INTERACTIONS AND ORGANIZATION IN ECOSYSTEM MANAGEMENT: THE USE OF MULTI-AGENT SYSTEMS TO SIMULATE INCENTIVE ENVIRONMENTAL POLICIES

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ABSTRACT

Since the end of the 70's, various forest policies have been implemented in the Sahel to address the problem of ecosystem degradation and the increasing need for fuelwood energy. In Niger, a new environment-oriented policy is now being implemented, in conjunction with the decentralization process and the transfer of specific forest user-rights to the local population. Incentives, regulations and new institutional arrangements are designed to take account of the forest ecosystem and forest uses. How can the robustness of policy rules be assessed when these rules are implemented in a dynamic ecological and economic environment? According to what criteria can the effects of these rules be analysed? How can a reorganization of the economic sector enhance the effectiveness of the rules?

We choose to explore these issues using a multi-agent modelling approach, based on the interactions between the forest resource, the economic agents (from harvesters to wood traders and urban fuelwood consumers) and the policy rules. We simulate scenarios for the various incentive measures which are implemented. The agent-based model offers an ecosystem-based approach to incentive measures and allows us to demonstrate how institutional arrangements, rules and rule compliance are affected by the behaviours of local actors and their interactions. The model relies on a case study of institutional change in Niger, where the new policy has led to a reorganization of ecosystem exploitation. On the basis of an initial model presented here, we illustrate how the approach based on multi-agent models can be used to study the implementation of ecosystem management rules.

INTRODUCTION

Fuelwood in the Sahel became an environmental issue in the 1980s. This can be explained by several factors: a series of severe droughts, rapid growth in urban wood demand and its consequences, and the disappearance of woodland zones around urban areas The Sahelian forest ecosystems ("bush") that supply wood resources are characterized by sparse, scrubby vegetation, with wood harvesting concentrated in geographical zones rather than on specific plant species.

Environment-oriented policies were implemented from the late 1980s, starting in Niger, with a view to developing sustainable fuelwood management practices. Similar policies have been implemented since the late 1990s in other Sahelian countries (Chad, Mali, Burkina Faso, northern Cameroon). They combine regulations (quotas and zoning of forest areas on the basis of their productivity), incentives (spatially differentiated taxes on wood trade related to the distance of exploited dry forest from urban areas, level of taxation of the fuelwood trade according to the origin of the resource, collection and distribution of taxes between stakeholders) and new institutions (rural markets) to organize fuelwood trading. The purpose of these policies is to encourage actors to adopt new modes of behaviour.

Our research concerns the implementation and the effects of these policy rules on actor categories and on wood resources in a dynamic economic and ecological environment. How can we analyse the robustness of these rules in terms of expected effects? What criteria should be used to analyse these effects? How can a reorganization of the economic sector enhance the effectiveness of the rules ?

In this paper, we present an agent-based modelling framework for the analysis of these questions. We use MAS to simulate the implementation and the effects of ecosystem management rules (Antona et al., 1998, Bousquet et al., 1999, Möhring and Troitzsch, 2001). Recent studies have reviewed the use of multi-agent systems to build economic models of natural resource use by a set of heterogeneous agents and to simulate evolution scenarios (Rouchier, 1998, Jager, et al., 2000, Jansen and Ostrom, 2001, Doran, 2001, Rouchier, 2001). This field has developed recently in agent-based modelling of social and economic processes (Gilbert and Doran, 1994, Gilbert, 1995, Epstein and Axtell, 1996, Kolher and Gumerman, 2000).

We started by developing a first multi-agent model to study the behaviour of actors subjected to these policy rules and to define criteria for assessing the effects of these rules in terms of ecological and economic dynamics. To this end, a reference conceptual model was established. It is based on data and observations concerning the biological dynamics of dryland forests and the structure of the fuelwood industry in Niger. The various actors in this economic sector and their interactions are represented using standard models of behaviour in economics (exchanges, rational behaviour of economic actors). To analyse the dynamics that can be represented by the model, we then performed simulations of various policy application scenarios. The discussion of these simulations raised new questions and led to new work in the field, culminating in a new model now under development.

ECONOMIC ANALYSIS OF MANAGEMENT ISSUES WITH MAS

The simulation model is built to analyse the system formed by the fuelwood resource, the actors in the economic sector (from harvesters, to wood traders and urban consumers) and the different management rules used. It uses CORMAS (Common Pool Resources and Multi-agent systems), a multi-agent simulation platform specifically designed for the simulation of renewable management systems. The platform is dedicated to the modelling of interactions between individuals and groups using natural resources and includes a spatial dimension (Bousquet, 1999, Bousquet et al., 1998).

As described by Arthur (1997), the agent-based modelling approach was first developed by economists to examine theoretical problems such as the economic structure of the market, the definition of equilibrium and control, the problem of individual strategies and collective coordination etc. and to analyse their solutions (Arthur, 1997). But its main interest is that it can be used to address questions, which are poorly explored by standard modelling in economics, such as the representation of interactions, the emergence of economic processes or the heterogeneity of economic agents (Axelrod, 1997, Kirman, 1997). Axtell lists the advantages and drawbacks of agent-based modelling for analysing these social and economic processes (Axtell, 2000).

In the case under study, the use of agent-based modelling enabled us to represent the combined ecological and economic dynamics of the system under study in a spatialized model. The model thus differs from standard models in resource economics in that the resource is spatially explicit. In the first version of the model presented here, we modelled agent categories and interactions between these represented agents using standard hypotheses in economics (exchanges, behaviours of actors). But the agents have a rationality limited by their representation of their environment. Here, this representation corresponds to the information used by the agents to decide what action to take with regard to the common resource and the other agents (Rouchier 2000). In this first model, this representation and the knowledge of the agents is static.

The agent-based modelling enabled us to consider heterogeneous actors, far from the fiction of the representative agent (Kirman, 1997). The modelled agents represent different actors in an economic sector. But within the group of harvesters and traders, the actors are heterogeneous, with differing initial characteristics (size, costs of actions etc…) and preferences. The modelled agents interact directly or indirectly with each other via a common exploited environment. In both cases, these interactions have a local and not global dimension.

We have thus freed ourselves from the highly restrictive hypotheses of standard economic analysis - a stable environment, homogeneous agents with no direct interactions – while retaining, for the first model version presented here, the standard hypotheses of agent behaviour.

THE MODEL: STRUCTURE AND MODE OF OPERATION

The general model structure comprises several components: agents with internal characteristics, an environment containing the agents, interactions between these agents and an organization structuring the actions of these agents within the system.

An Environment

The environment is represented by a spatial grid divided into 400 cells, the basic spatial units. The spatial grid stores and updates the state of the environment and the ongoing processes affecting it. Each cell corresponds to 10 hectares. A wood resource is distributed over the grid, with each grid cell supporting a quantity of green wood and dead wood. We have taken the density data and the growth and mortality criteria described in the literature for these bush ecosystems in Niger. These data are used to calibrate a biological model of resource growth. The dynamics of the resource are represented by a green wood growth model which also determines the quantity of dead wood available in the same cell. The dead wood disappears after several time steps if not collected. Each cell has a limited wood carrying capacity. The heterogeneity of wood distribution over the cells and the growth function represent the morphology of the ecosystem under study, known as "diffuse or tiger bush".

Agents

Social agents are divided into three categories: “harvesters”, “traders” and “consumers”. The social agents do not have information on the overall state of the resource. Each harvester agent is spatially located and has local knowledge of the resource, limited to his radius of perception and hence of movement. This is the only agent category whose behaviour is affected by his vision of the space in which he operates. Harvesters have the capacity to collect wood and move over the spatial grid, according to a personal characteristic (the scale of their farming activity) which influences the utility of the wood collection activity. The chosen behaviour rule takes account of the harvester agent attribute that reflects the

importance of his farming activity and serves to assess the opportunity cost of wood collection. The opportunity cost is compared by the agent with a criterion of expected income from wood collection, taking account of the collection distance, which is limited by the agent's representation of his environment.
We represented two configurations of wood harvesting. The one represented in figure 1 is that of a grouped system of harvesting (around a village for example). A second configuration, corresponding to greater harvester dispersion across the grid, is also simulated in the model. The different levels of wood resource productivity are shown on the grid (here green wood).

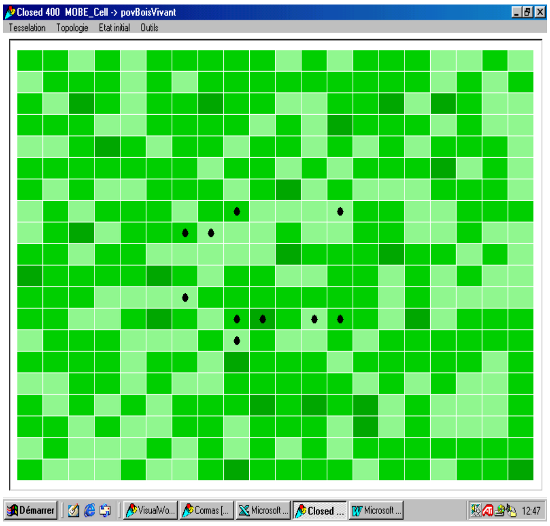

Figure 1: The spatial grid and location of harvesters.

Traders and consumers have the capacity to exchange wood. Traders are modelled as economic agents who seek to maximize their profit on the basis of their own transport capacity and transport costs. Each trader can buy wood from each harvester by means of a bilateral exchange at a price fixed by the trader at each time step.
To simplify the model, the final wood consumers are aggregated in a single "consumer" agent whose decision-making rule is represented by a wood demand function. The "consumer" agent makes no distinction between green wood and dead wood. The wood purchase price is revised by the "consumer" agent on the basis of the quantities proposed by the traders at the end of a time step.

A System of Interactions

The model includes direct and indirect interactions between agents. The direct interactions are wood exchanges between actors at different levels, i.e., between harvester and trader agents, and between trader and consumer agents. The indirect interactions are generated by the common exploitation of a single spatialized resource by the harvesters. These interactions render the collection results of a harvester dependent upon the activity of other harvesters in the same cell. They have a local and non global dimension and are thus influenced by the state of the resource and its dynamic reaction to exploitation.

An Organization of Interactions

At each time step, the agents' actions described above are organized by the model in two phases: The first phase is a "demand price" phase of information transmission from the consumer agent, who fixes this price and activates the rules of action of the heterogeneous agents – firstly traders, followed by harvesters – according to their specific characteristics and their internal calculation rules. Each harvester agent collects wood, according to his own decision-making rules, in response to a global demand from a trader agent, and then sells him the quantity collected at the price determined by the trader. The resource is updated. Exchanges are performed bilaterally between traders and harvesters.

The second phase is a phase of comparison between supply and demand at each stage, up to the consumer who reinitiates the price revision process for the following time step. The agents have no vision of the other agents or of the economic sector as a whole. The model is thus organized according to a circular representation of the economic sector.

General Structure of the Model

Initialisation

- Grid
- Green wood and dead wood (randomly distributed)
- “Harvester” agents (randomly distributed according to two harvesting configurations: grouped or dispersed)
- “Trader” agents (number, various capacity and costs of trade)
- “Consumer” agents (demand price)

↓ **Evolve**

- Consumer gives the “demand price” information to the traders
- Each trader defines, according to this information and his own capacity and cost of trade, the quantities requested and the price to be paid to the harvesters
- On the basis of the price information given by each trader, each “harvester” agent searches wood
- the harvester searches dead wood first, then green wood according to his own resource perception range and his own wood collection opportunity cost, moves and collects wood.

↓ **Update (end of the time step)**

- resources (renewal, taking account of exploitation)
- new consumer price defined on the basis of overall wood supply available from “trader" agents and the aggregate demand function of the "consumer"

Simulations :
Implementation of management rules

Zoning of the grid
Quotas by zone (global constraints to individual harvesting)
Taxes on resource use (extra-cost borne by the traders on the quantities bought from the harvesters)

SIMULATIONS

In this first model, each simulation deals with an external policy rule. In order to reach economic, social and environmental objectives, the public institution defines tools such as taxation, or environmental norms (zoning and quotas). Taxation on the use of renewable resources is designed to give a price-signal to resource users, in order to modify the costs and benefits of their action on this resource. The taxation instrument does not impose any particular behaviour upon resource users. Environmental norms such as zoning and quotas, on the other hand, aim to impose a particular mode of action and to exert a direct influence on the behaviour of actors. Policy rules appear as predefined and global constraints, restricting the behaviour of agents and their interactions.

Our hypothesis is that the effects of policy rules are dependent on the structure of physical space (distribution of the resource over space, location of the harvesting zone) and on the functioning of social networks and of interactions between actors. With a single structure of interactions (the circular representation of the sector) and identical behaviours of actors, we therefore simulated:

- a reference scenario representing the operation of the economic sector with no management instruments
- An "environmental norms" scenario with division of the exploited space into 3 zones and global quotas set at different levels for 2 zones. The third zone functions in the same way as the reference scenario.
- Two "taxation" scenarios, with a wood trade tax levied on traders. In this first model, we did not vary taxation according to the distance between the town and the exploited zone as we wished to test each instrument separately. We simulated two tax levels.

For each scenario, the simulation results enable us to analyse the environmental dynamics, represented by changes in the quantities of green wood and dead wood available on the spatialized grid. The economic dynamics are assessed on the basis of several criteria: a quantitative criterion represented by the comparative change in the quantities of wood collected, in the quantities demanded by traders and those available on the consumer market, and an "income distribution" criterion which compares the variations in income of the various actors so as to identify the winners and losers in each scenario.

For each of the various management rules, our aim is to simulate the dynamics in terms of resource availability over the medium term and in terms of variations in costs and incomes of the actors involved.

SIMULATION RESULTS

The four scenarios were simulated over 30 annual time steps. Each scenario was run 50 times. The results presented in the appended graphs are averages obtained for these 50 simulations. We use them to compare results between scenarios. The initial conditions and parameters were tested to estimate the validity of results.

Simulations 1: The Basic Model with no Taxation, no Zoning or Quotas (see figure 2)

In this basic model, no policy rules apply. The simulations serve to understand the different dimensions of competition for access to wood, i.e., the impact of resource supply variability, the effects of distance from the resource or the consequences of hypotheses concerning agent behaviour (perception range, location of harvesters on the grid, trade capacity).
With no incentive policies, the location of wood harvesting zones and the degree of perception of the resource by the harvester agent are decisive factors affecting the results obtained for the stocks of resources. With grouped harvesting, the decline of wood resources can be held in check by maintaining a volume of green wood in distant cells, whereas with dispersed harvesting, the dead wood resource has already disappeared by the 13th time step.

The transport-trade sector possesses substantial capacities that give rise to a high volume of demand by transporters, due to the slow adjustment of their trade capacity. The sharp variations in production lead to irregular market supply and although the traders regularly increase the price paid to harvesters, we note a progressive decline in profits over the sector as a whole as the simulation progresses.
In term of average performance of the wood collection activity (measured as the variance of fuelwood collection or of supply to the consumer over time), the system became instable with decreasing availability of fuelwood relative to the number of harvesters and their location in the grid.

Simulations 2: Simulations with No Taxation, but Zoning and Quotas (see figure 3)

In this simulation, the grid is divided into three zones in which different harvesting rules apply. In the first, dead wood and green wood harvesting quotas are fixed. These quotas are fixed at the start of the simulation on the basis of biological parameters relating to the resource growth model (such as maximum resource renewal of the cells in a zone). In the second zone, the quota is fixed on dead wood only, and green wood collection is prohibited. In the third zone, no rules apply, as in the reference simulation. These quotas are defined globally by zone. Once the quota has been reached, harvesting stops. The harvesters respect the quota rule.

The results demonstrate the efficacy of zoning and quotas for preservation of the resource and are largely unaffected by the harvesting pattern. The resource available on the space studied is maintained at double the level reached in the basic scenario. Indeed, the rules applied on the two quota zones offset the effects of intensive resource exploitation in the uncontrolled zone. Further to this result, it would be useful to see how model results are affected by changes in the surface area subject to quotas.
The impact on prices is less pronounced. Consumer prices remain practically identical and harvester prices increase by 5% compared with the reference situation.

While this instrument applies at the collection stage by reducing the quantities harvested and modifies the interactions between harvesters and resource, it is the traders who experience the most significant economic effects. The situation in this sector deteriorates with respect to the non-quota situation: the sector capacities remain large for several time steps before shrinking abruptly as many traders become incapable of pursuing their wood trading activities. The average margin of transporters in this scenario, initially higher than in the non-quota situation, becomes irregular before dropping sharply. We note that in Niger, the number of fuelwood traders has declined since this policy was introduced. The sector has become more concentrated and marginal businesses have abandoned their trading activity. The quota is thus a rule which permits only partial control over the system from the viewpoint of the resource and remuneration within the sector.

This simulation raises the question of compliance with policy rules. If one or more agents adopt a behaviour of non-compliance (with the quota for example), above what point does the proportion of cheating agents cancel out the effects of these regulations? Rule compliance is a factor to be tested and the cost of enforcement – not taken into account in this first model – becomes an important variable of the system.

Simulations 3 and 4: Simulation with low taxation (see figure 4) and high taxation (see figure 5) but no zoning or quotas

In these two simulations, a unit tax by unit volume (1 cubic metre) is paid by traders on the quantities purchased from harvesters. It thus modifies the trader's internal calculation process with regard to the quantities demanded and the prices offered to harvesters. Two tax levels were tested.

As expected, the tax slows down the degradation of both types of resource while maintaining a higher production level compatible with the market. This can be attributed to two factors: firstly, the collection distance decreases due to a reduction in the harvester's price which reduces the incentive to engage in wood collection activities; secondly, pressure on resources is reduced from the very start of simulations. Resources are thus maintained at sufficient levels in the cells to supply the market, whatever the spatial configuration of harvesting zones.
On the other hand, the tax destabilizes the prices in the sector, which are more variable than in the reference simulations and those with quota. This destabilization increases as the tax level increases. Similarly, we note that the trading sector adapts more slowly (slower reduction in quantities demanded) though at a variable pace.

These scenarios demonstrate that the three observation criteria of the model are very sensitive to tax levels. The tax affects the behaviour of traders and, consequently, the interactions between harvesters and resources. The collection activity adapts to these new conditions and we note a slightly higher production level in the case of dispersed harvesting.

Though the tax is paid by the traders on the quantities purchased, one of its most patent effects is to stabilize the price paid to the harvester at a low level. These taxation scenarios raise the question of which segment of the sector should be required to pay the tax. According to the simulation results obtained, the tax is passed down to the harvester. Indeed, the price at which the trader buys the wood remains unchanged throughout the simulation. However, the trader's margin is higher in the two cases with taxes than in the case where no instruments apply. It is also higher than in the case with quota. It is interesting to note that in Niger, a minimum purchase price from the harvester has been imposed in association with the tax system, probably to avoid this drop in prices paid to the harvester. The quota instrument, on the other hand, maintains a trend of increasing prices paid to the harvester due to a scarcity effect.

DISCUSSION

Zoning, quotas and taxes are management tools which modify the access rules (zoning or quotas) or usage rules (taxes) of a resource. These management rules are proposed solutions to a given problem of renewable resource allocation between economic agents or between alternative uses in the economy. The choice of an appropriate instrument is one of questions most frequently addressed in the economic analysis of resource management. But the implementation of these instruments is a much less common theme. Indeed, when examining the dynamic aspects of interactions between the resource, the social system and the management rules, several problems are raised. The problem may be, for example, to determine an optimal and acceptable tax level or quota for a fluctuating market, or to assess, *a priori,* its impact on practices. Economic operators do not form a homogeneous category and the incentive effect of instruments depends on the decision-making processes (risks, constraints, objectives) of these operators and on the evolution of relations between them.

The simulation framework is used to analyse the implementation of management rules and its effect on behaviour in the various stages of an industry. The simulations aim to analyse the environmental and economic efficacy of the rules applied, taking simultaneous account of ecological and economic variables. The same behaviour hypotheses are applied to the agents. These hypotheses, which correspond to a standard vision in economics, apply to heterogeneous agents with specific characteristics depending upon their category in the industry (size, perception radius, cost of collection or transport, transport capacity).

We focused on the processes by which the management rules are affected by the nature of interactions – between the resource and the economic agents or between the economic agents – and the organisation of these interactions. The aim is to better understand how the implementation of these management rules may or may not lead to the expected results.

This first model focused on the nature of interactions. It helped us to conceptualize the relations to be taken into account in the real system under study and to choose the right level of abstraction for comprehensive analysis of the theoretical question of management rules. The preliminary results obtained with this simple model raised questions which have served as pointers for the work now in progress, both in the field and with regard to developments in the multi-agent model. What is the link between the spatial configuration of harvesting zones and the agents' representation of the resource and of its limits? How does the heterogeneity of economic actors (with respect to their characteristics and resource constraints) affect the functioning of management rules and the way they are fixed? How should we factor in the question of compliance with management rules (quotas, zoning) and their enforcement (by the state, by the actors themselves, at what cost, etc.) ?

This stylised model is now being extended on the basis of the same behaviour hypothesis. It focuses on another form of organization of these interactions, a different mode of coordination between actors in economic terms, closer to the actual implementation of this policy in Niger. Quotas, zoning and taxation are applied with regard to rural fuelwood markets. A rural market is a market site supplied by forest resources from a zone subject to quotas and the only site entitled to sell fuelwood harvested from this zone. Wood traders are supplied via this rural market where harvester supply confronts trader demand. Interactions between traders and harvesters are no longer bilateral. The competitive environment of harvesting and wood trading is modified, thereby altering the economic constraints affecting individual behaviour.

The questions raised by this first simple model and by the analysis of results has led to the initiation of new field surveys in Niger to gain a clearer picture of these ongoing interactions and dynamics.

CONCLUSION

The ongoing research process starts out from a model which uses knowledge from several disciplines and establishes a stylised representation of reality in the field to analyse ecosystem management rules. By choosing standard models of individual behaviours in economics (maximization of a profit function) we were able to focus on the expected theoretical results of the implementation of these management rules. With multi-agent simulations, questions are raised regarding the way in which the interaction processes between agents (resource, economic agents) affect the results obtained.

By returning to the field to examine these questions, we will initiate a second phase in the research process for our second model. This new model could include new non-standard hypotheses to simulate the behaviour of agents, such as other behaviour objectives, a change in preferences or in agent knowledge (static in our first model).

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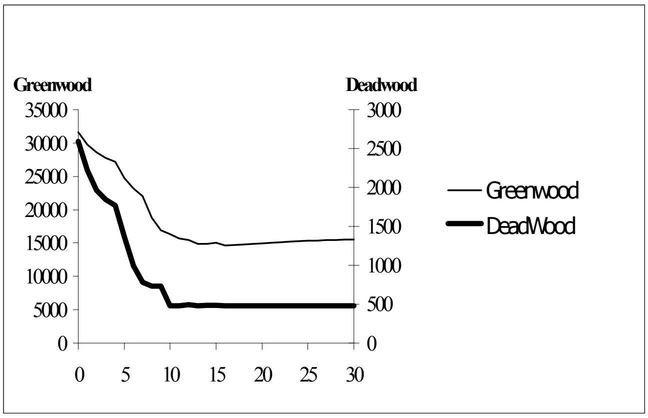
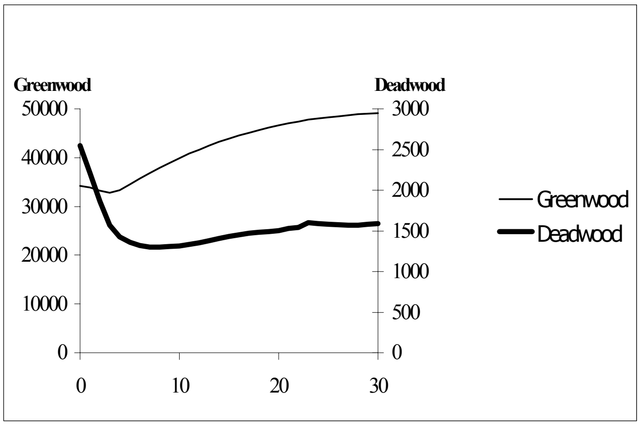
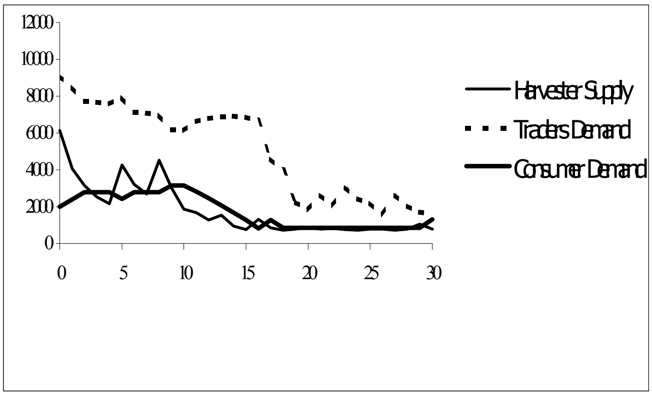
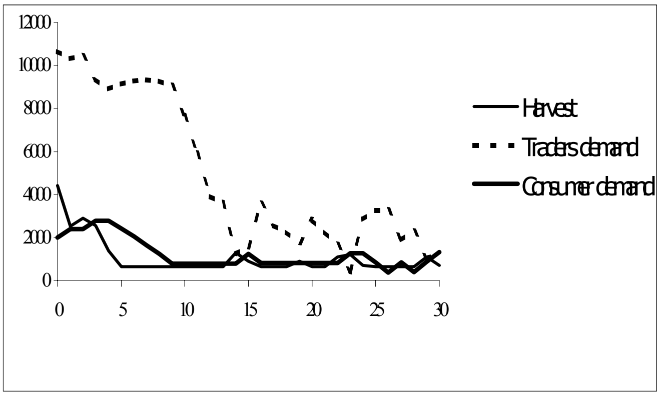
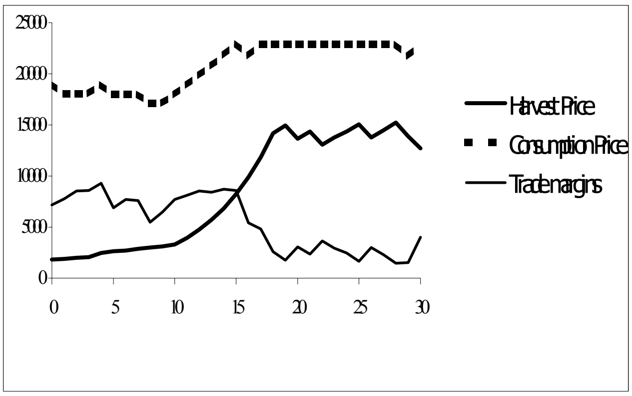
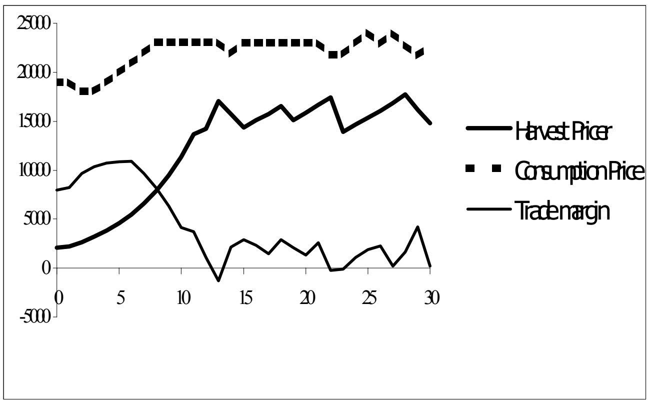
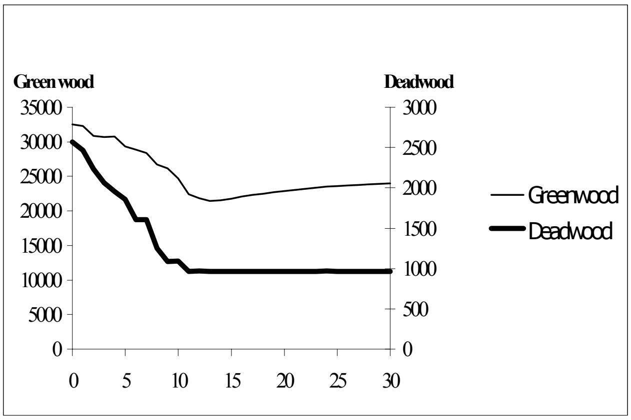
Simulation 1 – Basic model. Grouped Harvesting	Simulation 2 –Zoning and quota
Fuelwood Resources (30 times steps)	Fuelwood Resources (30 times steps)
	
Fuelwood trade (Harvest, traders demand, consumer demand) (cubic meters)	Fuelwood trade (Harvest, traders demand, consumer demand)
	
Prices and margins by agents (per cubic meter of wood)	Prices and margins by agents
	

Figure 2 : Basic Model with no taxation, no zoning and quotas.
Results for the pattern grouped harvesting
(30 time steps, 50 runs, Average data)

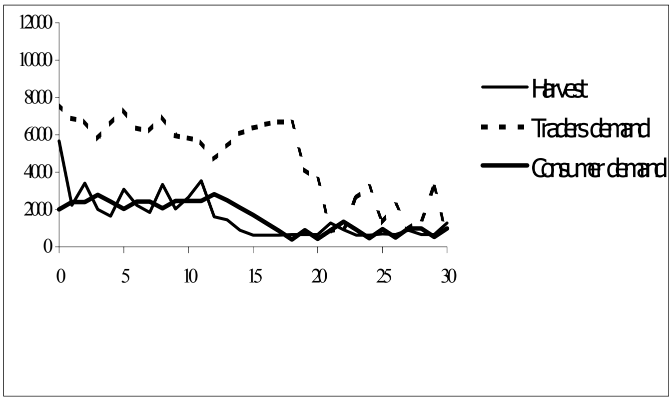
Figure 3 . Simulations 2 with zoning and quotas
Results for the pattern grouped harvesting
(30 time steps, 50 runs, Average data)

Simulation 3 – Taxation (low rate)

Fuelwood Resources (30 times steps)



Fuelwood trade (Harvest, traders demand, consumer demand)



Prices and margins by agents

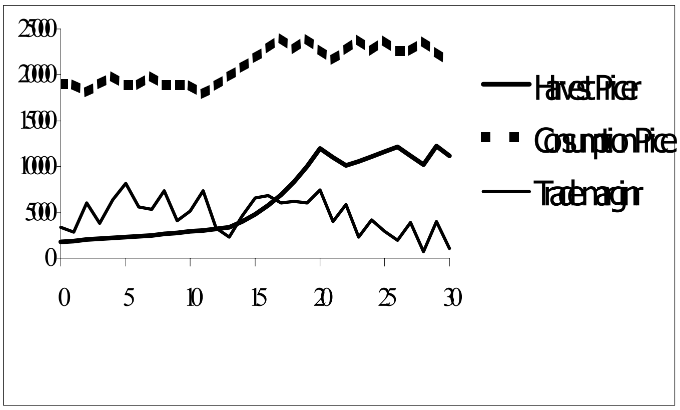
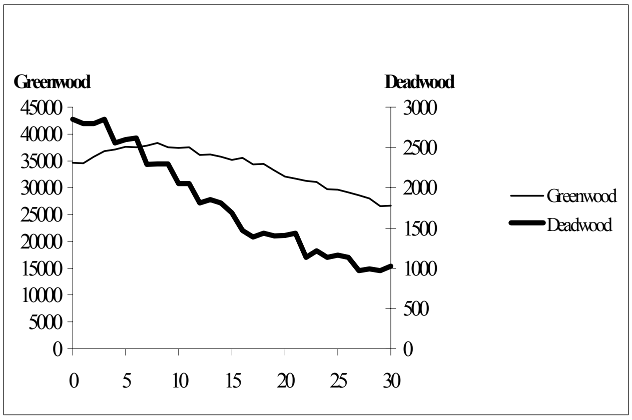


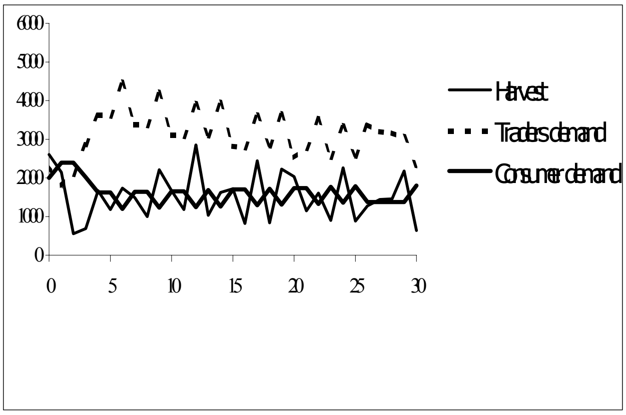
Figure 4 : Simulations 3 with taxation (low rate) (grouped harvesting, 30 time steps; 50 runs, average data)

Simulation 4 –Taxation (high rate)

Fuelwood Resources (30 times steps)



Fuelwood trade (Harvest, traders demand, consumer demand)



Prices and margins by agents

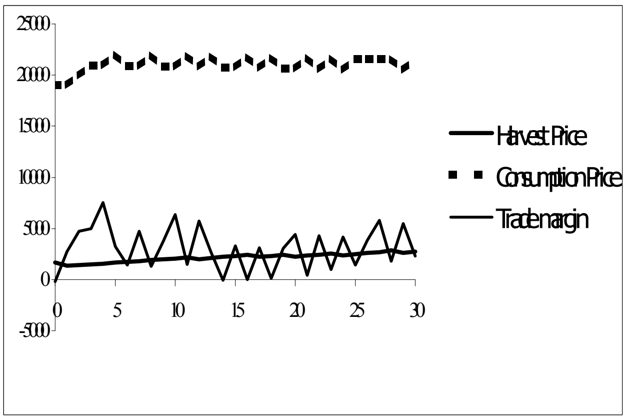


Figure 5 : Simulations 4 with taxation (high rate) (grouped harvesting, 30 time steps; 50 runs, average data).