Agent-Based Modeling as a tool for policy making towards common-pool resources: palm heart harvesting and traditional communities in Brazil

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ABSTRACT

Public environmental policies aiming at protecting endangered and shared natural resources are frequently imposed by governments on indigenous people. Based on traditional economic theory, they usually forbid the appropriation of resources from the natural environment. In the Brazilian Atlantic Forest, one of the world’s biodiversity hotspots, the prohibition imposed on the extraction of palm tree *Euterpe edulis* Mart. has resulted in a decrease in indigenous people’s household income and has not effectively preserved this keystone species, which is close to extinction in many areas. This scenario offers an opportunity to use computational simulations to test different institutional scenarios that could help tackling social and ecological issues simultaneously. By examining varied rules and anticipating outcomes before decisions are taken, computational models can help to optimize policy interventions.

In this paper we will show the outcome of two agent based models that aim at comparing the performance of two distinct policy scenarios to control palm heart harvesting. One represents the current situation and is based on central control by the government. Community members that violate the rules are subject to punishment and can be fined. The second model is decentralized and based on community control. The community sets out the rules and is responsible for supervising its members. In this model, a rule is proposed to reward or to punish the agents according to their actions (cooperate or defect). By varying the parameters, we tested if the decentralized model is more efficient to secure a sustainable harvesting of *E. edulis* from the forest. It will be shown how simulations can help to design and select public policies that both empower local communities and preserve endangered species.

KEY-WORDS: *agent based modeling, non-timber forest products, Atlantic Forest, Brazil, Euterpe edulis*

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1. INTRODUCTION

Ever since the publication of Hardin's seminal paper (1968) there has been a growing debate on the use and management of common pool resources (CPRs), property rights and institutional arrangements (Berkes 1989; Dietz *et al.* 2003; Ostrom *et al.* 2002). Several case studies have shown that resources held under common property regimes are not necessarily destined to over exploitation, and that privatization or state control and management are not the only solutions available (Baird 2013; Ito 2012; Dietz et al. 2003; Moreno-Sánchez and Maldonado 2010). Decentralized collective management of common pool resources has been suggested to effectively avoid the "Tragedy of the Commons" and, as a result, in many developing countries there has been a shift in natural resource management policies from centralized government management to local user groups (Agrawal and Ostrom 2001; Berkes 1989; Ostrom *et al.* 2002).

Local management of CPRs frequently involves non-timber forest products (NTFPs) (Mutenje et al. 2011; van den Berg et al. 2007, Yang e t al. 2009) and much attention has been given to their role in contributing to forest conservation and rural livelihoods (Hiremath 2004; Setty *et al.* 2008; Pattanayak and Sills 2001; van den Berg *et al.* 2013), although NTFP commercialization not always delivers the expected benefits (Arnold and Ruiz Pérez 2001; Belcher and Schreckenberg 2007; Kusters *et al.* 2006; Newton *et al.* 2006). Most NTFPs are consumed by the households and can be critically important as emergency foods, but others are produced for sale or barter. In this case, they not only help households to meet consumption needs, but can also be used as safety nets (Sunderlin et al. 2005). In Brazil, most of the research on the use of NTFPs by local people has been carried out in the Amazon region (Morsello 2006; Rizek and Morsello 2012; Duchelle *et al.* 2013; Muñiz-Miret et al. 1996), and less attention has been given to the Atlantic Forest, one of the world's top biodiversity hotspots (Myers *et al.* 2000).

The most abundant and valuable NTFP species in the Atlantic Forest is the palm tree *Euterpe edulis* Martius (Aracaceae) (Fantini and Guries 2007; Barroso *et al.* 2010). Despite being an excellent candidate for sustainable management, *E. edulis* has been a target of intensive and predatory harvesting in the last decades (Fantini and Guries 2007; Galetti and Fernandez 1998; Orlande et al. 1996). The result has been a decline in population density, leading to local extinctions in some places (Matos and Bovi 2002; Orlande et al. 1996; Reis et al 2000), and its conservation status is considered as threatened (Dransfield et al. 1988 apud Galetti and Fernandez 1998; Mamede *et al.* 2007).

Most of the *E. edulis* extracted from the Atlantic Forest can be considered an open-access resource, cut illegally in both private and public lands (Favreto *et al.* 2020; Reis *et al.* 2000), leading some authors (Fanelli *et al.* 2012; Orlande *et al.* 1996) to consider it a classic "tragedy of the commons" (Hardin 1968). The main reasons for this are: 1. market demand exceeding sustainable level harvest due to inability or unwillingness to implement management systems; 2. poorly defined and impractical use rights in terms of laws, regulations and other controls; 3. incapability of government authority in Brazil to limit access and enforce use rights; and 4. widespread corruption among governmental officials (Galetti and Fernandez 1998; Orlande *et al.* 1996).

Besides the ecological importance of *E. edulis* for the Atlantic Forest food web (Galetti and Aleixo 1998; Galetti 2000; Keuroghlian and Eaton 2008), the species has also economic and social value owing to the extraction industry of palm heart (*palmito*) and to other products derived from its steam, leaves and fruits (Favreto *et al.* 2010). This is specially the case in the Ribeira Valley (states of São Paulo and Paraná, Brazil), where smallholders and indigenous people have been involved in extraction of *palmito* to supply local factories. The Ribeira Valley (2,830,666 ha) (Santos and Tatto, 2008) is situated between two of the country's most important cities, São Paulo and Curitiba, and is the largest Atlantic Forest remnant in Brazil. The area is covered mainly by dense ombrophylous forest (Joly *et al.* 1999) and has a tropical monsoon climate (Am Köppen). The annual temperature varies between 17.4 °C and 30.4 °C (average 23.9 °C), and the mean annual rainfall is 1,521.5 mm and is concentrated in the summer (January–March) (CEPAGRIUNICAMP 2011). Due to the mountainous relief, the area is unsuitable for mechanized agriculture, and road access is difficult, which has limited the development of the region (Hogan *et al.* 1999; Santos and Tatto 2008). The regional economy is based on tea and banana plantations, limestone mining, palm heart extraction and tourism. Home to 59 *Quilombola* communities (Santos and Tatto, 2008), the region is characterized by a low human development index (HDI), due to low levels of education and income and high levels of infant mortality and illiteracy (Alves 2004; Hogan *et al.* 1999).

The *Quilombolas* are descendants of former Maroon colonies, and are among the poorest and most marginalized rural communities in Brazil (Penna-Firme and Brondizio 2007; Schmitt et al. 2002). In the Atlantic Forest, their livelihoods have traditionally been based on shifting cultivation (cassava, rice, beans, and maize), animal husbandry (pigs and poultry), hunting and fishing. Non-timber forest products, including *palmito*, were extracted only for subsistence needs. Since the 1960's, though, their livelihoods have been changing due to new policies (environmental, developmental and social) and increased access to markets (Adams et al. 2013).

Restrictions on subsistence activities imposed by environmental laws in the last decades made the extraction of palm heart from the forest illegal, putting at risk an important source of income for the *Quilombolas* (Queiroz 2006; Sanchez 2004). These regulations have not been successful in reducing extraction rates, but led to the criminalization of indigenous people in general, and the *Quilombolas* in particular. On the other hand, since 2000 many communities have been granted land titles by the government, based on ethnicity, settlement history, and Afro-Brazilian ancestry, as a compensation measure for the slavery period in Brazil. The *Quilombola* territories are collective properties of land that are governed by a local association elected among the community's members. The communities are not allowed to sell, transfer, or rent the land (Adams et al. 2013; Penna-Firme and Brondizio 2007).

Considering that self-governance and forest management decisions are strongly influenced by security of property rights, and that best long-term management practices often hinge on strengthening control over forest resources through participatory engagement with local actors (Ostrom 1990; Setty et al. 2008), the formal recognition of *Quilombola's* communal territorial rights creates an opportunity for new institutional arrangements that could contribute both to sustainable forest management and poverty alleviation. In other words, this scenario in which "a single, cohesive community has sole access to the resource" (Matos and Bovi 2002, 1755), opens up the possibility for decentralized community-level management of CPRs, and more flexible regulations on *palmito* management (Galetti and Fernandez 1998; Orlande et al. 1996).

This scenario offers an opportunity to use computational simulations to test different institutional scenarios that could help tackling social and ecological issues simultaneously. By examining varied rules and anticipating outcomes before decisions are taken, computational models can help to optimize policy interventions. Indeed, Newton et al. (2006) suggest that agent-based modeling could be a valuable tool in understanding how the availability of different livelihood options affects people's decisions about NTFP commercialization.

In this paper we will report the outcome of two agent based models aimed at comparing the performance of two distinct institutional scenarios to control *Euterpe edulis* harvesting. One represents current situation and is based on central control by the government. Community members that violate the rules are subject to punishment and can be fined. The second model is hypothetical and decentralized, meaning that the "central government cedes rights of decision making over resources to actors and institutions to lower levels in a politico-administrative and territorial hierarchy" (Agrawal and Ostrom 2001, 488). In this scenario, the community sets out the rules and is responsible for supervising its members. In this model, a rule is proposed to reward or to punish the agents according to their actions (cooperate or defect). By varying the parameters, we tested if the decentralized model is more efficient to secure a sustainable harvesting of *E. edulis* from the forest.

The paper is organized as follows: in the next section we briefly present the commons theoretical framework (Ostrom 2003); in section 3, we discuss the ecological, social and economic characteristics of *E. edulis* harvesting and existing institutional arrangements for its conservation; in section 4 we describe our methods, that are followed by the results obtained for each of the policy scenario and the discussion. A brief conclusion section ends the paper.

2. COMMON POOL RESOURCES (CPRs) AND NTFP'S

Common pool resources can be described as economic goods with high exclusion costs and which consumption is subtractive. In other words, one person's consumption of resource units subtracts from the total stock available to other consumers. CPRs may be held under different property regimes: state, private individuals or corporations, and communal groups. When there is no ownership this means that "everyone does" own the resource. In other words, there is no enforceable authority to determine the actions that individuals can take (access, withdraw, management, exclusion, alienation), and CPRs are used as open access resources (Ostrom 2003).

In cases where common pool resources are owned by the state but complete exclusion of resource users can't be ensured – due to large physical boundaries, proximity to the communities and limited financial and human resources – they are also considered as a *de facto* open access resources. This is the case in many developing countries, where members of local communities living in forested areas are dependent on forest resources for daily subsistence, such as NTFPs. As a result, in communities living close to forest two groups of people can be found: the law abiding or cooperators and those who use the forest illegally, or defectors (Shahi and

Kant 2007). Indeed, when the resource has a high value and when the ownership is undefined or questioned, this situation may introduce a “Commons Dilemma”. Individuals face strong incentives to extract more and more resource units, leading eventually to overuse (Ostrom 2005). But NTFPs can be exploited in different production systems, ranging from natural forests to agroforestry systems. Regulatory frameworks for NTFPs harvesting and management are also characterized by great local variation and complexity (van den Berg et al. 2007). Regulatory frameworks or institutions can be defined as “a set of accepted social norms and rules for making decisions about resource use: these define who controls the resource, how conflicts are resolved, and how the resource is managed and exploited (Richards 1997). They shape resource user’s actions and expectations” (Mutanje et al. 2011, 457).

In the *Quilombola* case, the communal ownership is threatened by very restrictive environmental laws, which prohibit *E. edulis* extraction. Thus the criminalization of a traditional activity leads to the misappropriation of the resource, which is under the control of official legislation. This situation makes the local management difficult and may cause a Common Dilemma and the overuse of a highly valuable resource. Nonetheless, by reconfiguring the institutional model and encouraging a decentralized process, community-based management could be more efficient to guarantee a sustainable exploitation of this natural resource within the *Quilombola* territory.

3. THE ATLANTIC FOREST AND THE *Euterpe edulis* PALM TREE

Broadly defined, the region known as the Brazilian Atlantic forest covered 148,194,638 ha and was distributed along the coastline from 3°S to 30°S, and from sea level up to 2,700 m (Metzger 2009; Ribeiro *et al.* 2009). The Atlantic forest region has historically harbored the largest share of Brazil's human population and experienced deforestation for timber, agriculture, cattle ranching, firewood, and urban expansion (Dean 1996). As a result, only 11.7% of the original forest cover remains (Ribeiro *et al.* 2009), of which 9,212,700 ha (56%) are under some level of protection in 1,400 protected areas, ranging from small private reserves to the Serra do Mar State Park (315,000 ha) (Scaramuzza *et al.* 2011; SOS Mata Atlântica 2011).

The large number of palm species in South America, combined with ethnic and cultural diversity of the region, has resulted in an extensive diversity of plant uses and management practices (Bernal *et al.* 2011). This is the case for *Euterpe edulis (palmito jussara)*, a slow growth native palm tree of the Atlantic Forest that germinates in the shade and reproduces best in forest environments (Fantini and Guries 2007). Although it can reach 20 m in height (10-15 cm in diameter at breast height – DBH), it is considered a subcanopy palm. *Palmito jussara* grows in concentrated areas (*palmitais*) and natural populations have high densities: 5,000-8,000 individuals per hectare, including seedlings and immature plants, or 255 adult individuals per hectare (Almeida-Scabbia 1996 *apud* Galetti e Fernandez; Orlande *et al.* 1996; Portela *et al.* 2010). The species has great ecological importance, producing large quantities of fruits that are eaten by a large number of medium and large birds and mammals that also help to disperse the seeds, including rodents, ungulates, pigeons, chachalacas, bats, monkeys, parrots, parkeets and guans (Favreto *et al.* 2010; Galetti and Aleixo 1998; Orlande *et al.* 1996; Reis *et al.* 2000). According to Reis *et al.* (2000), zoocoric seed dispersion is a key element of gene flow for this palm species.

Euterpe edulis apical meristem and undifferentiated stem leaves compose the palm heart (*palmito*), which is considered a delicacy in Brazil and one of the most valuable forest resources (Matos and Bovi 2002). Additionally, the stems and leaves can be used for housing and house utensils, food for domestic livestock, and the fruits provide a juice similar to the Amazonian *Euterpe oleraceae* (*açai*). The *palmito* takes from 5 to 10 years to grow to the point it can be harvested for commercial purposes (Galetti and Fernandez 1998; Orlande *et al.* 1996; Portela *et al.* 2010). Because it's a single-stemmed plant, extracting the palm heart means killing the palm tree. *E. edulis* is harvested year round, but there is a preference for dry weather, when it is easier to carry and transport the *palmito* "heads" (Barroso *et al.* 2010; Orlande *et al.* 1996; Reis *et al.* 2000). An estimated 200 tones are extracted monthly from the Ribeira Valley (Ribeiro *et al.* 1993 *apud* Galetti e Fernandez 1998) and *E. edulis* palm heart production is completely absorbed by internal market (Reis *et al.* 2000).

Legal regulation of *E. edulis* harvesting and management used to be based on Resolution SMA-SP 16, issued by the state government of São Paulo in 1994. Until 2006, the harvesting of *palmito* hearts could be done legally in natural or replanted populations, but the land owner needed to ask for a license and submit a management plan to the Environmental Company of the State of São Paulo (CETESB). Areas with primary forest or secondary forest in medium or advanced regeneration stages could be managed, provided populations had a minimum of 50 adult seed bearing palms and 5,000 seedlings per hectare. Unmanaged harvest was banned and considered a federal crime. A management plan could cost between US$ 10,000-35,000 (Galetti and Fernandez 1998). As a result, resource owners were faced with two alternatives: either sell them legally and incur with all the costs of obtaining a license and competing with overexploited natural stands, or sell them to illegal harvesters (Galetti and Fernandez 1998).

However, since the Atlantic Forest Law (Federal Law 11.428/2006) was issued, in 2006, commercial extraction of any native species is prohibited, even in areas where they have been replanted or managed. *Palmito* extraction is allowed only for local consumption by indigenous and traditional people. Unmanaged palm harvest is still banned and those involved face a risk of paying fines, being arrested and prosecuted (Fanelli et al. 2012; Matos and Bovi 2002; Orlande *et al.* 1996). Nevertheless, illegal harvesting did not stop. The illegal industrial chain involves the harvesting of the palm tree from the forest by *palmiteiros*, the transporting of palm hearts to the cities by middlemen, and their insertion into the legal trade (Galetti and Fernandez 1998). Armed conflicts among *palmiteiros*, the environmental police and private guards are not uncommon in the state of São Paulo (Fanelli et al. 2012).

Despite the fact of being an illegal activity, exploitation of *E. edulis* is an important source of income for smallholders and indigenous people from the Ribeira Valley that work as *palmiteiros*, including the *Quilombolas*[5]. Harvesting of *palmito* usually occurs at night, to avoid being caught by the environmental police, and each *palmiteiro* cuts and transports an average of 50 heads in bundles (60 kg), working with one or more family members. *Palmiteiros* can be full-time harvesters or occasional workers who harvest during inactive periods, self-employed or contracted

[5] Accordingly, the *Quilombolas* showed great ethnoecological and ethnobotanical knowledge about the species, listing a wide range of animals that feed on *palmito* and help to disperse its seeds (Barroso et al. 2010).

by *palmito* companies (Galetti and Fernandez 1998; Orlande *et al.* 1996). In traditional selective systems, all plants > 2 m tall are harvested, and few or no productive plants are left behind (Reis et al. 2000). Frequently, the *palmiteiros* cook and bottle the heart palms in the forest or at home, in unsanitary conditions (Galetti e Fernadez 1998; Orleande *et al.* 1996).

As a result of overexploitation, access to *E. edulis* populations has become increasingly difficult, and *palmiteiros* have to travel long distances in difficult terrains (5-20 km), spending a few days away from home (Galleti and Fernandez 1998; Raimbert, *person. comm*.). Most *palmiteiros* work 15 - 20 days per month, harvesting 96 palm trees per day, or two boxes of 15 jars (300 g each) weekly (Galleti and Fernandez 1998)[6]. The price received for each head ranges from US$ 0.50-0.90, depending on the region, size and quality of the heart palm (Orlande et al. 1996). Monthly income of an average *palmiteiro* ranges from US$ 360.00-500.00 (Galetti and Fernandez 1998; Orlande *et al.* 1996). Some estimates indicate that illegal *palmito* production is twice as profitable as legal production (Orlande et al. 1996). Although participatory regeneration projects have been used to increase natural populations, they are not yet economically viable (Fanelli et al. 2012).

Some authors have suggested that *E. edulis* could be managed to permit a sustainable harvest (Fantini and Guries 2007), but lack of knowledge and current forest regulations, that do not allow changes in the forest structure to improve the productivity of single species, have hindered initiatives. Sustainable management systems in tropical forests require reliable knowledge on population structure and dynamics, reproductive biology and silvicultural practices, which are rarely available (Reis et al. 2000). Existing demographic data for *E. edulis* (Reis et al. 2000) shows that populations have a pyramid-shaped structure, with a large seedling bank (12.000/ha on average) depending on a proportionally small number of genetically effective individuals (61-113 palms/ha) (Reis et al. 2000).

Although there are no models for the coupled *Quilombola-palmito* system, a few ecological models have been proposed aiming at the sustainable management of natural populations. Most of them have been based on optimization models for timber trees or on matrix population models (MPMs) (Freckleton *et al.* 2003; Kirchner et al. 1987; Orlande et al. 1996; Portela et al. 2010; Reis et al. 2000; Silva-Matos et al. 1999). None of the proposed models presented above integrates economic, social and environmental criteria, and workable models of *palmito* sustainable management will also depend on institutional changes (Matos and Bovi 2002; Orlande et al. 1996). So, the main goal of this paper is to present an agent-based model (ABM) that integrates ecological, social and economic variables in the *Quilombola-palmito* coupled human-environment system.

4. METHODS

Defining the agents

[6] According to Matos and Bovi (2002), the production of a 500 g can (300 g drained net weight) of heart of palm uses, in general, one palm tree with DBH of about 12 cm (12-18 years from seedling stage), or 18 small plants (6-8 cm DBH 0r 6-10 years old).

In this study we simulate two different scenarios using ABM, a computer simulation technique in which the researcher creates a virtual community of independent agents, the environment in which they act and the rules of interaction and decision making. ABM is a useful tool in cases where an individual´s decision making is highly dependent on other agent´s characteristics and decisions and on the current state of the environment, and when these conditions vary in time and/or from the interactions of the agents with the environment and among themselves. Another advantage of using ABM is the possibility to consider heterogeneity among agents, allowing individuals to act differently, and non-linearity, which can provide a richer analysis (Berger 2001; Bousquet and Le Page 2004; Matthews et al. 2007; Miranda et al. 2012).

Shahi and Kant (2006) used an evolutionary game-theoretic approach to model interactions among agents, and proposed two models. In the first one, the community was formed by cooperators (non-extractors) and defectors (illegal extractors) and the resource was ruled solely by the government. In this scenario, the authors found that the only Nash equilibrium strategy[7] was to defect, which caused degradation of the resource. In the second n-person game, the resource was jointly managed by the government and the community, and a new type of agent appeared: the enforcers. In this scenario there was a set of different equilibria, conditioned to parameters such as enforcer's sophistication and wages. Each type of agent had a different payoff function, and changes in behaviors depended on the payoff of the agent´s type and the average payoff in the population as a whole.

An evolutionary game-theoretic approach is useful when analyzing situations in which there is a large population of interacting agents that may have different payoff functions, which are expected to learn, imitate and discard strategies, and adapt to new circumstances in the course of repeated interactions. In this paper we adopt this adaptive evolutionary perspective, but move forward to a micro-level: we used ABM to analyze changes in each agent's behavior, taking into account its surrounding neighbors, instead of only analyzing the types of agents.

Our model has two types of agents: extractors (defectors) and non-extractors (cooperators). However, non-extractors are divided in two categories: engaged people, who are willing to incur in organization costs for managing the resource, such as collective decision making efforts, monitoring and sanctioning, and non-engaged people. Differently from the model in Shahi and Kant (2006), all categories of agents have very similar payoff functions. In fact, a single payoff function was determined, but different parameters of that function are enabled depending on the type of agent and its neighborhood, at each period.

The choice of approximating the categories of agents was based on four assumptions: the first one is that agents in the *Quilombola* communities can be assumed to be culturally homogeneous and socio-economically very similar; the second is that a non-extractor can easily become an extractor (and vice-versa) from one period to another, since there are no relevant initial capital costs for the harvesting of *E. edulis*; the third assumption is based on the previous two, and has the goal of "keeping it simple". Considering that the agents are subject to basically the same set of incentives, using a single payoff function is useful to better understand how decisions are being made by each one of them.

[7] Nash equilibrium strategy is the best strategy an agent can choose, given the expected choices made by other agents.

In addition, contrary of the evolutionary game-theoretic approach of comparing the payoffs of different types of agents to update their proportion in the next period (an external evaluation, which demands their payoff functions to be different) (Shahi and Kant 2006), in the present model the agent's behavior changes depending on its type – extractor, non-extractor, engaged, non-engaged – and the neighborhood conditions for each individual, and are made at the individual level (agent i´s decision).

Finally, our last assumption is that in the community-management scenario, monitoring and punishing will be carried out by peers, i.e. by the members of the community (there is not an "enforcement job position"). One may argue that this is a naïve assumption, since potential punishers would have the tendency to free-ride, expecting others to punish and assume other management costs, but we are considering the fact that the real communities are small, people usually know how other members are making their living, and expect them to follow the same rules (specially cooperators). Nevertheless, this could be an interesting point for further development and variations of the model.

As mentioned before, we focused on two scenarios based on different institutional arrangements, and compared the main variable final stock, which represents the biomass of *Euterpe edulis* left in the forest after a certain period of time. The first scenario – Business as usual – simulates the current state of palm tree exploitation activities and stock depletion, despite legal prohibition and state enforcement. The other scenario – Community level management of *E. edulis* – consists of a hypothetical situation in which the *Quilombola* community is allowed by the government to explore the common resource, but incurs in management and sanction costs. The biological dynamics of *E. edulis* was not included at this stage. The simulation code was written in MATLAB software. Hereafter, we explain how the models work.

Initial conditions (given):

The initial conditions are externally established every time a simulation starts, and work the same way in Models 1 and 2:

1. A virtual community is created in a lattice framework, with n agents. Each individual is randomly considered an extractor or non-extractor, and is surrounded by 8 neighbors, who are also randomly extractors or non-extractors;

2. Each individual is attributed a parameter for:

   - Discount rate *d* (importance of the resource in the future, compared to the payoff of its extraction at present time);
   - Alternative income *RA* (income from non-extractive activities, such as subsistence agriculture, or other legal sources of income, such as government allowances and job salaries);

3. The natural palm tree biomass stock (natural stock) is also pre-determined;

4. The Payoff of extraction (*Payoffextraction*) equals to 1, and represents the price paid for a unit of biomass stock.

Models in environmental economics usually consider discount rates as directly related to interest rates and opportunity cost for capital. However, smallholders in *Quilombola* communities rarely have access to financial services and, when they do, they may face much higher personal interest rates (Muñiz-Miret et al. 1996). Thus, in our model the discount rate, defined as the difference between the value attributed to the resource in the future compared to its value in the present time, is interpreted as a more individualized parameter, and may vary according to basically two factors:

1. Urgent and non-expected necessity of cash: in emergency situations such as having a sick member in the family, agents consider the value of immediate use of the resource much higher than its importance in the future and have the incentive to harvest. This is very common in *Quilombola* communities, and means that discount rate may have stochastic variations for the same household;

2. Stage of the household cycle: *d* may vary during the household cycle, which is determined by changes in household demographics across time. Usually, a new household is formed by a newlywed couple, and incorporates new members as children are born. While the offspring is still young the parents have to work for all the household members, but as the children grow older they also contribute to total income, and eventually leave to constitute a new residence. During this cycle the number of people in the household and the age and gender structure affect the need for immediate cash and the livelihood strategy, as well as decisions on allocation of labor and land use (Sherbinin et al., 2008; Perz et al. 2006; Gray 2008).

The alternative income parameter *RA* reflects the fact that most poor rural people maintain diversified livelihood strategies. One reason for this is to minimize risks, and the other is because they cannot obtain enough income from any other single strategy, that is, their labor opportunity cost is low (Ellis 1999; Sunderlin et al. 2005).

Model 1: Business as usual

This scenario represents the situation under the current prohibition policy, in which the community in not allowed to explore or manage the resource but the resource stock is being depleted, despite governmental efforts to monitor and punish extractors. The following parameters arise from this situation:

- Considering that the community is not allowed to explore the resource *E. edulis*, no agent incurs in management costs: there are no collective decision-making, and monitoring and punishing are exclusively governmental activities.
- There are no peer-pressure dynamics for a preservation rule to be enforced. On the contrary, observing neighbors extracting and not being caught generates an incentive for an agent to extract too.
- Punishment is dependent on the probability of being caught by the environmental police, which is represented in the model by parameter ρ;
- When extractors are caught, they receive a fine, represented in the model by the parameter λ. This fee, however, is shared by the community. This may seem inadequate, but is what really happens in real life, since households are

too poor to pay the fines themselves, and the community association[8] usually assumes the payments;

In this scenario, the payoff function is:

*PayoffTotal,i = (PayoffExtraction) * ease * (1+di) – sharedfinesi – RAi*

Where *PayoffExtraction=1+nvz/8* and *nvz* is the number of neighbors that harvest. This was made in order to represent the temptation to extract that an individual has when he realizes that his/her neighbors are benefiting from illegal extraction.

The variable *ease* represents how easy it is to find and extract the resource, and is equal to the fraction of the current stock over the initial (natural) stock.

The relations established in this payoff function mean:

- The harder to find and extract the resource, the lower the total payoff of extraction;
- The higher the value of the resource in the future, the lower discount rate (*di*), and the lower total payoff for the extraction at the moment of decision-making;
- The higher the level of fines received by extractors (and then shared among all community members), the lower the total payoff of extraction;
- The higher the alternative income of a household (*RAi*), the less dependent it is on the income from illegal extraction, and the lower is the benefit of extracting. It is important to highlight that the *E. edulis* harvesting activity occurs in harsh and deleterious conditions, which means that an alternative income would always be preferable.

If the result of $PayoffTotal_i$ is non-positive, agent *i* decides NOT to extract. If, however, this condition is not met, it is favorable for *i* to extract, and so he/she does.

After the above decision making is carried out for every agent in the community, the initial stock of biomass is updated, subtracting the sum of all units extracted at that period, and multiplying the resulting stock by a regeneration rate. The final number consists on the initial stock of the next period, and the *ease* variable is also updated for the next period.

[8] It is important to distinguish between the association that currently exists in the community and the association for managing the resource *Euterpe edulis*. The later does not exist, since the palm tree harvesting is forbidden by the government.

Model 2 - Community-level management of E. edulis

The second model is decentralized and based on community control. The community sets out the rules and is responsible for supervising its members. In this model, a rule is proposed to reward or to punish the agents according to their actions (cooperate or defect). By varying the parameters, we tested if the decentralized model was more efficient in securing a sustainable harvesting of *E. edulis* from the forest.

In this model, interaction rules are highly dependent on an individual's neighborhood, and the key variables that influence behavior are *peer-pressure* and *management costs*. The following parameters arise from this situation:

- Non-extractors may exert peer-pressure and punish extractors, depending on a probability φ of being an engaged person, and depending on the number of neighbors that are extractors. The variable γ represents the number of extracting neighbors an engaged non-extractor cannot tolerate – the lower the γ, the lower the amount of extracting neighbors an agent cannot tolerate and, therefore, the higher the peer-pressure;
- When an engaged non-extractor cannot tolerate his/her neighbors behavior, he/she incurs in management costs, which can be interpreted as the cost of monitoring, punishing, peer-pressuring and participating in collective-decision making. The greater the number of extracting neighbors, the higher the engaged agent's management cost;
- Extractors may receive a punishment, depending on the number of non-extractor neighbors they have and the latter's probability φ of being engaged agents. The greater the number of non-extractor neighbors, the higher the punishment received;
- Extractors never assume management costs;

In order to make the decision to extract or not, an agent *i* considers the payoff of the extraction, the peer-pressure received, the management costs assumed, the discount rate, the ease to find and extract the resource, and the alternative income for the household. The *total payoff* of the extraction follows the function:

$$PayoffTotal,i = (PayoffExtraction – Punishmentsi) * ease * (1+di) + managementcosti – RAi$$

On the contrary of Model 1, in this payoff function the variable $managementcost_i$ adds to the total payoff of extracting the resource. This means that the higher the management cost for a non-extractor agent *i*, the harder it is for he/she to sustain the local management of the resource, and more likely it is for *i* to give up and extract too. In addition, the payoff of the extraction is subtracted by the punishment received, which increases as the number of neighbors that are engaged non-extractors (punishers) increases. Consequently, the greater the punishment received, the lower the total payoff of extracting.

As in Model 1, if the result of the *PayoffTotal,i* function is positive, the agent decides to extract. Otherwise, he/she does not extract. The subsequent steps of updating the variables *stock* and *ease* are also the same as in Model 1.

In both models, the simulations stopped when the resource went extinct, or at a limit of Tmax = 2,000 periods, which was sufficient to reach an equilibrium in all simulation runs. As an initial simplification, the alternative income *RAi* was considered 1 for all individuals, and the discount rate *di* was also considered equal for all *i*.

The initial natural stock was equal to 10,000 units of biomass. In order to focus our analysis on the interactions among agents and its impact for the resource stock, at this moment we also considered the regeneration rate equal to zero.

We tested Model 1 for different combinations of ρ and λ, and we tested Model 2 for different combinations of φ and γ. Different levels of discount rate were also tested.

5. RESULTS AND DISCUSSION

We first simulated the scenario “Business as usual”, and tested the impact of different combinations of the probability of being caught (ρ) and three different levels of fines (λ) in the final stock of the resource. For each combination (ρ, λ), we ran 50 simulations and extracted the average of the final results. We also wanted to check the impact of different discount rates in the final stock of resource, so we ran the same set of simulations for *d*=0 and for *d*=5, representing low and high extreme values for this parameter. The final stock levels presented in the graphics below are the average of the last 500 periods of those 50 runs. This was made in order to diminish the impact of over variations. Results are illustrated in Figure 1.

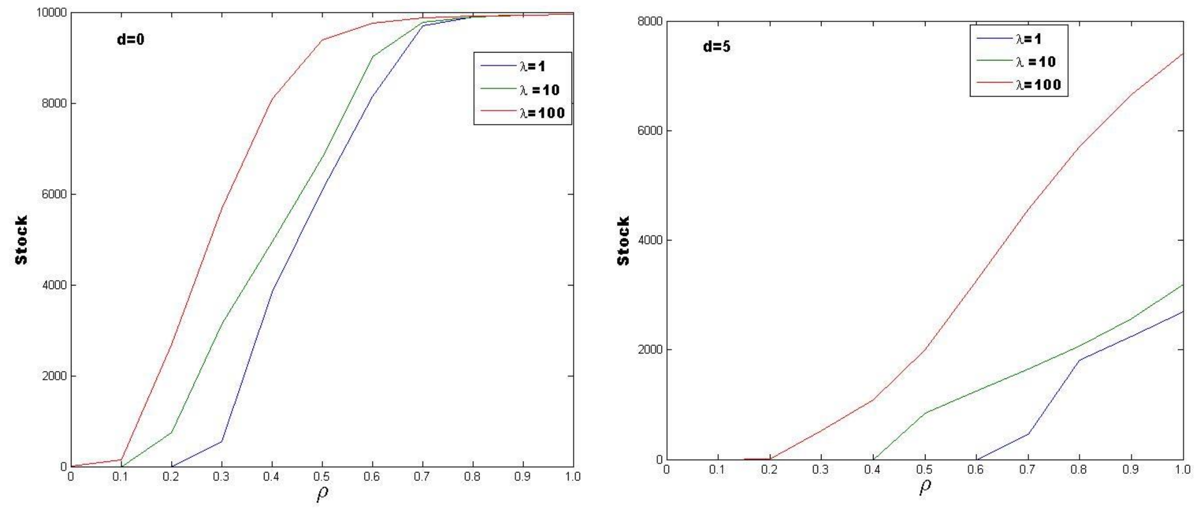

Figure 1 - Final Stock after Tmax=2,000 periods against the probability to be punished ρ. Punishment increases when ρ goes from 0 to 1. Number of agents was N=100, initial stock=10,000, and discount rates *d*=0 and d=5. The fee λ assumes values: 1, 10 and 100.

When the discount rate is zero, agents consider that the value of the resource in the future is the same as it is in the present, so there is no urge to extract the resource immediately. In this hypothetical situation we can observe that for a very low probability of being caught (ρ <=0.1) the resource tends to extinction, but the situation rapidly reverses when this probability increases to 0.3, 0.4 and 0.5. Even though we can see that higher fee levels (λ) have a positive impact in compliance, the probability of being caught (ρ) has a more dramatic effect.

When analyzing the results we must consider, however, that in real life conditions the probability of being caught is very low due to the reduced number of state agents and the large and difficult terrain to be monitored. Therefore, the results obtained in the simulation, even for very low discount rates, are consistent with the evolution of the resource stocks in real life.

When the discount rate is high the situation is worse: even for higher probabilities of being punished, more agents harvest the resource, and final stocks are lower for every combination (ρ, λ). The fee levels seem to be more determinant, but only after a high probability of being caught is reached, which in many cases is too costly for state authorities. In either case, we can conclude that for a realistic level of punishment probability, the resource is being severely depleted and a “Tragedy of the Commons” is happening.

For the scenario in which the community is allowed to explore and manage the resource, we also tested different combinations of parameters (proportion of engaged agents among non-extractors and peer-pressure level) to analyze the impact on final stock of resource. Again, for each pair (φ, γ), we ran 50 simulations.

We ran simulations for the parameter d = 0, 0.2 and 5.0 (discount rate), in order to investigate the impact of future expectations on the level of resource extraction. The input of other simulation parameters was set up as N = 100 agents and initial stocks as 10,000 units of palm trees. The results can be found in the next three phase diagrams (Figures 2, 4 and 6).

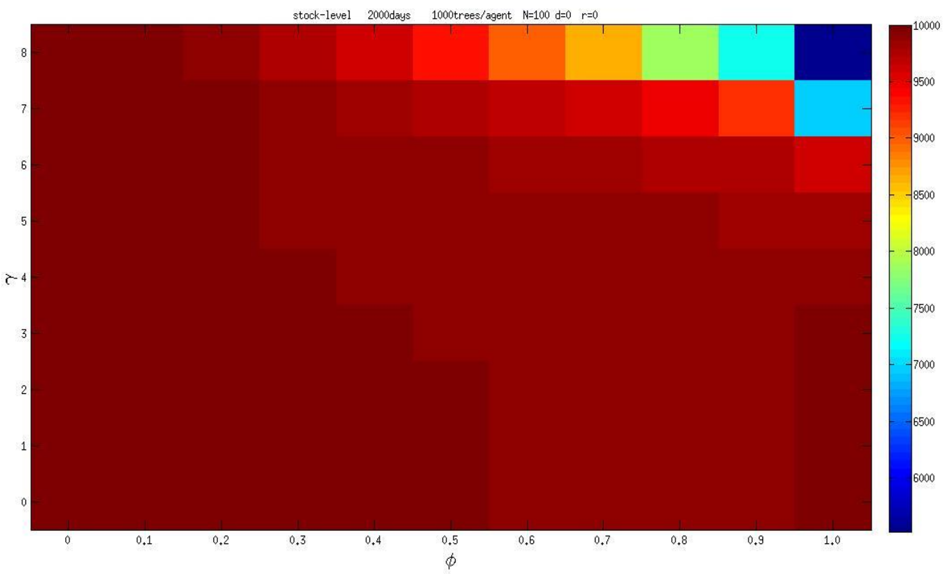

Figure 2 - Phase diagram. Peer pressure γ against the proportion of engaged agents φ. Peer-pressure increases when γ decreases. The level of punishment increases when φ goes from 0 to 1. Number of agents was N=100, initial stock=10,000, and discount rate d =0.

When *d*=0, the value of the palm tree today is the same as in the future and there is no pressure to extract more trees in the present. Figure 2 exhibits the results for the final stock of *E. edulis* for several values of *φ* and *γ*. The worst case for conservation of native trees was found for *φ* =1 and *γ*=8. This is the combination of the higher proportion of people engaged in organizing, monitoring and sanctioning and the minimum level of peer-pressure (high tolerance to extraction and many "potential punishers", that may be interpreted as fear to punish or absence of norms to punish). In this case, the management cost is very high and no enforcement is carried out, so this scenario favors extraction.

The situation rapidly improves for conservation of the resource when peer-pressure (and, therefore, punishment) is enabled, what can be observed as *γ* decreases. In this case we can see that even a low level of punishment is sufficient to make a big difference. On the other hand, lack of punishment is very bad for conservation of resource stock. This is a very intuitive result and is consistent with empirical studies and with the literature on the commons (Ostrom, 1990).

We can also observe that when *φ* equals to 1 or is smaller or equal to 0.5, the system achieves the best level of conservation of tree stocks. It is intriguing that for the higher-intermediate proportion of punishers the outcome was poorer when compared to lower levels.

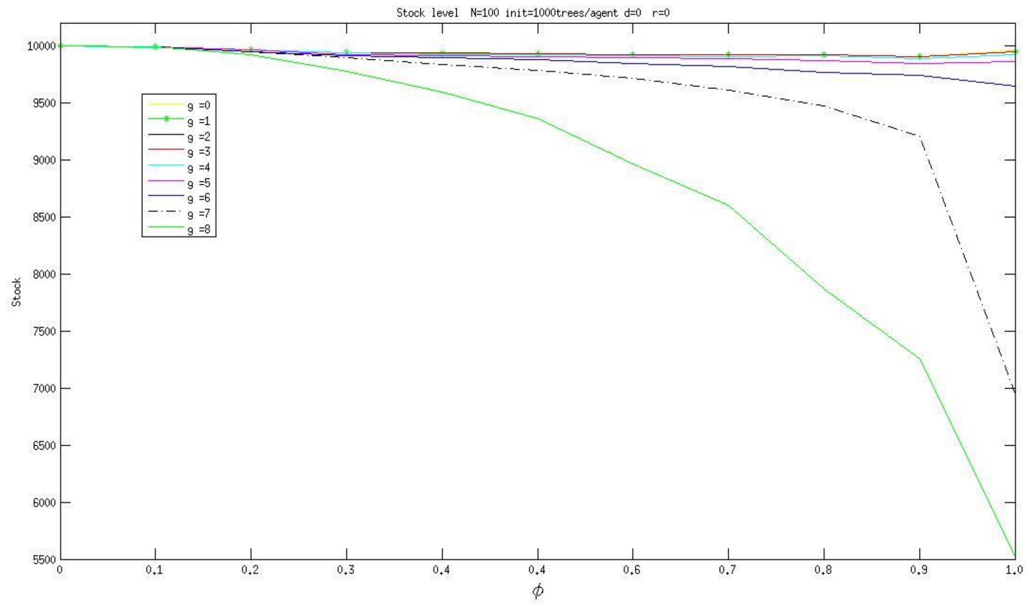

Figure 3 - Final stock after Tmax=2,000 periods, against proportion of engaged agents *φ*, for level of peer-pressure (γ). Peer-pressure increases when *γ* decreases. Punishment increases as *φ* goes from 0 to 1. N=100 agents, initial stock=10,000, discount rate *d*=0

Figure 3 shows in more detail the stock level of *E. edulis* trees for several levels of punishment. For *d*=0, the agents behavior favors preservation. Only for high values of *γ* and *φ* does the stock level fall dramatically to 55% of the initial stock for the minimum peer-pressure level and maximum punishment level. As we explained before, this is due to a situation in which there are individuals incurring in organizational costs but there is no enforcement against defectors, and the result is a change in the behavior of potential punishers, who give up the organization and become extractors.

Even though this situation suggests that the community is wasting resources and, therefore, is worse off than it would be if there was no organization at all, it is important to highlight that such a situation may not be feasible in the real world, since it is expected for such organizations to have legitimate sanctioning procedures and for community members to have liberty for, at least, to express their disapproval.

We ran a second round of simulation, varying the discount rate to *d* =0.2, and the diagram phase is illustrated in Figure 3. The first thing we can notice is a dramatic difference in the final stock levels of the resource for lower levels of peer-pressure, in comparison to the previous scenario. When the discount rate increases, the value of the resource use in future time decreases in comparison to the value of its immediate use, which means that agents have an incentive to harvest the palm trees.

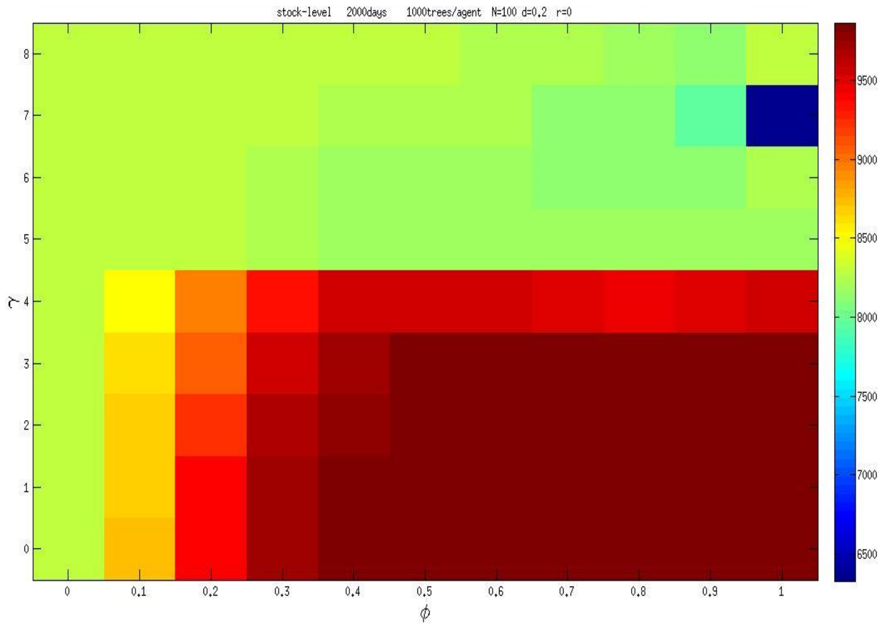

Figure 4 - Phase diagram. Peer pressure γ against the proportion of engaged agents φ. Peer-pressure increases when γ decreases. The level of punishment increases when φ goes from 0 to 1. Number of agents was N=100, initial stock=10,000, and discount rate *d* =0.2.

We can notice that, for a wide range of combinations (φ , γ), especially when γ is lower (higher peer-pressure), it is possible to reach an equilibrium in which the resource is not over exploited, even with relatively low proportions of engaged agents (punishers) among non-extractors (φ).

In Figure 5 the stock level analysis can be split in two regimes. Here we see the effect of high peer-pressure acting over agents with non-null future expectation combined with punishment. For $\gamma \leq 4$ the stock of palm trees increases linearly in the interval of φ from 0 to 0.5. The control of the stock is achieved after a fifty percent of engaged agents (punishers) is reached. For lower levels of peer-pressure, the level of resource stock remains at an intermediate level and decreases when peer-pressure disappears. When peer-pressure is low and the proportion of engaged agents is at its maximum, the same phenomenon observed in *d* = 0 occurs: organization costs are high and little enforcement is going on, so potential punishers have incentives for changing behavior and harvesting.

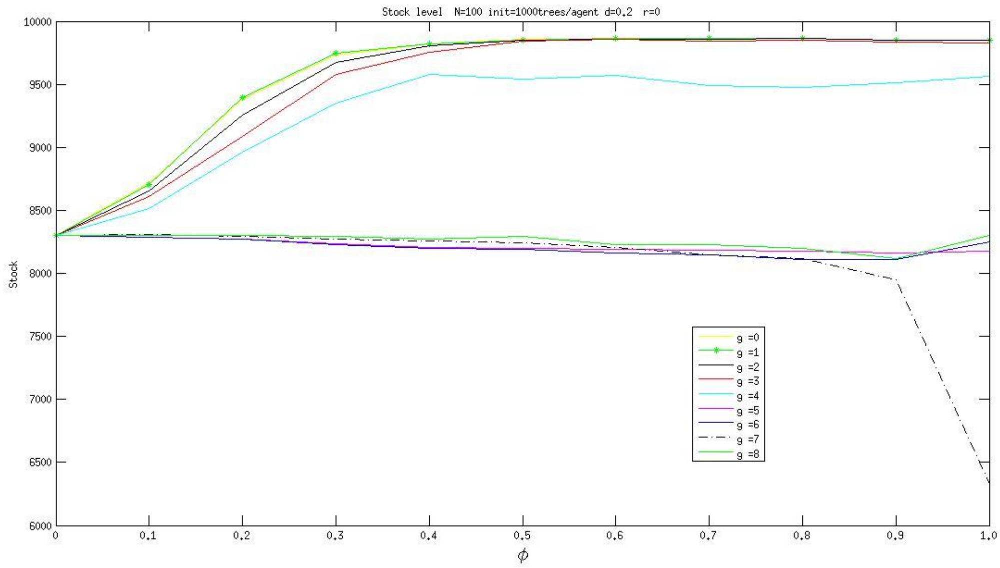

Figure 5 - Final stock after Tmax=2,000 periods, against proportion of engaged agents *φ*, for level of peer-pressure (*γ*). Peer-pressure increases when *γ* decreases. Punishment increases as *φ* goes from 0 to 1. N=100 agents, initial stock=10,000, discount rate *d*=0.2.

In order to analyze the impact of the discount rate in the final stock, we ran another simulation for *d* = 5. With a higher discount rate, final stocks were dramatically reduced, which means that extraction occurs at a much faster pace. In addition, we can conclude that there is a much tighter action space to establish a local management scheme, demanding a combination of a very high proportion of punishers among non-extractors and a very low tolerance limit (Figure 6). The comparison of Figures 2, 4 and 6 also suggests that for lower discount rates, peer-pressure seems to exert a greater role than the proportion of punishers, while in situations with higher discount rates the proportion of punishers seems to be more decisive.

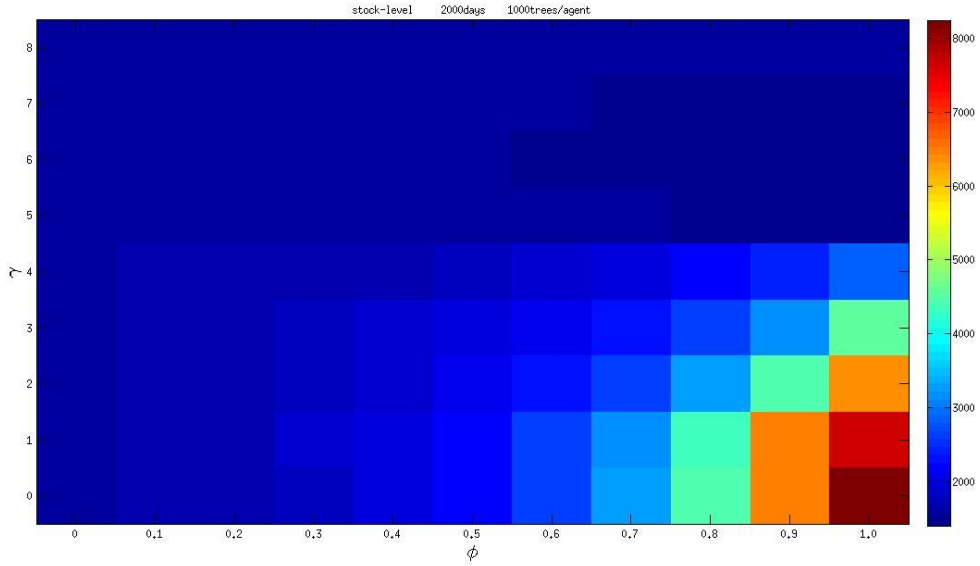

Figura 6 - Phase diagram. Peer pressure *γ* against the proportion of engaged agents ***φ***. Peer-pressure increases when *γ* decreases. The level of punishment increases when ***φ*** goes from 0 to 1. Number of agents was N=100, initial stocks=10,000, and discount rate *d* =5.

Finally, in Figure 7, for medium and lower proportions of engaged agents among the non-extractor population, there is an intense level of extraction, irrespective of the level of peer-pressure. This means that even though all extractors are being punished, the amount of punishment received is not enough to compensate the incentives to harvest at the present time. When punishment increases, the higher peer-pressure, the higher preservation. Thus, we see a nonlinear effect in the role of the pressure done by neighbors.

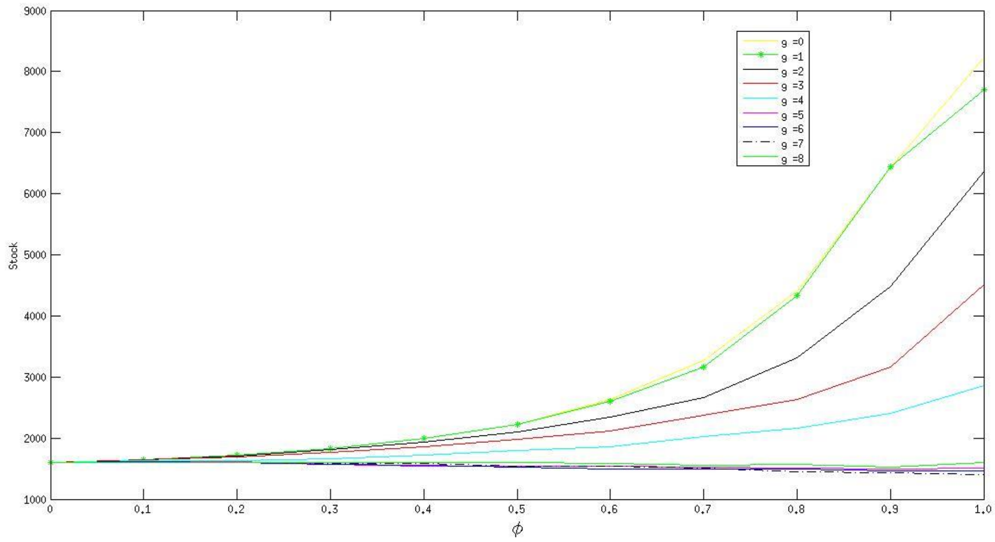

Figure 7 - Final stock after Tmax=2,000 periods, against proportion of engaged agents *φ*, for level of peer-pressure (*γ*). Peer-pressure increases when *γ* decreases. Punishment increases as φ goes from 0 to 1. N=100 agents, initial stock=10,000, discount rate *d*=5.

6. CONCLUSIONS

The agent-based model presented in this study is an over-simplified version of the *Quilombola-palmito* coupled human-environment system existing in the Ribeira Valley. Nevertheless, it can illustrate that, under certain conditions, community-level management of *E. edulis* is able to bring better social and ecological benefits.

When the discount rate is zero, peer-pressure acts as the main control parameter to drive the system towards forest conservation. On the other hand, when discount rate increases, the punisher fraction is the key variable controlling the dynamics of resource extraction.

The next step towards building a useful tool to optimize policy interventions aimed at resource conservation and rural development in the Atlantic Forest is the calibration of this basic model (Model 2 - Community-level management of *E. edulis*). As one can see from the results, the model captured nonlinear relations among the social agents, and has showed results consistent with real life dynamics.

The future enhancement and calibration of the model with better data concerning variables such as alternative income (and the heterogeneity of its distribution among households), discount rates and stock regeneration rates will allow us to comprehend under which conditions a local community-level sustainable management scheme could be reached[9]. As such, the model can provide a tool for the discussion of public policies linking rural development, *Quilombola's* empowerment and the conservation of a keystone species from the Atlantic Forest.

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[9] The data that will be used the social and economic parameters, as well as preferences and interaction rules, will be obtained from field research and the literature. Since 2003 an interdisciplinary team has been collecting data in *Quilombola* communities situated in the municipalities of Eldorado and Iporanga (State of São Paulo, Brazil) (Adams et al. 2013). These communities were founded by slaves and their descendants following the abolition of slavery in 1888 (Queiroz 2006). Some of them have already received the land titles, while others were officially recognized as *Quilombola* territories, but are still waiting for the titles (Adams et al. 2013). Additionally, of us (CR) did ethnographic research in one of the communities for a more in depth investigation on community-based management of resources and spaces, including the illegal *palmito* harvesting.

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