Mobility, Resource Harvesting and Robustness of Social-Ecological Systems

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Purpose

The purpose of the model is to analyze how mobility affects the sustainability of SESs and to examine specific conditions that reduce the vulnerability of communities to the incursion of new resource appropriators.

Entities, state variables, and scales

The entities of the model are agents moving and harvesting resources in a 50x50 torus landscape. Agents differ in their location, the amount of resources that they are willing to store, and their stock of energy. Agents may copy the desired storage level of more satisfied agents in their same location. Each patch has an amount of resource and is governed by a government-agent. In this version, few institutional arrangements are included. Government-agents differ in their enforcement level. Government-agents may imitate the enforcement level of neighboring government-agents who have higher fitness (i.e., higher number of agents). Each cell has a logistic growth function for the resource. Each patch might have from 0 to *n* agents. The model runs for a period of 3000 time steps. The values of the parameters used in the default model are showed in Table 1.

Table 1. Variables and parameter definitions of the model and parameters' values of the default setting.

Parameter	Description	Value
agMSY	Harvest level encouraged by governments	-
ar_{max}	Maximum distance around the patch where agent is located in which agent can set its potential destination	5
br	Birth rate of agents	0.03
C_{mov}	Cost of mobility	-
Crep	Cost of reproduction	-
Cost	Cost of enforcement	-
dH	Desired harvest level of agents	-
E_t	Accumulated energy of agents	-
E	Enforcement level	-
H	Total resource harvested at each patch	-
hr_{max}	Radius around patches as potential destinations for offsprings' settles	5

Parameter	Description	Value
I_a	Probability of agents coping the attributes of other agents in the same patch	0.5
I_g	Probability of governments imitating the enforcement rate of neighboring patches	0.5
k	Carrying capacity of resource	100
met	Metabolism of agents	0.3
n	Number of agents in patch	-
netCost	Net enforcement cost	-
nrmarks	Number of marks of potential intruders governments can read	0
P	Punishment imposed to cheaters by each government	-
p_c	Probability of each government to catch a cheater	-
p_m	Probability of random movement of agents	0.2
R	Resource level of each patch	-
r	Growth rate of resource	0.075
S	Storage level of agents	-
Ta	Factor that determines the benefit threshold of agents	0.3
Tg	Accumulated enforcement cost threshold. Beyond this threshold governments reduce their enforcement level by 10%	3000

Process overview and scheduling

Every time step, agents assess the available amount of resources in their patch. If this amount does not satisfy their desired harvest level (*dH*), agents may move to the nearest cell with the highest resource level. The *dH* is:

$$dH_i = met * (1 + S_i)$$

Where *met* is the energy spent in the metabolism. Agents are assumed the desire a harvest level higher than the minimum required to meet their metabolism. The parameter S_i is between 0 and 1 so that the agent will meet the strict metabolism value with $S_i = 0$, or a maximum of double the metabolism rate with $S_i = 1$.

Besides movement due to dissatisfaction, agents can move to another random patch with a fixed probability (p_m). Movement costs energy to the agent. Every time step an agent changes its location, its accumulated energy (E_t) is reduced a certain amount (C_{mov}). Then agents decide how much resource to harvest, they harvest and they store energy. As the resource has a logistic growth, agents are encouraged by the government to harvest an amount near to the maximum sustainable yield (*agMSY*):

$$agMSY_j = \frac{K_j * r}{8} / n_j$$

Where K_j is the carrying capacity at patch *j*, *r* the growth rate of the resource, and n_j the number of agents at the patch *j*.

Agents may ignore sustainable practices and cheat and consequently harvest (*H*) the desired amount of resource (*dH*) when this amount is higher than the *agMSY*. Agents will cheat if they expect to receive a significant benefit of cheating taking into account the expected penalty of being caught:

$$\text{Agents cheat if: } Ta * p_{c_j} * F_{ij} > agMSY_{ij}$$

Where *Ta* is the benefit threshold of agents, p_{c_j} is the probability of catching a cheater in patch *j* (see below) and F_{ij} is the fee cheaters will pay if they are caught by the government. F*ij* is proportional to the enforcement level:

$$F_{ij} = (agH_i - agMSY_j) * E_j$$

Where agH_i is the amount of resource harvested by agent *i*. The value of F_{ij} is 0 if agent *i* is not caught or harvests an amount equal or less $agMSY_j$.

We selected as default value a moderate value of *Ta* (Table 1). Low values ($Ta < 0.2$) makes agents decide not cheat, thus in all circumstances the system reaches a stable threshold. On the contrary, high values ($Ta > 0.5$) makes agents decide to cheat and the system rapidly collapse. Agents do not have full knowledge of the probability of being caught (i.e., p_c). The capacity of agents to predict p_c increases the longer they stay in a certain patch, thus newcomers will more frequently predict an erroneous risk of cheating.

The probability of governments to catch a cheater (p_c) is proportional to their enforcement. We consider that the capacity of governments to detect a cheater decreases as the population increases since it require more effort to monitor all the agents. Hence, if the number of agents in a certain patch is 10 or less, p_c is *E*; an increase of 10 agents reduces p_c to 10%:

$$If\ 10(1-i) < n_j \leq 10i;\ p_{c_j} = E_j * \left(1 - \frac{i-1}{10}\right)$$

Where n_j is the number of agents at patch *j*, p_{cj} is the probability of government at patch *j* to catch a cheater, E_j is the enforcement level at patch *j*, and $i \in \{1,2,\ldots,5\}$.

In this version of the model, we do not include technological innovation, only learning the local context. Hence unsatisfied agents may copy the attributes (*S*) of the more satisfied agent in the same cell with the highest fitness (i.e., accumulated energy stored).

The enforcement has a cost to governments. Although we don't explicitly model the payment for enforcements by governments, we assume that some governments are more willing to invest in monitoring and sanctioning than others, and that governments do not have infinite resources for monitoring and sanctioning. The net enforcement cost is proportional to the number of agents in the cell but it is reduced by the income from penalties:

$$netCost_j = cost * n_j - \sum_{i=1}^{n_j} F_{ij}$$

Where *cost* (=1) is the cost of enforcement, n_j is the number of agents at patch *j*, and $\sum_{i=1}^{n_j} F_{ij}$ is the total revenue from penalties at patch *j*.

The enforcement cost is accumulated each time step. If the accumulated cost of enforcement goes above a certain threshold (*Tg*), governments reduce 10% their enforcement level. With a fixed probability (I_g), governments will look to its neighbors and copy the enforcement value for the neighbor with highest fitness. The fitness of a government is the number of agents.

The energy stored by agents each time steps (E_t) is:

$$E_{t_{ij}} = E_{t-1_{ij}} + agH_i - F_{ij} - met - C_{mov} - C_{rep}$$

Where, H_i is the amount of resource harvested by agent *i* in time step *t*, F_{ij} is the punishment imposed to agent *i* by government of patch *j*, *met* is metabolism, C_{mov} is the cost of movement and C_{rep} the cost of reproduction.

If the energy stored by an agent becomes 0 or lower, the agent will die. With a birth rate (*br*), agents will reproduce. Birth rate depends on the stock of energy of agents:

$$br * \left(\frac{Et}{100}\right)$$

Offspring will reproduce the attributes of its parent. Parent and hatchling share the stock of energy from parent. Offspring will be allocated at the nearest patch (hr_{max}) with the highest resource level to avoid overpopulation in successful patches and to increase the spread of successful strategies.

At the end of each time steps the resource grows accordingly to a logistic equation:

$$R_j - H_j + r * R_j * (1 - \frac{R_j}{K_j})$$

Where R_j is the resource level at patch j, H_j is the total resource harvested at patch *j*, r is the resource growth rate, and K_j is the carrying capacity of the resource at patch *j*.

Design concepts

Emergence: The population size and resource level as well as the characteristics of agents and the enforcement level of government are emergent properties of the systems.

Adaptation: Agents adapt to the landscape by storing resources and by moving to other patches if they expect that resource is not sufficient to satisfy expectation.

Objectives: Fitness of agents is the amount of energy storage. If energy becomes 0, the agents die. Agents need to meet a minimum amount of resources to be satisfied. If this is not possible they may move to another location. Moving cost energy. The reproduction capacity of agents is related with the amount of energy storage. Governments’ fitness is the number of agents.

Interaction: Agents may interact with other agents by coping the harvesting amount of best adapted agents with the highest fitness. Governments interact with other patches by imitating the enforcement of higher fitness.

Stochasticity: The order in which agents and patches are updated is random. Other random processes are the probability of cheating, of coping other agents or governments, and of detecting cheaters.

Observation: To evaluate the model output, we observe the emergent population and resource levesl, the time steps each simulation is running, as well as the characteristics of agents and patches.

Initialization

Simulations are initialized with 5000 agents randomly allocated to cells on the landscape of 50x50 cells. Initially, each agent receives an amount of 10 units of energy. The storage rate of agents and the enforcement level of patches are uniformly distributed. Resource is initialized at half of its carrying capacity. Each simulation consists of 5000 time steps to explore the long-term dynamics.