# The Harvester Model

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## I. Purpose

This model is derived from a model described by Pérez and Janssen (2015[i]), but is simplified and focused on a different purpose. The model addresses the general issue of cooperative vs. selfish behavior in social systems. Natural selection is believed to be driven mainly by selfishness ("survival of the fittest"), yet cooperative societies often offer higher overall success to their members. Selfish individuals are likely to be even more successful when competing in a society of mostly unselfish individuals, compared to competing with other selfish individuals. How can cooperative behavior persist in competition with selfishness? One answer is via punishment: if selfish individuals are sometimes caught and fined for using more resources than cooperative individuals, they may lose enough of their advantage to allow the cooperative individuals to persist. This model is designed to explore how punishment affects co-existence of cooperative and selfish individuals, in a very simple system that loosely resembles an agricultural society. It also explores the interacting effect of landscape structure—how the resources harvested by the individuals are distributed over space. Example analyses the model can address are: (a) How does the risk of punishment affect overall abundance and harvest by cooperative and selfish harvesters? (b) How does the risk of punishment affect the average level of "greediness" in selfish harvesters? (c) How do the answers to (a) and (b) depend on the level of spatial variability in resource availability?

## II. Entities, state variables, and scales

The model represents space as a two-dimensional landscape made up of square patches. These patches can be thought of as small regions or villages within which resources are produced and shared by the harvesters that occupy the patch. The landscape is made up of 50 × 50 patches; distance units and patch size are arbitrary.

Time is represented as steps that represent the time within which resources are produced and consumed; one time step can be thought of as a year with its resource growth and harvest cycle and one cycle of harvester reproduction. Simulations have a standard duration of 1000 time steps.

### A. Patches

Patches have two state variables. *Resource* is a dynamic variable representing the amount of resource currently available for harvest, in arbitrary energy units. *Max-resource* is a static variable that varies among patches and is the maximum value that *resource* approaches if there is no harvest for many time steps. The resource growth submodel uses *max-resource* in updating the value of *resource*.

### B. Harvesters

Harvesters are the agents that consume resources and potentially move among patches. Their state variables describe their location, their behavior, and their energy state. Location is tracked as the patch occupied by a harvester. The variable *behavior-type* has a value of either "cooperative" or "selfish", distinguishing these two types of harvesters. Harvesters of type "selfish" have a static state variable *greediness* that represents how much resource they attempt to harvest and need to be satisfied. The value of *greediness* is between zero and one. The dynamic variable *energy* is the harvester's current energy state, in the same energy units as *resource*. *Harvest* is a variable used only to record how much resource was harvested in the current time step.

## III. Process overview and scheduling

The following actions are executed on each time step, in the following order. Within each action, the order in which harvesters execute it is randomized each time step, to represent the lack of a hierarchy.

1. Patches grow resource, regenerating the material that harvesters consume (the resource growth submodel, detailed below). The rate at which patches grow more resource varies nonlinearly with amount that resource has been depleted below its maximum level, so that the maximum rate of resource growth (and, therefore, harvest) is at an intermediate level of harvest (explained in the harvest submodel).

2. Harvesters harvest resource (the harvest submodel). There are usually many more harvesters than patches, so harvesters can either share or compete with the other harvesters on their patch. The cooperative harvesters share: each consumes an amount that would maximize long-term harvest if all harvesters on the patch took that same amount. The selfish harvesters compete: each tries to consume an amount greater than cooperative harvesters do, with that amount depending on their *selfishness* variable.

3. Selfish harvesters are subjected to potential punishment, a "fine" that takes away some of their energy (the punishment submodel).

4. Harvesters move to a new patch if they are dissatisfied with their harvest (the resettlement submodel).

5. Harvesters die if their energy is completely consumed (the death submodel).

6. Harvesters reproduce, producing at most one new harvester of the same type (the reproduction submodel). The probability of reproducing increases with the harvester's value of *energy*.

7. Model outputs (the "Observation" design concept) are updated.

## IV. Design concepts

### A. Basic principles

This model addresses two important concepts of social science: the evolution of cooperation and management of shared ("common-pool") resources. How cooperative behavior can arise and persist in a society of selfish individuals has been the subject of numerous models, many using the “prisoner’s dilemma” game as a framework (e.g., Axelrod 1984[ii]). This model addresses this question in the framework of shared harvest or shared use of common resources. How social groups can share common resources to their mutual benefit and avoid the “tragedy of the commons” (Loyd, 1833[iii]) has also been extensively studied and modeled, prominently in the work of Elinor Ostrom. In this model, “cooperative” harvesters consume a resource at its maximum sustainable rate, so the system is expected to be most productive when all harvesters are cooperative. However, the system also has “selfish” harvesters that can consume more than the sustainable rate, raising questions about how selfish behavior—and punishment to deter it—affect the system’s productivity.

## B. Emergence

Key outcomes of this model are the total number of cooperative and selfish harvesters, their spatial arrangement (are they mixed together or isolated?), and the total harvest, which can be considered a measure of the whole system’s productivity. These outcomes emerge from the rate of resource production and the methods by which the two kinds of harvesters decide how much resource to harvest. Because harvesters can move, these results also emerge in part from the spatial distribution of resources and how harvesters decide when and where to resettle.

The degree of greediness among selfish harvesters also emerges from model mechanisms. When selfish harvesters reproduce they produce new selfish harvesters that inherit the parent’s value of *greediness*. More successful harvesters are more likely to reproduce, so *greediness* is actually subject to “evolution” in the population.

## C. Adaptation

The model includes two kinds of adaptive behavior by harvesters, although the first is not represented explicitly as a decision. This first adaptation is adjusting harvest to the amount of resource available in the patch (the harvest submodel): cooperative harvesters adjust their harvest so that, if only cooperative harvesters occupied the patch, maximum sustained yield would be obtained. Selfish harvesters adapt to resource availability by using the harvest rule that provides highest harvest.

The second adaptive behavior is deciding to resettle in a new patch if harvest is unsatisfactory (the resettlement submodel). The decision of whether to resettle is stochastic, but the choice of a new patch is made to maximize a specific objective.

## D. Objectives

When harvesters resettle, they select the patch, among the available alternatives, with highest current value of *resource*. It is important to understand this objective does not clearly maximize the harvester’s future harvest, energy level, reproductive output, etc. For example, a patch may have highest resource availability because it has a low resource production rate and is therefore occupied by few or no harvesters, while the most productive patches are already occupied by harvesters that consume all their resources. A productive patch could also not provide high future harvest if multiple harvesters move into it.

## E. Learning

The model includes no learning.

### F. Prediction

Harvesters do not use explicit prediction in their adaptive behaviors. However, the objective used in the resettlement behaviors is based on the implicit prediction that the patch with currently high resource will provide high harvest in the future. As discussed above, this prediction could often be wrong.

### G. Sensing

The harvest obtained by each harvester depends on how many others are in the patch (the harvest submodel), so harvesters are assumed to sense how many harvesters are in their patch. The resettlement submodel assumes harvesters know which surrounding patch has the highest value of *resource*.

### H. Interaction

The harvesters interact with each other indirectly via competition for their patch's resource. Punishment is often a type of interaction, in that a society imposes the punishment on an individual. However, in this model punishment is not clearly represented as an interaction; e.g., fines imposed on selfish harvesters are not made available to others.

### I. Stochasticity

The model landscape is created by drawing each patch's value of *max-resource* from a random distribution. This approach is used because variability among patches in resource production is considered important, but the amount and characteristics of this variability need to be controlled. Alternative distributions (uniform, normal, and exponential) are used to represent different types of variability among patches. There is no spatial correlation in *max-resource*: each patch's value is independent of the value of adjacent patches.

The punishment, resettlement, and reproduction submodels are each partially stochastic, as a way of inducing variability and controlling the rate of punishment, movement, and reproduction.

### J. Collectives

The harvesters on a patch could be thought of as a simple collective because they intentionally share its resources. However, the model does not treat patches explicitly as collectives.

### K. Observation

Key results are the total number of cooperative and selfish harvesters, their spatial arrangement, and the total harvest. The total numbers of cooperative and selfish harvesters are plotted over time. Their spatial arrangement is displayed visually via the NetLogo View, with patches shaded by *max-resource* and harvesters colored by behavior type. The production of resource (increase in resource, in the resource growth submodel) is observed via file output of the total production over all patches, on each time step. Harvest of resource is observed by file output of the total harvest, summed over all harvesters, at the end of each time step.

## V. Initialization

### A. Landscape and patches

Initialization begins by setting the value of *max-resource* of each patch. The user selects one of four optional distributions of this variable, with the distribution treated as a model parameter. Upon initialization, the value of *max-resource* for each patch is drawn randomly from the selected distribution. For all four distributions, the mean of *max-resource* is a model parameter *max-resource-mean*, which has a standard value of 100 energy units. The four alternative distributions are:

- Homogeneous landscape: all patches have *max-resource* equal to *max-resource-mean*.
- Uniform: *max-resource* is drawn from a uniform distribution with minimum of 0.5 *max-resource-mean* and maximum of 1.5 *max-resource-mean*.
- Normal: *max-resource* is drawn from a normal distribution with mean of *max-resource-mean* and standard deviation of 1/3 *max-resource-mean*.
- Exponential: *max-resource* is drawn from an exponential distribution with mean of *max-resource-mean*. (Exponential distributions have few high values and many low values.)

Next, the patches' value of *resource* must be initialized; it is arbitrarily set to half of *max-resource*.

### B. Harvesters

Simulations start with 5000 initial harvesters, which have their state variables initialized in these ways:

- Location is set by moving the harvester to a randomly selected patch.
- *Behavior-type* is assigned randomly to either "cooperative" or "selfish", with equal probability of each type.
- For selfish harvesters, the value of *greediness* is drawn randomly from a uniform distribution between 0.0 and 1.0.
- *Energy* is set to 10 energy units.

## VI. Input data

No time-series input data are used.

## VII. Submodels

### A. Resource growth

Resource growth is modeled using a simple logistic model, which assumes the amount of resource produced in a time step increases and then decreases as *resource* increases (Figure 1). The equation for updating *resource* is:

$$\mathit{resource} = \mathit{prev\text{-}resource} + (\mathit{growth\text{-}rate} \times \mathit{prev\text{-}resource} \times (1 - (\mathit{prev\text{-}resource} \,/\, \mathit{max\text{-}resource})))$$

where *resource* is the value of *resource* in the current time step, *prev-resource* is the value of *resource* after being updated in this submodel the previous time step minus the total harvest by all harvesters in patch during the previous time step, and *growth-rate* is a parameter with value of 0.075.

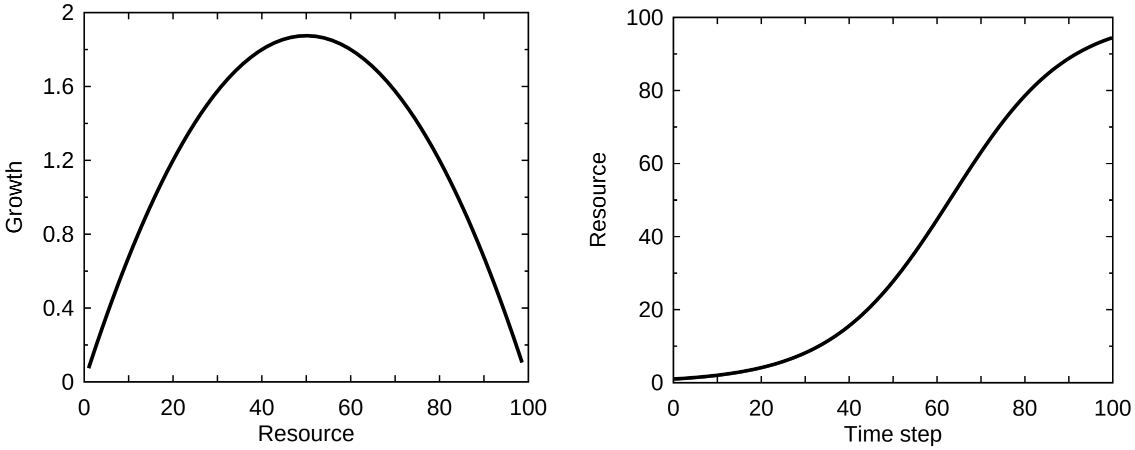

Figure 1. The resource growth submodel, assuming *max-resource* is 100 units. Left: growth (resource produced per time step) depends on the current value of *resource*, peaking when *resource* is half of *max-resource*. Right: the resulting logistic trajectory in *resource* over time, when *resource* is 1.0 unit at time 0.

## B. Harvest

The harvest submodel updates a harvester's value of the state variables *harvest* and *energy*.

Cooperative harvesters (with *behavior-type* = "cooperative") are assumed to harvest the amount that each occupant of a patch would get if each got an equal share of the "maximum sustainable yield" (MSY) of the resource. MSY is the harvest rate that maximizes long-term resource production and harvest, and can be shown mathematically to equal (*max-resource*×*growth-rate*)/8 for the logistic model of resource growth. Therefore, the harvest of a cooperative harvester is equal to a variable *cooperative-harvest* = MSY / *num-harvesters* where *num-harvesters* is the number of all harvesters on the patch. The value of *harvest* for cooperative harvesters is set to *cooperative-harvest*.

Selfish harvesters are assumed to desire a higher harvest, the variable *selfish-harvest*, which is equal to *maintenance-energy*×(1 + *greediness*). *Maintenance-energy* is a harvester parameter representing a harvester's energy requirement per time step, with value of 0.3 energy units. However, *selfish-harvest* may sometimes be less than *cooperative-harvest*, so for selfish harvesters, *harvest* is set to the highest of *selfish-harvest* and *cooperative-harvest*.

For all harvesters, the value of *energy* is updated by adding *harvest* to it.

## C. Punishment

This harvester submodel determines whether energy is lost due to punishment for selfish harvesting. A variable *fine* represents the energy lost this way. The parameter *punishment-probability* is the risk of being punished for harvesting more than cooperative harvesters do. If the value of *harvest* was higher than the value of *cooperative-harvest* in the harvest submodel, punishment is simulated as a stochastic event with probability *punishment-probability* of occurring. *Punishment-probability* is a key model parameter because examining the effect of punishment is a main purpose of the model; the parameter's standard value is 0.2. If punishment occurs, then the value of *fine* is two times the amount by which *harvest* exceeded *cooperative-harvest*.

The value of *fine* is subtracted from the harvester's value of *energy*.

### D. Resettlement

This submodel is executed by each "dissatisfied" harvester: those whose value of *harvest*, for the current time step, was less than desired. For cooperative harvesters, the desired harvest is the minimum energy need, equal to the parameter *maintenance-energy*. For selfish harvesters, the desired harvest is the value of *selfish-harvest* calculated in the harvest submodel.

Each dissatisfied harvester has a probability of 0.5 of moving to the neighboring patch (one of the eight surrounding patches) with highest current value of *resource*. When a harvester moves, none of its state variables change except its location and *energy*; *energy* is reduced by the cost moving. This cost is the parameter *move-cost*, with a value of 0.6 energy units.

### E. Death

This submodel represents the maintenance energy costs of harvesters and their death due to lack of energy. Maintenance costs are represented by the parameter *maintenance-energy*. The value of *energy* is updated by subtracting *maintenance-energy*. If the result is less than or equal to zero, the harvester immediately dies and is removed from the simulation.

### F. Reproduction

This submodel determines whether a harvester creates an offspring and, if so, creates the new harvester. Reproducing is a stochastic event with probability increasing with the harvester's energy. The probability of reproducing is equal to 0.0003 × *energy*.

When a harvester produces an offspring, its value of *energy* is reduced by half. The offspring is a new harvester created immediately, with state variables set as follows:

- Location is set by moving the new harvester to the patch with highest value of *resource*, within a radius of 5 patches.
- *Energy* is set to its parent's value (which is half the parent's pre-reproduction energy).
- All other state variables, including *greediness*, are set to the parent's value.

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[i] Pérez, I., and M. A. Janssen. 2015. The effect of spatial heterogeneity and mobility on the performance of social–ecological systems. Ecological Modelling 296: 1-11.

[ii] Axelrod, R. 1984. The evolution of cooperation. Basic Books, New York NY.

[iii] Lloyd, W. F. 1833. Two lectures on the checks to population (Oxford Univ. Press, Oxford, England, 1833), reprinted (in part) in Population, Evolution, and Birth Control, G. Hardin, Ed. (Freeman, San Francisco, 1964), p. 37.