ago, scientists started to realize the importance of the commons for the livelihood of human populations, and to apprehend the problems caused by exploitation activities. The degradation and depletion of natural renewable resources described by Hardin (1968) happened in many places around the world, and numerous tragedies are still ongoing. The state of world fisheries is still highly concerning. Many marine species are endangered as fishing races continue to deplete fish stocks. In several regions of developing countries, forest lands are also severely degraded due to the high pace of deforestation. The availability of water for human consumption, agriculture, or energy production is a major concern for the decades to come.

However, the tragedy is only one part of the story of the commons. Fortunately, the situation of the commons is not all doom and gloom. In opposition to the dark side characterized by destructive use, the other side is that humans have constantly tried to set up rules and norms in order to exploit their common resources in a sustainable way. Although the institutional arrangements devised by local users for coping with resource overuse can fail to produce the desired outcomes, many case studies have highlighted the ability for local communities to enforce sound harvesting rules (Ostrom, 1990).

Given the successes achieved through systems of local governance, a large number of scholars have proposed a new vision for resource policies. Instead of promoting centralized control of the commons through the supervision of governments and ministries, the idea of involving local users in resource governance has been increasingly advocated. Consequently, the shift of paradigm from top-down to bottom-up approaches of resource management has gain a strong momentum. As stated in chapter 2, many governments have taken initiatives to decentralize resource management during the last twenty years. Even though the devolution of power from governmental agencies to local people is not always effective in reality, the general pattern of modern resource management is constituted by a real tendency toward more decentralization of responsibilities.

Game theory has been widely used to model interactions between resource users. Yet, despite numerous achievements in explaining phenomena related to overexploitation and finding solutions for coping with overuse, several features have not been taken into account by standard game theory. In the traditional framework, economics agents are assumed to maximize their benefits by computing optimal strategies in a "rational" way. Rationality is defined as the ability to handle the knowledge of the structure of interactions and to calculate the best choice given the optimal choices of others. This approach allows the formulation of predictions regarding the behavior of common resource users. However, experiments as well as empirical studies suggest that outcomes often deviate from the usual predictions. Given the shortcomings of the standard framework for dealing with situations where humans do not behave as rational maximizers, it may be desirable to look at an alternative version of game theory to describe how people behave.

Recently, an extension based on the principles of evolution has emerged in the field of economics. In evolutionary game theory, instead of postulating agents gifted with unlimited computing abilities, individuals are assumed to adapt progressively their behavior to the environment. Put it simply, instead of computing their best strategies, humans tend to imitate the choices of others. The relevance of imitation as a fundamental part of human behavior has been extensively highlighted by studies from several disciplines, including economics. In chapter 3, we argued that evolutionary game theory is a well-adapted tool to study interactions that take place in the commons. Generally, the evolutionary theory is suited to deal with situations where interactions take place among large numbers of people and are repeated over long periods of time. These characteristics match the environment of many common property resources, in particular when resource management is undertaken at the community level. Moreover, evolutionary game theory is a powerful tool to explain why, rather than free-riding, resource users can follow social norms and rules of conduct. Determining how individuals cooperate on norms is important given the large number of case studies revealing the existence of informal and formal rules devised at the local level. Identifying the conditions that allow individuals to comply with social norms is one of the major objective of the empirical research conducted during the last twenty years. However, in stark contrast with the huge amount of empirical studies, only a very few theoretical analyzes have accompanied the study of the conditions of cooperation in the commons.

In the line with the recent evolutionary literature on the commons, we proposed three applications of evolutionary games to study the exploitation of natural resources. In the first one (chapter 4), before turning to the study of social norms, we looked at the dark side of the commons. Under the traditional Nash behavior, the prediction is unambiguous, common resources are clearly overexploited. Also, the degree of overexploitation is positively correlated with the number of users. Unfortunately, this pessimistic vision is supported by experimental studies as well as empirical evidence of destructive resource use. But even worse, evidence showed that in some cases the degree of overuse is higher than Nash. In particular, intensive resource exploitation can take place even in situations where the number of participants is rather limited. In chapter 4, we tried to explain why individuals can adopt such destructive behavior. We showed that when individuals adopt a behavioral rule such that they imitate the strategy yielding the highest payoff in the population, they will tend to overexploit the resource at a more intensive level than under the standard Nash outcome. This result suggests that tragedies of the commons can be indeed worse than expected.

In the other applications, we took the opposite direction by looking at the bright side of common resource exploitation. We studied how, instead of being inevitably trapped into the logic of the commons' dilemma, individuals are able to develop rules for coping with problems of overuse. The empirical literature has identified that self-enforcement of norms and rules by monitoring and sanctioning is a crucial condition for successful governance. In chapter 5, the objective was to see whether resource users, by sanctioning violators, can indeed promote cooperation on a norm limiting the harvesting efforts. This problematic is the same as most of evolutionary models of common property resources. However, on the contrary to former models where those who cooperate on the norm can carry out sanctions, in this chapter individuals who overexploit the resource are able to undertake punishments. The existence of such behavior has been highlighted in several experimental studies on common resource extraction, and public good provision as well. Its occurrence has been accompanied with negative judgments characterized by disregard and moral criticism. Counterbalancing this negative view, we showed that by sanctioning while overharvesting, resource users of this kind can encourage cooperation by forcing others to follow the harvesting norm. In terms of resource management, the idea for inciting users to undertake self-enforcement activities is to compensate the cost of monitoring and sanctioning by allowing punishers to harvest more than the level corresponding to the norm.

In chapter 6, we turned our interest on the concept of property. Although this notion may seem very intuitive, defining precisely a property and the rights attached to it represents a challenging task. In natural common resources, several legal scholars have proposed to define property as a bundle of rights. Seeing property as a bundle means that rights can be separated among several actors, and divided at different levels. Thus, ownership of common resources is often characterized by complex arrangements where rights are shared between different actors. As a consequence, some rights can be held a the individual level, while other rights remain at the collective level, or the state level. Interestingly, the possible imbrication of rights at different levels means that common and private property often coexist in resource governance. This statement enters into contradiction with the vision held by many economists, where collective and private property are traditionally opposed.

Many case studies have highlighted the existence of property arrangements in which private rights are held by individuals at the operational level, while collective rights regarding resource management are exercised by communities at the collective level. Put it simply, harvesting rights or territorial rights over the resource system can be individualized. On the contrary, rights concerning the structure of management generally remain at the collective level. In chapter 6, we tried to provide a formal representation introducing individual rights over a common resource. Users can either defect by exploiting the resource under an open access regime for community members, or cooperate by enforcing a system of private rights over the resource stock. We found that it is fundamental to set up limitations to the use of private property. Granting a property right without restricting the use would lead the holder to exploit the resource unwisely from a collective point of view. The authority in charge of resource management, whether it is a collective representation of resource users or an external agency, may have to fix some limitations to individual rights. For example, the decision-maker can control resource use by setting a share of the property that must be preserved from exploitation.

7.2 Beyond the Natural Commons

The analysis of the commons can be extended in further directions. The change in economic conditions faced by the commons, accompanied by the recent and still ongoing evolution of systems of resource governance, is creating new challenges. Resource management needs more and more adaptability and flexibility to respond to external pressures generated by the increase of human populations or the integration of the world markets. As well, internal pressures from members of communities can arise as their expectations can change in response to economic and democratic development. Identifying the conditions that allow resource management to adapt and resist to internal and external pressures may represent a fruitful field for future research. In fact, a number of studies have already started to analyze the adaptability of some systems of resource governance in the recent years.

Yet, we would like to end our discussion by suggesting another path to analyze the problem of the commons. Beyond the field of natural resources, other kinds of resources share the characteristics of common property. Among them, resources related to the use of Internet may constitute a promising way for extending the scope of studies on the commons. Although the Internet relies on both private goods and public goods, the spectacular raise of the worldwide web during the last fifteen years has been accompanied with an increasing development of resources shared in common. The key common resource is the *bandwidth*, which can be defined as the volume of information per unit time computers can handle (Kollock and Smith, 1996). Other common resources related to the Internet are shared storage, platforms of discussion, and so on. At a global scale, the Internet can be seen as a common-pool resource in cases of cyber riots (Axelrod, 2010). Cyber attacks, by blocking access to websites and applications, reduce the availability of Internet services to everyone. In this view, online services are subtractable, which is a characteristic of common goods. Beyond the special case of cyber attacks, Internet security, as a shared resource, is affected by the tragedy of the commons. Users carrying virus and worms on their computers inflict cost on other users. Their inaction to patch their system cause their computers to consume more Internet resources, thereby causing further deterioration of the network (Rose and Gordon, 2011).

Even if physical means are largely rented by service providers, the Internet commons have a tendency to be put under pressure for the same reason why open pastures are overexploited. Web users have a priori no incentives to restrict their usage of a shared bandwidth or a storage capacity. Doing so would essentially encourage the others to exploit the resources left free. According to the type of common resource, free-riding on the Internet can take different forms. Rule-breakers can use the bandwidth unwisely, being off-topic on platforms of communication, or being disrespectful of decorum, and so forth.

The issues and features underlying the management of natural resources are also significantly valid for the digital commons. Since the early developments of the worldwide web, rules and institutions have been developed by users on a global and local level. As communities of users tend to oppose strong resistance to outside pressures encouraging external regulation, community-based management is particularly developed. Hence, the structures of governance of the Internet commons are fundamentally decentralized.

The patterns of community-management of the virtual commons are quite similar to those of natural resources. Individuals have developed social norms and rules for coping with overuse and misuse. Interestingly, it has been observed that cooperation on norms is possible in small communities, as well as in larger ones (Kollock and Smith, 1996). Like for self-enforcement of natural resources, monitoring and sanctioning activities are also undertaken by web users. Monitoring is often considered as relatively simple to accomplish. However, the range of sanctions is different for the Internet commons than in physical interactions. Imposing monetary fines, or using the threat of physical violence is usually hardly possible. Rather, sanctioning takes the form of banishment of the community, by blocking the access of the resource, or social sanctions by indicating that a behavior is undesirable.

Despite the strong similarities shared by natural and virtual commons, Internet resources have nevertheless specific attributes. In addition to the characteristics defining common-pool resources, that is excludability and substractability, technological factors are important to define the structure and the nature of interactions. The ability to transform a resource system and to increase its capacity is much higher for human-made resources than for the natural commons. Beyond the role of informal and formal norms and rules, the impact of changes in information and telecommunication technologies, phenomena of joint use in production, and other features need to be taken into account in the analysis of institutional solutions for promoting more efficient use (Hofmokl, 2009).

As well as for the natural commons, evolutionary game theory may represent a suitable tool to study the Internet commons. As recalled above, we stated that evolutionary games are particularly well-adapted for modeling situations where resources are used by large communities of people and interactions are repeated many times. This is the case for an important class of Internet commons. Because of the huge and quickly increasing number of Internet users, many digital commons are indeed shared among numerous users. For example, bandwidths are often used by many thousands of people at the same time. The functioning of peer-to-peer platforms, used on a constant basis by millions of individuals to exchange files, is interesting. Such systems can only work if users allow others to copy their files and to exploit their own personal bandwidth. The problem is that participants have little incentives to share their files and allow other to use their bandwidth. The temptation of free-riding is important. By downloading files without considering the balance with sending capacities, individuals tend to be net creditors, rather than contributors. As a result, the demand can be much higher than the supply, hampering the speed of the system. Yet, despite this major problem, it is also striking to see how communities of web users successfully manage to provide files or information for free. Although providing freely some contents can be an illegal activity, it is often an act funded on nothing else than a willingness to contribute. The evolutionary framework may represent a useful tool for analyzing the existence of such kind of norms.

The Internet commons create new challenges and opportunities, not only for the community of users, but also for the community of scholars. The complexities and differences of the virtual commons can stimulate the finding of new solutions for coping with overuse and misuse problems. In particular, it may be interesting to check whether solutions that are used to govern natural commons can be applied as well to cope with the problems related to the virtual commons. Conversely, it may be useful to see if the institutional arrangements set up for dealing with the Internet commons can bring some insight for the governance of natural resources.

Finally, we conclude with the following statement. The analysis of the commons have greatly evolved during the last decades, and this momentum is likely to continue in the future. Scholars from different disciplines are actively participating to the development of the field. In several respects, we are indebted to the work of legal scholars who developed the concepts of norms, rules, institutional arrangements, or property rights. All these notions were essential here to study how people use of the commons. Besides, in our opinion, evolutionary game theory will have, along with the conventional approach, a significant role to play in the future developments of common resource economics. Human behavior is multi-faceted. Individuals are neither rational maximizers only, nor purely imitators. Disposing of several choices to describe how humans behave is therefore a richness that should be exploited without restrictions.

Appendix A

Appendix

A.1 Appendix Chapter 5

A.1.1 Proof of Propositions 2 and 3.

The two-dimensional system (5.10) is in equilibrium when the shares of the different strategies do not change, formally $\dot{s_1}$ and $\dot{s_2}$ must equal zero. Let us rewrite (5.10) with the payoff functions (5.11) - (5.13),

$$\begin{cases} \dot{s_1} = s_1[-(1-s_1)(e_h - e_l)(A(E)-c) + (1-s_1-s_2)(1-s_1-1/n)(\sigma+\gamma)] \\ \dot{s_2} = s_2[s_1(e_h - e_l)(A(E)-c) + (1-s_1-s_2)[\gamma - (s_1+1/n)(\sigma+\gamma)]] \end{cases} \tag{A.1}$$

This system, consisting of autonomous differential equations, is nonlinear. However, stability of steady states can be checked by linearizing around the steady states. Hence, we apply the Jacobian analysis to determine the possible stable equilibria (see for example Brock and Malliaris (1989)).

$$J = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} = \begin{pmatrix} \frac{\partial \dot{s_1}}{\partial s_1} & \frac{\partial \dot{s_1}}{\partial s_2} \\ \frac{\partial \dot{s_2}}{\partial s_1} & \frac{\partial \dot{s_2}}{\partial s_2} \end{pmatrix} \tag{A.2}$$

where

$$\begin{aligned} J_{11} &= -(e_h - e_l)[(1-2s_1)(A-c) + s_1(1-s_1)A_E E_{s_1}] + \\ &\quad [(1-2s_1-s_2)(1-s_1-1/n) - s_1(1-s_1-s_2)](\sigma+\gamma) \\ J_{12} &= -s_1(1-s_1-1/n)(\sigma+\gamma) \\ J_{21} &= s_2[(e_h-e_l)(A-c+s_1 A_E E_{s_1}) - \gamma - (1-2s_1-s_2-1/n)(\sigma+\gamma)] \\ J_{22} &= s_1(e_h-e_l)(A-c) + (1-s_1-2s_2)[\gamma - (s_1+1/n)(\sigma+\gamma)] \end{aligned}$$

with $A = A(E)$, and $A_E E_{s_1} = n(e_h - e_l)\frac{f(E)-Ef_E(E)}{E^2} > 0$ by concavity of $f(E)$. The positive sign describes the obvious fact that average returns increase when the proportion of cooperators rises, and conversely.

In a steady state, all remaining strategies must yield the same payoff, which is equivalent to the average payoff $\bar{\pi}$. All steady states possibilities (in qualitative terms) and their stability are listed below:

- $\mathbf{S_C} = (1,0,0)$. For the state composed only of cooperators, the elements of J are:

$$\begin{aligned} J_{11} &= (e_h-e_l)(A-c) + \frac{\sigma+\gamma}{n} > 0 \\ J_{12} &= \frac{\sigma+\gamma}{n} \\ J_{21} &= 0 \\ J_{22} &= (e_h-e_l)(A-c) > 0 \end{aligned}$$

J_{11} and J_{22} are positive, so S_C is always unstable.

- $\mathbf{S_D} = (0, 1, 0)$. For defectors, J becomes:

$$\begin{aligned} J_{11} &= -(e_h - e_l)(A - c) < 0 \\ J_{12} &= 0 \\ J_{21} &= (e_h - e_l)(A - c) + \frac{\sigma + \gamma}{n} - \gamma \\ J_{22} &= \frac{\sigma + \gamma}{n} - \gamma \end{aligned}$$

$J_{22} < 0$ if $\gamma(n-1) > \sigma$. This condition is necessary and sufficient for $\det(J) > 0$ and $\mathrm{tr}(J) < 0$. Then, S_D is locally asymptotically stable when $\gamma(n-1) > \sigma$.

- $\mathbf{S_P} = (0, 0, 1)$. For punishers only, J is:

$$\begin{aligned} J_{11} &= -(e_h - e_l)(A - c) + (1 - 1/n)(\sigma + \gamma) \\ J_{12} &= 0 \\ J_{21} &= 0 \\ J_{22} &= \gamma - \frac{\sigma + \gamma}{n} \end{aligned}$$

$(e_h - e_l)(A - c) > (1 - 1/n)(\sigma + \gamma)$ and $\gamma(n-1) < \sigma$ are necessary and sufficient conditions for asymptotic stability.

- $\mathbf{S_{CD}} = (s_1^*, s_2^*, 0)$. Obviously, a state composed only of cooperators and defectors cannot be a stable state, since without punishment defectors perform better than cooperators. Formally, the steady state condition $\pi_1 = \pi_2$ would imply $e_h(A-c) = e_l(A-c)$, which is rejected by definition.

- $\mathbf{S_{CP}} = (s_1^*, 0, s_3^*)$. Setting $s_2 = 0$ and $(e_h - e_l)(A-c) = (1 - s_1 - 1/n)(\sigma + \gamma)$ (for $\pi_1 = \pi_3$), the elements of the Jacobian are

$$
\begin{aligned}
J_{11} &= -s_1(1-s_1)(\sigma+\gamma+(e_h-e_l)A_E E_{s_1}) < 0 \\
J_{12} &= -s_1(1-s_1-1/n)(\sigma+\gamma) \\
J_{21} &= 0 \\
J_{22} &= (1-s_1-1/n)\gamma-\sigma/n
\end{aligned}
$$

J_{11} is always negative, whereas $J_{22} < 0$ if $\sigma > (ns_3 - 1)\gamma$ with $s_3 = 1 - s_1$. Eliminating s_3, this condition can be rewritten as $\frac{\sigma}{\gamma} > n\frac{(e_h-e_l)(A(E)-c)}{(\sigma+\gamma)}$, and is sufficient for global asymptotic stability of S_{CP}.

Of course, S_P and S_{CP} cannot be stable at the same time. We verify this because average returns $A(E)$ evaluated at S_{CP} are higher than $A(E)$ in S_P, hence conditions $(e_h - e_l)(A - c) = (1 - s_1 - 1/n)(\sigma + \gamma)$ for S_{CP} and $(e_h - e_l)(A - c) > (1 - 1/n)(\sigma + \gamma)$ for S_P cannot be fulfilled simultaneously. Indeed, it would require $s_1 < 0$ for $(1 - s_1 - 1/n)(\sigma + \gamma) > (1 - 1/n)(\sigma + \gamma)$ to hold.

- $\mathbf{S_{DP}} = (0, s_2^*, s_3^*)$. With the condition $\sigma = (n - 1)\gamma$ for $\pi_2 = \pi_3$, the elements of the Jacobian are

$$
\begin{aligned}
J_{11} &= -(e_h-e_l)(A-c)+(1-s_2)(n-1)\gamma \\
J_{12} &= 0 \\
J_{21} &= s_2[(e_h-e_l)(A-c)-(1-s_2)n\gamma] \\
J_{22} &= 0
\end{aligned}
$$

$J_{11} < 0$ if $(e_h - e_l)(A - c) > s_3(n - 1)\gamma$. $J_{22} = 0$ means that we obtain a nonhyperbolic equilibrium in this case. Consequently, linearization cannot help us to ascertain stability. One must use techniques of nonlinear analysis to check whether the equilibrium is locally stable or not. Stability would require the coincidence that the punishment technology σ/γ exactly equals $n-1$.

- $\mathbf{S_{CDP}} = (s_1^*, s_2^*, s_3^*)$. This steady state requires $\bar{\pi} = \pi_1 = \pi_2 = \pi_3$, which implies $\sigma = \gamma(n(1-s_1)-1)$ and $(e_h - e_l)(A-c) = (1-s_1-s_2)\sigma$. Then, the elements of the Jacobian are now

$$
\begin{aligned}
J_{11} &= -s_1[(1-s_1-s_2)\gamma + (1-s_1)(\sigma + A_E E_{s_1})] < 0 \\
J_{12} &= -s_1 n(1-s_1)(1-s_1-1/n)\gamma < 0 \\
J_{21} &= s_1 s_2(\sigma + A_E E_{s_1}) - (1-s_1-s_2)\gamma \\
J_{22} &= s_1 s_2 \sigma > 0
\end{aligned}
$$

$\mathrm{tr}(J) = -s_1(1-s_1)[(1-s_1-s_2-s_3)n\gamma + A_E E_{s_1}] < 0$. However, after some calculation we find $\det(J) = -s_1(1-s_1)[(1-s_1-s_2)n\gamma + A_E E_{s_1}] < 0$. Thus, the state is unstable. All three types of agents never coexist in the long run. □

A.1.2 Proof of Proposition 4.

Under payoff function (5.14) - (5.16), the system (5.10) becomes

$$
\begin{cases}
\dot{s_1} = s_1[-(1-s_1)(e_h - e_l)(A(E) - c) \\
+(1-s_1-s_2)(\sigma+\gamma)(s_2 + \lambda(1-s_1-s_2-1/n))] \\
\dot{s_2} = s_2[s_1(e_h - e_l)(A(E) - c) - (1-s_1-s_2)\gamma \\
+(1-s_1-s_2)(\sigma+\gamma)(s_2 + \lambda(1-s_1-s_2-1/n))]
\end{cases}
\tag{A.3}
$$

Evaluated at $\mathbf{S_{CP}} = (s_1^*, 0, s_3^*)$, the elements of the Jacobian are:

$$
\begin{aligned}
J_{11} &= -s_1(1-s_1)[(e_h - e_l)A_E E_{s_1} + \lambda(\sigma+\gamma)] < 0 \\
J_{12} &= s_1(\sigma+\gamma)[(1-2\lambda)(1-s_1) + \lambda/n] \\
J_{21} &= 0 \\
J_{22} &= -(1-s_1)\sigma + \lambda(\sigma+\gamma)(1-s_1-1/n)
\end{aligned}
$$

$\det(J) > 0$ and $\mathrm{tr}(J) < 0$ if $J_{22} < 0$, which is the case when $[(1-\lambda)s_3 + \lambda/n]\sigma > \lambda(s_3 - 1/n)\gamma$. Substituting s_3 gives the stability condition $[(1-\lambda)(e_h - e_l)(A(E)-c) + \lambda(\sigma+\gamma)/n]\sigma > \lambda(e_h - e_l)(A(E)-c)\gamma$. When the number of agents tends to infinity, it reduces to $(1-\lambda)\sigma > \lambda\gamma$. □

Proof of Claim 1 The implicit function theorem is used to perform comparative statics. The effects of changes in parameters (respectively c,σ,γ, λ and n) on s_1^* are determined by the signs of derivatives:

$$\frac{\partial s_1^*}{\partial c} = -\frac{\partial \dot{s}_1/\partial c}{\partial \dot{s}_1/\partial s_1^*} = \frac{e_h - e_l}{(e_h - e_l)A_E E_{s_1} + \lambda(\sigma+\gamma)} > 0 \tag{A.4}$$

$$\frac{\partial s_1^*}{\partial \sigma} = \frac{(1 - s_1 - 1/n)\lambda}{(e_h - e_l)A_E E_{s_1} + \lambda(\sigma+\gamma)} > 0 \tag{A.5}$$

$$\frac{\partial s_1^*}{\partial \gamma} = \frac{\partial s_1^*}{\partial \sigma} > 0 \tag{A.6}$$

$$\frac{\partial s_1^*}{\partial \lambda} = \frac{(1 - s_1 - 1/n)(\sigma+\gamma)}{(e_h - e_l)A_E E_{s_1} + \lambda(\sigma+\gamma)} > 0 \tag{A.7}$$

$$\frac{\partial s_1^*}{\partial n} = \frac{(e_h - e_l)A_E E_n - \lambda(\sigma+\gamma)/n^2}{(e_h - e_l)A_E E_{s_1} + \lambda(\sigma+\gamma)} \lesseqgtr 0 \tag{A.8}$$

□

A.2 Appendix Chapter 6

A.2.1 Proof of Proposition 5

The methodology is similar than that of chapter 5. A steady state will be stable under the condition $\mathrm{tr}(J) > 0$ and $\det(J) < 0$.

$$J = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} = \begin{pmatrix} \frac{\partial \dot{K}}{\partial K} & \frac{\partial \dot{K}}{\partial s_c} \\ \frac{\partial \dot{s}_c}{\partial K} & \frac{\partial \dot{s}_c}{\partial s_c} \end{pmatrix} \tag{A.9}$$

with

$$
\begin{aligned}
J_{11} &= \rho(1-2K/\bar{K}) - 1 + (1-\theta)\lambda(s_c) \\
J_{12} &= K(1-\theta)\lambda'(s_c) > 0 \\
J_{21} &= s_c(1-s_c)\frac{1}{n}\left[\frac{\lambda(s_c)\theta}{s_c} - \frac{1-\lambda(s_c)}{1-s_c}\right] \\
J_{22} &= (1-2s_c)\frac{K}{n}\left[\frac{\lambda(s_c)\theta}{s_c} - \frac{1-\lambda(s_c)}{1-s_c}\right] + \\
&\quad s_c(1-s_c)\frac{K}{n}\left[\theta\frac{\lambda'(s_c)s_c - \lambda(s_c)}{s_c^2} + \frac{\lambda'(s_c)(1-s_c) - (1-\lambda(s_c))}{(1-s_c)^2}\right]
\end{aligned}
$$

- Mixted equilibrium. $\mathbf{S_{cd}} = (s_c^*, s_d^*)$. The steady state condition $\dot{s_c} = 0$ involves $\pi_c = \pi_d$, hence $\frac{\lambda(s_c)\theta}{s_c} - \frac{1-\lambda(s_c)}{1-s_c} = 0$ and $\lambda(s_c) = \frac{s_c}{s_c+\theta(1-s_c)}$. The reevaluated elements of the Jacobian are now:

$$
\begin{aligned}
J_{11} &= \rho(1-2K/\bar{K}) - 1 + (1-\theta)\lambda(s_c) \\
J_{12} &= K(1-\theta)\lambda'(s_c) > 0 \\
J_{21} &= 0 \\
J_{22} &= 0
\end{aligned}
$$

By substituting $\lambda(s_c) = \frac{s_c}{s_c+\theta(1-s_c)}$ and $\lambda'(s_c) = \frac{\theta}{[s_c+\theta(1-s_c)]^2}$, we find that $J_{22} = 0$. This result means that trajectories inside the s_c interval $(0,1)$ are non-hyperbolic. Therefore, no fixed point can be candidate for asymptotic stability.

- Equilibrium formed uniquely of cooperators. $\mathbf{S_c} = (s_c = 1, s_d = 0)$. The elements of the Jacobian are:

$$
\begin{aligned}
J_{11} &= \rho(1 - 2K/\bar{K}) - \theta < 0 \\
J_{12} &= K(1-\theta)\lambda'(s_c) > 0 \\
J_{21} &= 0 \\
J_{22} &= -\frac{K}{n}\left[\theta - \frac{1-\lambda(s_c)}{1-s_c}\right]
\end{aligned}
$$

J_{11} is negative according to the following calculation. From equation 6.6 defining the resource dynamics, we can determine the level of resource stock at the cooperative equilibrium. For $s_c = 1$, $K = (1 - \theta/\rho)\bar{K}$. Substituting in J_{11}, we find that $J_{11} = -\rho$, which is negative since the intrinsic growth rate of the logistic function ρ is positive.

As for the sign of J_{22}, it is not obvious since both $(1 - \lambda(s_c))$ and $(1 - s_c)$ tend to zero when s_c approaches the unity. Using L'Hôpital's rule we get:

$$
\lim_{s_c \to 1} \frac{1-\lambda(s_c)}{1-s_c} = \lim_{s_c \to 1} \lambda'(s_c)
$$

Hence, $J_{22} = K/n(\lambda'(s_c) - \theta)$. J_{22} is negative if $\theta > \lambda'(1)$.

The cooperative state is asymptotically stable when $\theta > G'(K)$ and $\theta > \lambda'(1)$.

- Equilibrium composed of defectors. $\mathbf{S_d} = (s_c = 0, s_d = 1)$. the Jacobian is:

$$
\begin{aligned}
J_{11} &= \rho(1 - 2K/\bar{K}) - 1 \\
J_{12} &= K(1-\theta)\lambda'(s_c) \\
J_{21} &= 0 \\
J_{22} &= \frac{K}{n}\left[\theta\frac{\lambda(s_c)}{s_c} - 1\right]
\end{aligned}
$$

The sign of J_{11} can be determined by using equation 6.6. For $s_c = 0$, $K = \bar{K}(\rho - 1)/\rho$. Replacing in J_{11} gives $J_{11} = 1 - \rho$.

Concerning J_{22}, l'Hôpital's rule gives us:

$$\lim_{s_c \to 0} \frac{\lambda(s_c)}{s_c} = \lim_{s_c \to 0} \lambda'(s_c)$$

This time $J_{22} = K/n(\theta\lambda'(0) - 1)$. It is negative when $\theta\lambda'(0) < 1$.

The noncooperative state is asymptotically stable if $G'(K) < 1$ and $\theta\lambda'(0) < 1$. □

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