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Modelling the emergence of resource-sharing conventions: an agent-based approach

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Abstract

This paper presents an agent-based simulation framework for the analysis of the emergence of resource-sharing conventions. The model is based on Sugden's article entitled "Spontaneous order", which looks at the conditions under which conventions regarding access to a natural resource become established. The aim of the model is to explore the potential of agent-based modelling for the analysis of these questions. First, the structure of a simulation model based on the example of driftwood collection used by Sugden is presented. Second, simulations of various scenarios about the behavioural rules followed by agents are described, and simulation results are presented. The paper concludes with a brief discussion of the advantages of agent-based models for analysing social processes such as the emergence of conventions regulating access to natural resources.

Keywords:
Conventions, natural resources, multi-agent systems

In a fishing village on the Yorkshire coast there used to be an unwritten rule about the gathering of driftwood after a storm. Whoever was first onto a stretch of the shore after high tide was allowed to take whatever he wished, without interference from later arrivals, and to gather it into piles above the high-tide line. Provided he placed two stones on the top of each pile, the wood was regarded as his property, for him to carry away when he chose. If, however, a pile had not been removed after two more high tides, this ownership right lapsed (...). We can be sure that the inhabitants of a fishing village would not have appealed to law courts or police to enforce a custom about driftwood. Somehow this rule was self-enforcing

R. Sugden (1989: 90)

Introduction

1.1

In his article entitled "Spontaneous order", Sugden (1989) analyses the conditions under which collective rules regulating access to a natural resource can evolve and maintain themselves without conscious design, and without external enforcement. The author adopts a critical perspective with respect to classical game-theoretic approaches to this issue. According to Sugden, the problem of access rules is a typical case of co-ordination games with more than one uniquely rational outcome, with the ensuing difficulties for classical game-theory in predicting which outcome may obtain: agents following a particular rule will be guided by something more than the axioms of rational choice as normally understood by economists.

1.2

As an illustration, he cites the example of a self-enforcing resource-sharing arrangement on the coast of Yorkshire, in England, where people compete for the gathering of driftwood brought to the shore by storms. The arrangement, he stresses, can be looked at from the perspective of its efficiency properties. The allocation of a stretch of the shoreline to the first who gets there avoids the allocation of too much labour to the wood collection activity; the ownership rights to properly marked wood piles avoids people having to monitor and protect their piles. In effect, the arrangement thus enhances the efficiency of driftwood collection, relatively to a free-for-all situation.

1.3

Such efficiency properties, however, are not much help in explaining why and how this particular arrangement - or convention - became established. Among the other possible arrangements that could have come about for allocating access to driftwood, the author mentions taking turns based on days of the week or using a lottery. Either of these, he notes, could have proved more efficient, as it would avoid people wasting resources in the race-to-shore competition.

1.4

Sugden is interested in the processes leading to the emergence of such conventions in a collective, without resorting to the hypothesis of an external, over-arching, agent capable of enforcing a particular rule. He considers that this question can be cast in terms of a co-ordination problem in an evolutionary game, which allows him to define a convention as an evolutionary stable strategy:

The idea here is that a convention is one of two or more rules of behaviour, any one of which, once established, would be self-enforcing. (p. 96)

He then focuses his analysis on the process by which conventions evolve in a collective, raising the questions of (i) how a convention starts to evolve, i.e. significantly more people follow it than follow any other convention; and (ii) what self-reinforcing processes lead the convention to become established in the collective. Sugden analyses various factors which may help to respond to these two questions, including the prominence of certain forms of co-ordination and the role of common experience in this respect, as well as the versatility of particular conventions.

1.5

The aim of this paper is to present an agent-based simulation framework which was developed in order to explore the potential of agent-based modelling for the analysis of these questions. Agent-based modelling of social phenomena has developed rapidly in recent years (Gilbert and Doran, 1994; Epstein and Axtell, 1996; Kohler and Gumerman, 2000). The approach appears particularly well-suited to the type of issues considered by Sugden. It allows one to tackle explicitly questions of process and emergence in the economy (Gilbert, 1995), which have presented difficulties to traditional modelling in economics. In particular, it allows the explicit representation of a heterogeneous collective of agents of variable sizes, and the analysis of its evolution at both individual and collective levels.

1.6

The paper is organised as follows. First, the structure of a simulation model based on the metaphor of driftwood collection described by Sugden is presented. Second, to illustrate the type of dynamics that this model can represent, simulations of various scenarios regarding the behavioural rules followed by agents are described, and simulation results are presented. The paper concludes with a brief discussion of the advantages of agent-based models for analysing social processes such as the emergence of conventions regulating access to natural resources.

Approach and methods

2.1

The simulation model uses CORMAS (*Common-Pool Resources and Multi-Agent Systems*), a multi-agent simulation platform specifically designed for the simulation of renewable resource management systems (Bousquet et al., 1998). The platform, based on the programming environment VisualWorks, was used because it is dedicated to the modelling of interactions between individuals and groups using natural resources, and because it includes a spatial dimension[1].

2.2

The model has three main components (see Figure 1) [2]:

1. a spatial grid (" *the beach* ");
2. a passive object (" *driftwood* ") which is distributed in the grid, any single cell having the capacity to store an unlimited number of pieces of wood;
3. social agents (" *driftwood collectors* ") having the capacity to move over the spatial grid, and to collect driftwood.

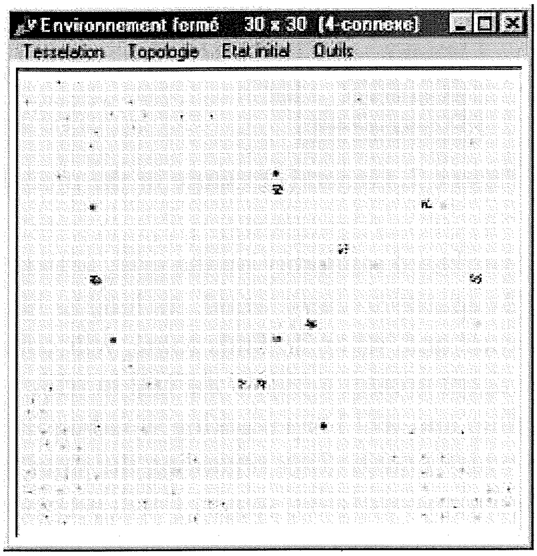

Figure 1. The spatial grid with driftwood (black dots), wood piles and collectors (with different colours reflecting varying behaviour of collectors).

General structure of the model

2.3

The general structure of the model is as follows.

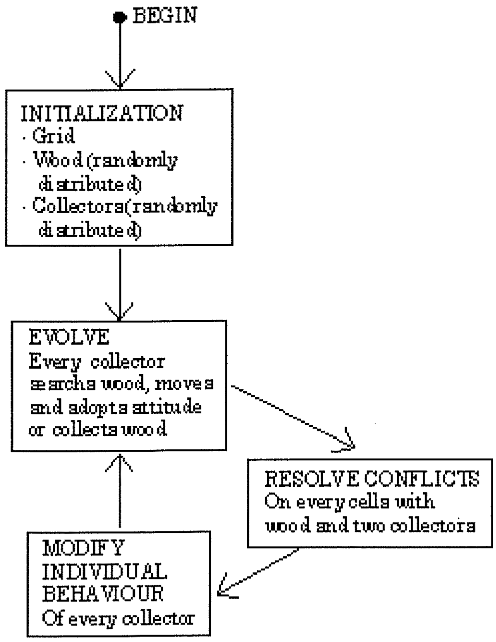

Figure 2. General structure of the model

2.4

Initially, the supply of wood is distributed randomly on the grid, with no more than one piece of wood per cell. Each agent has a limited capacity to carry wood. As long as his carrying capacity is not reached, an agent will look for wood and, when he finds some, will collect it. When he reaches his maximum carrying capacity, the agent creates a pile in the cell in which he picked up his first piece of wood. He can then go on collecting, and will keep stacking wood on the same pile for the rest of the simulation. To study the way in which conventions regarding the sharing of wood can evolve, rules of individual behaviour are specified at two different stages in this process:

1. *at the stage of search*, assumptions are tested regarding the way in which agents define the set of possible actions in terms of moving towards observable driftwood;
2. *at the stage of collection*, assumptions are tested regarding the way in which agents behave when they meet on a cell containing driftwood to be collected.

A basic model of search and collection behaviour

2.5

First, a basic model of search and collection behaviour is specified, in which no particular rule concerning access to driftwood is postulated. Basic behavioural rules are as follows.

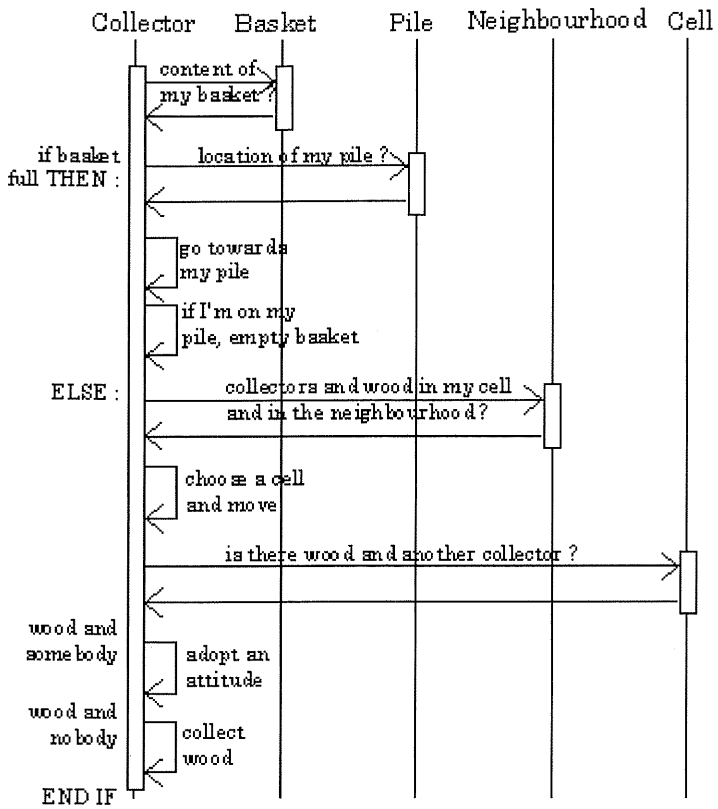

Figure 3. Behavioural rules

Search

2.6
Agents are given a capacity to observe their surroundings within a given range. They can identify driftwood, both stranded pieces and existing piles, as well as other agents in their vicinity. When observing wood in a cell, agents can distinguish between a pile and a single piece of driftwood left uncollected.
2.7
The range of visibility can be fixed anywhere between zero and the entire grid, in order to allow for variable levels of individual information about the availability of wood and the actions of other agents. While no driftwood is observed, an agent will move randomly to a neighbouring cell in the grid. As soon as driftwood comes within sight, the agent will move as quickly as possible to the cell in which the wood is located. The only constraint on possible movements is that no more than two agents may meet on the same cell in any time step.

Collection

2.8
As long as he is alone on a cell containing wood, and as long as he has not reached his carrying capacity, the agent will pick up wood piece by piece. The only rule specified in this version regarding collection is for cases where two agents meet on a cell containing wood. When this is the case, it is assumed that the agents play a " *Game of Chicken* ", with the following structure. Each player has a choice between an aggressive strategy (to pick up a piece of wood) and a conciliatory strategy (to seek compromise, but to let the other player pick up the wood if he looks determined to do so). The payoff matrix for this game is a follows:

Table 1: The payoff matrix of the game

		Player 2	
		Aggressive	Conciliatory
Player 1	Aggressive	-1/-1	1/0
	Conciliatory	0/1	0.5/0.5

1 = get a full piece of wood; 0 = get nothing; 0.5 = share the piece of wood

2.9
The value of 0.5 in the payoff matrix means that there is an equal chance for both agents to collect the piece of wood when both are conciliatory. A random procedure in the model determines which agent wins the piece of wood in any particular encounter.

2.10
The key assumption here is that, while each player prefers being aggressive if he knows that the other player will be conciliatory, he will prefer being conciliatory if he can be sure that the other player will be aggressive, i.e. agents will prefer backing off to avoid conflict. This is modelled by assuming that each agent's payoff in case of conflict is negative.

2.11
The choice of this game structure in the model is motivated by its use in Sugden's article as a basis for the understanding of the emergence of conventions. Indeed, games of this type are specific in that they have more than one Nash equilibrium, i.e. more than one pair of strategies which are simultaneously best replies to the opponent's strategy. Sugden argues that the only stable equilibria in an evolutionary game of this kind are the ones in which the two players behave differently. This implies that the players be distinguished in a way leading them to reach different conclusions regarding their own best strategy in a particular interaction.

2.12
In the initial version of the model presented here, it is assumed that agents confronted with a wood-sharing conflict adopt an aggressive strategy with a given probability equivalent to the "degree of aggressiveness", specified when initialising the model. If located on a wood-pile, the agents repeat the game until no wood remains to be collected, or until either of them has reached his carrying capacity.

Simulation experiments

3.1
The arrangement Sugden describes in his work can in fact be separated into three different rules: (i) a first come - first served rule for the allocation of access to a stretch of the shore; (ii) a property rule for wood gathered into marked piles; and (iii) a first come - first served rule for the collection of wood on abandoned piles.

3.2
The simulation framework was used to analyse these three rules based on variations in the assumptions used to simulate agent behaviour. The emphasis in this article is on simulating various processes by which the convention regarding the property of marked wood-piles could become established in this metaphorical model. The main focus is thus on strategies of avoidance of wood piles, and their diffusion in the collective. For this reason, relatively little use is made here of the rules regarding collection behaviour and the resolution of conflicts, other than as a means to allocate wood where these conflicts occur (following the principles described above). In this, the analysis presented here departs from Sugden's article.

3.3

This section presents some of the simulation experiments which were carried out using the model. After introducing the basic version of the model, two general mechanisms are simulated with variants in their definition: (i) *peer pressure* as a control on individual behaviour; (ii) *imitation* as a determinant of individual strategies. The conditions under which a property convention may become established in this metaphorical model are discussed in the following section of the paper, based on the simulation results.

The basic model

3.4
In the basic model, no particular rule regarding the property of wood-piles was postulated. Simulations were used to understand the role played by different parameters of the competition for wood thus modelled, e.g. the impacts of varying wood availability, the effects of relative distances between wood piles, or the consequences of various assumptions regarding agent behaviour (range of vision, degree of aggressiveness).

3.5
In order to test for the performance of aggressive versus conciliatory strategies, simulations were run with 25 agents and 300 pieces of wood on a 900-cell grid[3]. Agent strategies were held constant during the simulation, i.e. each agent had a strategy fixed at the beginning (aggressive or conciliatory). 20 simulation runs using different distributions of agent strategies were then implemented, and the average size of wood piles in the system was tracked.

Peer pressure

3.6
In this version of the model, the rule for search behaviour was modified in two different ways:

1. Agents head towards existing wood piles only if no one is observing them. If another agent is visible (i.e. if he can also observe them), they will avoid cells in the grid which contain wood piles, hence they will not pick wood from existing piles.
2. Agents become identified as wood pile owners if the size of their pile is above a given limit. It is then assumed that it becomes in their interest, as pile owners, to enforce the rule of property. This is modelled by assuming that all agents will avoid cells containing wood piles if a pile owner is visible. It amounts to assuming that pile owners have the means to deter other agents from cheating (for example through the imposition of monetary or psychic costs).

3.7
Two variants of this second rule were simulated. In the first variant, pile owners enforce the property rule, but do not respect it when no other owner is watching. This version of the model illustrates problems of imperfect enforcement of a collective rule. In the second variant, pile owners respect (and enforce) the property rule in all cases. This is more akin to a moral norm or a code of conduct among a group of pile owners. In effect, members of this group adopt a particular rule of conduct whatever the consequences for them in terms of resource collection.

3.8
As simulations showed that the initial location of agents induced large variability in the results, it was decided to start all simulations with the same geographical configuration in order to study the effects of varying parameter values. This variant of the model was run 10 times for each set of parameter values (see table below), with 10 agents and a total supply of 300 pieces of wood.

Table 2: Effects of varying parameter values

	#1	#2	#3	#4	#5
Group of simulation runs	#1	#2	#3	#4	#5
Minimum pile size for being pile-owner	20	20	20	15	25
Range of vision	3	1	5	3	3

With both variants, changes in the numbers of property-respecting agents and non-respecting agents were tracked during simulation runs.

Imitation

3.9
In this version of the model, two variants of the rule for search behaviour were simulated:

1. Agents compare the wood piles they observe while searching for wood with their own pile, and if the observed pile is larger than their own (including the wood they are currently carrying), they adopt the strategy of its owner with regards to the property rule, i.e. they decide to respect it or not.
2. As in the previous version of the model, agents become identified as pile owners if the size of their pile is above a given limit. As pile owners, they will enforce the rule of property, hence all agents will avoid cells containing wood piles if a pile owner is visible. In this variant of the model, pile owners will initially respect property in all circumstances (see the second variant of the peer pressure model above).

3.10
However, they will also observe the behaviour of the other agents around them. If it appears to them that more than one half of the agents they can see (themselves included) is not respecting the property rule, agents will change their strategy to non-compliance with the rule (except if forced to comply by a neighbouring pile owner). Pile owners may thus disregard the property rule if they feel that only a minority respects it. Furthermore, they will change their strategy if, while emptying their basket on their pile, they notice that enough wood has been stolen from it for its size to be below the pre-determined threshold for pile-ownership status.

3.11
In both variants, the initial population of agents was randomly mixed, with some agents respecting property and some collecting wood without respect for other's piles, and the system was allowed to evolve. Again, changes in the numbers of property respecting agents and non-respecting agents were tracked during the simulation runs.

Simulation results

The basic model

4.1
As expected, a general feature observed in all simulations was the central role of the initial size of the wood resource in the system. In terms of average performance of the wood collection activity (measured as the variance of wood pile sizes in time), the system became increasingly unstable when the initial availability of wood relative to the number of collectors was reduced.

4.2
Simulation runs showed that there was no significant difference between the size of wood-piles of aggressive and conciliatory agents in this first version of the model (see figure below), the exact results depending on the initial allocation of wood piles in space.

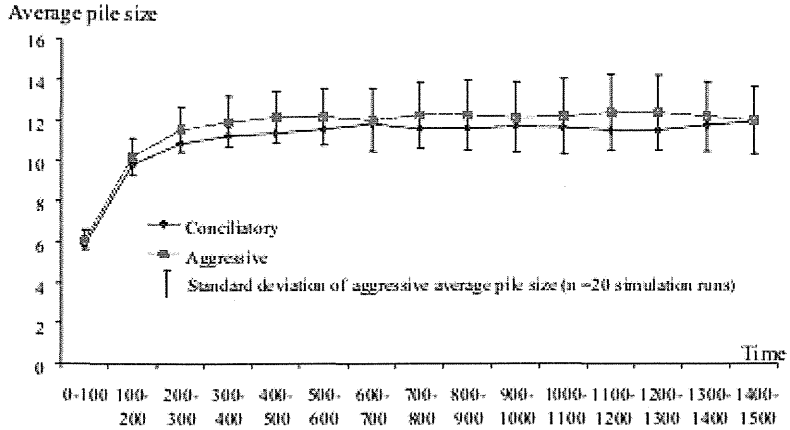

Figure 4. Evolution of average pile size of conciliatory and aggressive agents during 20 simulation runs (25 agents, wood resource = 300, range of vision = 3)

Peer pressure

4.3
The range of vision of agents proved to be a key parameter in the first variant of the peer-pressure version of the model. With agents able to observe the entire area, full compliance with the property rule was obtained. But as soon as the range of vision of agents was less than the entire area, there were situations in which agents could move to wood piles without being observed, and less than full compliance was then observed.

4.4
In the second variant, the initial distribution of agents and their number relative to the availability of wood played a key role, as they determined the length of time which agents had to accumulate wood (and become members of the group of pile owners) before someone started stealing from their piles while they were absent, leading them back to a situation in which they could no longer claim to be pile owners (their pile being too small).

4.5
An example of the results obtained is presented below, for the second variant of the peer-pressure version of the model, and for different values of two parameters (range of vision, and threshold pile size for becoming a pile owner). As all agents became property respecting after a certain length of time, the simulations were stopped when the property rule had become fully established in the collective. Analysis of the results is in terms of the average value of this length of time.

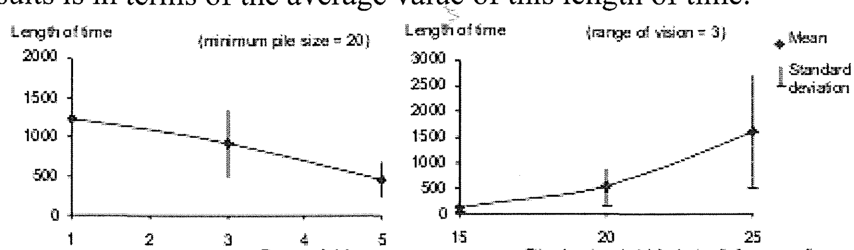

Figure 5. Influence of two key parameters on the mean and the standard deviation of length of simulations (10 agents, wood resource = 300)

4.6
The results show that the wider the range of vision, the quicker the simulation ran (see Figure 5). This can be explained by the fact that a wide range of vision allows greater enforcement of the property rule, thus leading to quicker accumulation of wood by individual agents in the collective. Also, when the pile size threshold is low, agents can easily create piles larger than the minimum necessary for becoming respectful of the property rule. But results showed that the duration of simulations increased

with this threshold; and that if the threshold was too high (i.e. more than 40), a stable state was never achieved.

Imitation

4.7
In the first variant of the imitation rule, simulations showed that all agents ended up respecting the property rule (see Figure 6), except in some extreme cases (e.g. with just one property-respecting agent at the beginning). This can be explained by the way search behaviour was specified. As non-respecting agents tried to take wood from existing piles, they passed near piles which belonged to property-respecting agents. If this pile was larger than their own, they became property-respecting. On the contrary, since property-respecting agents excluded cells containing wood piles from their range of movement, they had less chance of going near to wood piles belonging to non-respecting agents, and thus less chance of shifting to non-respect of the property rule.

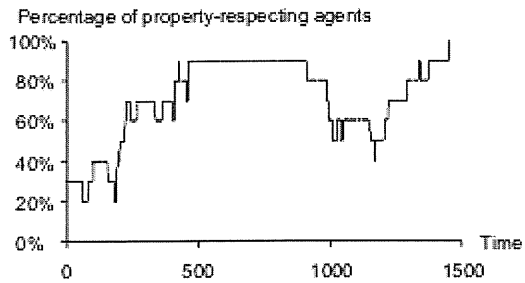

Figure 6. Evolution of rule respect during one simulation run (10 agents, wood resource = 300, range of vision = 3)

4.8
The second variant of the imitation rule was used in particular to assess the role played by the threshold limit for becoming a pile-owner, and a property-respecting agent, when imitation also plays a part in determining individual behaviour.

4.9
With a low threshold (e.g. 20 in this version of the model), the system quickly stabilised, with all agents respecting the property of wood piles (see Figure 7). This occurred after an initial reduction in the number of respecting agents due to the spatial interactions allowing some imitation of cheating behaviour, while none of the agents had accumulated enough wood to acquire pile-ownership status. After a certain length of time, with their piles increasing, agents became owners and shifted to property-respecting behaviour, and imitation re-enforced this process.

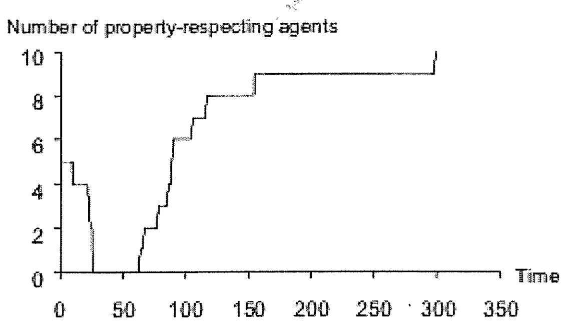

Figure 7. Evolution of rule respect during one simulation run (10 agents, wood resource = 300, cells = 900, range of vision = 3, threshold = 20)

4.10
With higher levels of this threshold (e.g. 40 in this version of the model), the system never achieved a stable state of either all-cheating or all-respecting behaviour. The two strategies co-existed, with most agents changing their behaviour many times in any simulation run. The consequence of raising the

threshold was in fact to increase the resource-scarcity constraint to which agents were confronted: because of the limited availability of wood, all agents could not become pile owners at the same time, and imitation made it possible for cheating behaviour to subsist durably in the system.

4.11

Introducing imitation as a determinant of individual behaviour also made the range of vision of agents a key parameter in the evolution of the system. Extending the range of vision of agents in this case played against the property rule, as it favoured observation of non-respectful behaviour, hence increasing the shift to non-respect. Another way to see this was to change the size of the grid while maintaining the number of agents, their range of vision, and the supply of wood. This amounted in particular to increasing the range of vision of agents. Results of such a simulation run for a low property threshold (20) are presented in Figure 8. In this case, the system remained unstable, with frequent shifting of individual behaviour from respect to non-respect of the property rule.

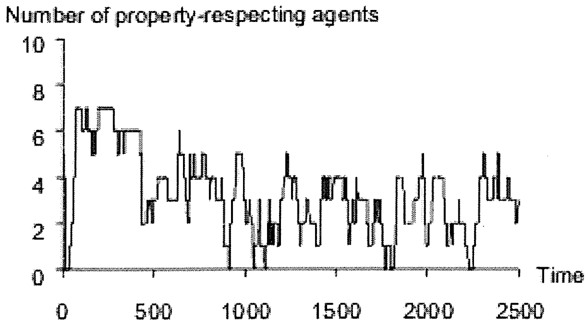

Figure 8. Evolution of rule respect during one simulation run (10 agents, wood resource = 300, cells = 400, range of vision = 3, threshold = 20)

Discussion and conclusion

5.1

The rules governing access to natural resources play a central role in the economic analysis of resource management issues. The reasoning is that where access rules are lacking, or if existing rules are deficient, there is a tendency for resources to be misallocated between economic agents and between alternative uses in the economy. An important component of resource economics has focused on the way in which changing the structure of access rights to a resource, usually by the State, could correct these inefficiencies. On the other hand, the processes by which particular access rules, including sub-optimal ones, become established and are enforced have attracted less research in economics, possibly due to the difficulties in taking explicitly into account the dynamic properties of social systems in analytical models.

5.2

The aim of developing the agent-based simulation framework described in this article was to explore the potential of agent-based modelling for the analysis of such processes. The model is based on a metaphorical example used by Sugden to discuss the issue of self-organisation in social systems, and the limitations of classical game-theoretic approaches to this issue. As already noted, our model makes relatively little use of the rules regarding the resolution of conflicts, other than as a means to allocate resources where these conflicts occur. In this, the analysis presented here departs from Sugden's article.

5.3

Simulation experiments show that agent-based modelling provides a rich framework for the study of social dynamics. The preliminary results of this simple model of resource-sharing conventions illustrate the many possibilities associated with such an approach. For example, issues discussed in the literature with respect to the role of sanctions and norms in the collective management of natural resources can be given an explicit treatment.

5.4
The model as it stands is highly simplistic in its description of individual behaviour. This was in fact one of the aims pursued by the authors, in anticipation of the difficulties that can appear in the interpretation of simulation results in complex - and more realistic - models. Despite this simplicity, the agent-based approach already allows for a degree of complexity in that it offers the possibility of modelling interactions between a large number of agents, heterogeneous in terms of individual behaviour and resource constraints.
5.5
Further developments based on this simulation framework could include:

1. The analysis of the conflict resolution mechanisms to which Sugden gives specific attention in his article. Analysing the impact of various assumptions regarding agent behaviour in repeated resource-sharing conflicts should allow testing of some of the factors proposed by the author to explain why certain conventions emerge rather than others. Agents developed in our model could have a capacity for memory and could act according to their representation of past events.
2. The specification of economic constraints on individual behaviour. The entire analysis is based on a simplistic model of wood collection behaviour. A possible way to use the model would be to include costs (including opportunity costs) and benefits as determinants of search and collection behaviour, with a profit-maximising or cost-minimising objective function for agents. The model would then allow the comparison of various scenarios from an efficiency perspective, as well as from the perspective of which collective arrangement becomes established.

Acknowledgements

The authors would like to thank F. Bousquet and C. Lepage for their support in developing the modelling platform.

Notes

[1] See http://cormas.cirad.fr for more information.

[2] Code for the model is available from the authors.

[3] This size of grid was also used for all the following simulation experiments.

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