THE EFFECT OF SPATIAL HETEROGENEITY AND MOBILITY ON RESOURCE USE IN SOCIAL-ECOLOGICAL SYSTEMS

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Purpose

The purpose of the model is to analyze how agents' mobility (i.e. the extent agents can move) affects the performance of social-ecological systems in different landscape configurations (spatial distribution of resource richness: homogeneous, uniform, normal, and exponential).

Entities, state variables, and scales

The entities of the model are agents moving and harvesting resources in a 50x50 torus landscape. There are two types of agents with different harvest strategies: cooperative and selfish. Agents also differ in their location, the amount of resources that they are willing to store, and their stock of energy. Agents may copy the strategy and desired storage level of more satisfied agents in their same location. Each patch has an amount of resource which grows by the logistic growth function. Each patch might have from 0 to n agents. In this version, institutional arrangements, like property rights, are not included. The model runs for a period of 5000 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.

Parameter	**Description**	**Value**
X_S	Sustainable harvest level	0-k
ar_{max}	Maximum distance around the patch where agent is located in which agent can set its potential destination	1,5,25
μ	Reproduction rate of agents	0.03
C_{mov}	Cost of mobility	0.6
Crep	Cost of reproduction	$E_t / 2$
H_D	Desired harvest level of agents	0-1
E_{t0}	Initial energy level of an agent	10
E_t	Accumulated energy of agents	>0
H	Total resource harvested at each patch	0-n
hr_{max}	Radius around patches as potential destinations for offsprings' settles	5
I_a	Probability of agents copying the attributes of other agents in the same patch	0.2

Parameter	Description	Value
k	Carrying capacity of resource	100 for the homogeneous landscape
met	Metabolism of agents	0.3
n	Number of agents in patch	0-n
F	Amount paid by cheaters	0-1
P(0)	Initial population size	5000
p_c	Probability of catching a cheater	0-1
p_m	Probability of random movement of agents	0.2
R	Resource level of each patch	0-*k*
r	Growth rate of resource	0.075
S	Storage level of agents	0-1
	Initial probability of being selfish	0.5

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, cooperators 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*.

Selfish agents harvest more than x_S if the desired amount of resource (H_D) is higher than the x_S. With a certain probability (p_c), agents who harvest more than x_S are caught and pay a penalty fee (F_i).

$$F_{i=}(H_{Di} - x_{Sj}) * 2$$

The value of F_i is 0 if agent *i* is not caught or harvests an amount equal or less than x_S.

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*) and strategies (cooperative, selfish) of the more satisfied agent in the same cell with the highest fitness (i.e., accumulated energy stored). In addition, with a certain probability (p_m) selfish agents will become cooperative or vice versa. We included pm to have always both types of agents in the population.

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_i is the fee imposed to agent *i*, *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 (b_r), agents will reproduce. Birth rate depends on the stock of energy of agents and a reproduction rate (μ):

$$b_r = \mu * \left(\frac{Et}{100}\right)$$

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.

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 proportion of cooperators in the population 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.

Interaction: Agents may interact with other agents by coping agents with higher fitness.

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

Observation: To evaluate the model output, we observe the emergent population and resource levels, as well as the proportion of cooperators in the population.

Initialization

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