Chapter 19
Agent-Based Modelling and Simulation Applied to Environmental Management

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Why Read This Chapter? To understand the recent shift of paradigms prevailing in both environmental modelling and renewable resources management that led to the emerging rise in the application of ABMS. Also, to learn about a practical way to characterize applications of ABMS to environmental management and to see this framework applied to review a selection of recent applications of

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ABMS from various fields related to environmental management including the dynamics of land use changes, water, forest and wildlife management, agriculture, livestock productions and epidemiology.
Abstract The purpose of this chapter is to summarize how agent-based modelling and simulation (ABMS) is being used in the area of environmental management. With the science of complex systems now being widely recognized as an appropriate one to tackle the main issues of ecological management, ABMS is emerging as one of the most promising approaches. To avoid any confusion and disbelief about the actual usefulness of ABMS, the objectives of the modelling process have to be unambiguously made explicit. It is still quite common to consider ABMS as mostly useful to deliver recommendations to a lone decision-maker, yet a variety of different purposes have progressively emerged, from gaining understanding through raising awareness, facilitating communication, promoting coordination or mitigating conflicts. Whatever the goal, the description of an agent-based model remains challenging. Some standard protocols have been recently proposed, but still a comprehensive description requires a lot of space, often too much for the maximum length of a paper authorized by a scientific journal. To account for the diversity and the swelling of ABMS in the field of ecological management, a review of recent publications based on a lightened descriptive framework is proposed. The objective of these descriptions is not to allow the replication of the models but rather to characterize the types of spatial representation, the properties of the agents, the features of the scenarios that have been explored, and also to mention which simulation platforms were used to implement them (if any). This chapter concludes with a discussion of recurrent questions and stimulating challenges currently faced by ABMS for environmental management.

19.1 Introduction

In this chapter, we state that there is a combined shift in the way of thinking in both ecosystem management and ecological modelling fields. Over the last 20 years, the status of computer simulation in the field of renewable resources management has changed. This chapter investigates how agent-based modelling and simulation (ABMS) may have contributed to this evolution and what are the challenges it has to face for such a combination to remain fruitful.

Biosphere 2, an artificial closed ecological system built in Arizona (USA) in the late 1980s, was supposed to test if and how people could live and work in a closed biosphere. It proved to be sustainable for eight humans for 2 years, when low oxygen level and wild fluctuations in carbon dioxide led to the end of the experience. Biosphere 2 represents the quest for "engineering Nature" that has fascinated a lot of people (including a non-scientific audience) during the second part of the last century. The human aspect of this "adventure" mainly dealt with the psychological impact on a few people living in enclosed environments. In the real world, the relationships between human beings and the biosphere are based on tight linkages between cultural and biological diversity. Launched around 20 years before the Biosphere 2 project, the Man and Biosphere Program (MAB) of UNESCO is seeking to improve the global relationship between people and their environment. This is now the kind of approach – in line with the Millennium Development Goal #7 from the United Nations – that is attracting more and more interest.

In ecological management, the place of people directly involved in the management scheme is now widely recognized as central, and the impact of their activities has both to be considered as promoting and endangering different types of biodiversity. At the same time, ABMS has progressively demonstrated its ability to explicitly represent the way people are using resources, the impact of this management on plant and animal dynamics and the way ecosystems adapt to it. The next section discusses how both trends have been reinforcing each other in more detail.

The third section of this chapter gives a review of recent applications of ABMS in the field of environmental management. To avoid confusion due to the co-existence of multiple terms not clearly distinguishable, we use ABMS here as an umbrella term to refer indifferently to what authors may have denominated "agent-based modelling", "multi-agent simulation", or even "multi-agent based simulation" (also the name of an international workshop where applications dealing with environmental management are regularly presented). Our review is covering the dynamics of land use changes, water, forest and wildlife management, but also agriculture, livestock productions and epidemiology. We are focusing here on models with explicit consideration of the stakeholders (in this chapter this is how we will denominate people directly concerned by the local environmental management system). Bousquet and Le Page (2004) proposed a more extensive review of ABMS in ecological modelling. For a specific review of ABMS dealing with animal social behaviour, see Chap. 22 in this handbook (Hemelrijk 2013).

19.2 A Shift in Intertwined Paradigms

During the last two decades, evidences accumulate that the interlinked fields of ecosystem management and environmental modelling are changing from one way of thinking to another. This is a kind of paired dynamics where agents of change from one field are fostering the evolution of conceptual views in the other one. A survey of the articles published in "Journal of Environmental Management" and "Ecological Modelling" – just to refer to a couple of authoritative journals in those fields – clearly reveals this combined shift of paradigms. Another indication from the scientific literature was given when the former "Conservation Ecology" journal was renamed "Ecology and Society" in June 1997.

Among ecologists, it has become well accepted that classical equilibrium theories are inadequate and that ecosystems are facing cycles of adaptive change made of persistence and novelty (Holling 1986). Concepts from the sciences of complexity are now widely adopted in ecology (Levin 1998), and the perception of ecosystems as complex adaptive systems, in which patterns at higher levels emerge from localized interactions and selection processes acting at lower levels, has begun to affect the management of renewable resources (Levin 1999).

Beyond the standard concept of "integrated renewable resource management", the challenge is now to develop a new "integrative science for resilience and sustainability" focusing on the interactions between ecological and social components and taking into account the heterogeneity and interdependent dynamics of these components (Berkes and Folke 1998). The relationships between stakeholders dealing with the access and use of renewable resources are the core of these intertwined ecological and social dynamics that are driving the changes observed in many ecosystems.

Panarchy is a useful concept to understand how renewable resources management is affected by this new paradigm in ecology. It has been formalized as the process by which ecological and social systems grow, adapt, transform, and abruptly collapse (Gunderson and Holling 2002). The back loop of such changes is a critical time when uncertainties arise and when resilience is tested and established (Holling 2004). This new theoretical background is making sense to social scientists working on renewable resources management (Abel 1998) and to interdisciplinary groups expanding ecological regime shifts theory to dynamics in social and economic systems (Kinzig et al. 2006).

For a long period, the mainstream postulate in ecological modelling has been that science should first help to understand the "natural functioning" of a given ecosystem, so that the impacts of external shocks due to human activities ("anthropic pressures") could be monitored. Models were mainly predictive, oriented towards decision makers who were supposed to be supported by powerful tools (expert systems, decision-support systems) in selecting the "best", "optimal" management option. Nowadays, command-and-control approaches are seen as "being worse than inadequate" (Levin 1999).

Evidently, there is a growing need for more flexible (usable and understandable by diverse participants) and adaptive (easily modified to accommodate unforeseen situations and new ideas) models that should allow any involved stakeholders (ecosystem and resource managers among others) to gain insights through exploration of simulation scenarios that mimic the challenges they face. Similar to the role of metaphor in narratives, such simulation models do not strive for prediction anymore, but rather aim at sparking creativity, facilitating discussion, clarifying communication, and contributing to collective understanding of problems and potential solutions (Carpenter et al. 1999). To underline the change of status of simulation models used in such a way, the term "companion modelling" has been proposed (ComMod 2003; Etienne 2011).

In recent years, ABMS has attracted more and more attention in the field of environmental management (Bousquet and Le Page 2004; Hare and Deadman

2004). Recent compilations of experiences have been edited (Gimblett 2002; Janssen et al. 2002; Bousquet et al. 2005; Perez and Batten 2006). We propose to review recent ABMS applications in the field of environmental management based on a simplified framework presented in the next section.

19.3 A Framework for Characterizing Applications of ABMS to Environmental Management

To standardize the description of ecological models based on the interactions between elementary entities (individual-based models and agent-based models), Grimm and others (Grimm et al. 2006) have recently proposed a protocol based on a three blocks sequence: overview, design concepts, details (ODD). It is a kind of guideline for authors wishing to publish their model whose fulfilment corresponds to an entire article devoted to communicating the details of the model. Hare and Deadman (2004) also proposed a first classification scheme from the analysis of 11 case studies. Revisiting some elements from these two contributions, we propose here to successively give some insights about: (1) the purpose of the model; (2) the way the environment is represented; (3) the architecture of the different agents; (4) the implementation (translation of the conceptual model into a computer programme); (5) the simulation scenarios.

19.3.1 What Is the Model's Purpose?

As recommended by Grimm and the 27 other participants to the collective design of the ODD protocol (2006), a concise formulation of the model's purpose has to be stated first: it is crucial to understand why some aspects of reality are included while others are ignored. The reasons leading to start a modelling process are not always clearly given. Is it mainly to gain understanding and increase scientific knowledge? Is it more about raising awareness of stakeholders who do not have a clear picture of a complex system? Does it aim at facilitating communication or supporting decision? The more the information about the model's purpose will be precise, the less confusion and disbelieving about its real usefulness will remain.

19.3.2 How Is the Environment Represented?

Applications of ABMS to investigate environmental management issues are relying on a fundamental principle: they represent interacting social and ecological dynamics. On one hand, agents represent some sort of stakeholders, at the level of individual people or/and at more aggregated levels some groups of individuals defining (*lato* *sensu*) institutions (social groups such as families; economic groups such as farmers' organizations; political groups such as non-governmental organizations). On the other hand, the environment, holding some sort of renewable resources, stands for the landscape. The renewable resources are contributing to define the landscape, and in turn the way the landscape is structured and developed influences the renewable resources. Typically, the resources are modified by direct actions of agents on their environment, whereas the resources also exhibit some intrinsic natural dynamics (growth, dispersal, etc.. . .). At the same time, agents' decisions are somehow modified by the environment as the state of resources evolves. In such situations, the implementation of the social dynamics is performed through defining the behaviours of agents, whereas the implementation of the natural dynamics is commonly ascribed to the spatial entities defining the environment. Furthermore, spatial entities viewed as "management entities" can support the reification of the specific relationships between a stakeholder using the renewable resource and the renewable resource itself.

Yet some applications of ABMS to environmental management do not represent any spatially-explicit natural dynamics. The data related to the environmental conditions (i.e. the overall quantity of available resource), used by the agents to make their decisions, are managed just like any other kind of information. But even when the environmental conditions are not spatially-explicit, the explicit representation of space can help to structure the interactions among the agents. For instance, in the simulation of land use changes, the cognitive reasoning of agents can be embedded in cellular automata (CA) where each cell (space portion) represents a decisional entity that considers its neighbourhood to evaluate the transition function determining the next land use. Typically, acquaintances are then straightforwardly set from direct geographical proximity. It is still possible to stick on CA with more flexible "social-oriented" ways to define the acquaintances, but as soon as decisional entities control more than a single space portion, they have to be disembodied from the spatial entities. The FEARLUS model proposed by Polhill et al. (2001) and described in Sect. 19.4 is a good illustration of such a situation.

Applications of ABMS explicitly representing some renewable resources have to deal with the fact that renewable resources are usually heterogeneously scattered over the landscape being shaped by their patterns. Any irregularities or specificities in the topological properties of the environment legitimate to incorporate a spatially-explicit representation of the environment. The combined use of geographic information systems (GIS) and ABMS is a promising approach to implement such integration (Gimblett 2002), particularly when there is a need to refer explicitly to an actual landscape in a realistic way. More generally, the relationship between an artificial landscape and a real one can be pinpointed by referring to 3 levels of proximity: (1) none, in case of theoretical, abstract landscape; (2) intermediate, when the reference to a given landscape is implicit; (3) high, when the reference to a given landscape is explicit. Theoretical ABMS applications frequently use purely abstract landscapes, such as in the well-known sugar and spice virtual world of Sugarscape (Epstein and Axtell 1996). In the intermediate case, the implicit reference to a given landscape may exist through matching proportions in the composition of the landscape and similar patterns in its spatial configuration. When the reference to an actual landscape is explicit, the use of GIS is required to design the environment. An example of such realistic representation of a given landscape is given by Etienne et al. (2003). Characterizing the relationship between the simulated environment and the reality is a good way to estimate to what extent the model may provide a wide scope: the rule "the more realistic, the less generic" is hardly refutable.

From a technical point of view, the representation of space in ABMS applications with spatially-explicit representation of the environment could be either continuous or discrete. Most of the time, the representation of space is based on a raster grid (the space is regularly dissected into a matrix of similar elementary components), less frequently it is made of a collection of vector polygons. The continuous mode is quite uncommon in ABMS. This is related to the standard scheduling of ABMS that relies on either a discrete-time approach or on a discrete-event approach. Therefore, dealing with time (regular or irregular) intervals, the spatial resolution of the virtual landscape can be chosen so that the elementary spatial entity (defined as the smallest homogeneous portion of space) can be used as the unit to characterize distances or neighbourhood. Using a discrete mode to represent the space allows to easily define aggregated spatial entities that directly refer to different ecological scales relevant to specific natural or social dynamics, as well as to the management units specifically handled by the stakeholders. The corresponding spatial entities are interrelated according to a hierarchical organization, through aggregations.

19.3.3 How Are the Agents Modelled?

As we restrict our study to the sole applications with explicit consideration of the stakeholders, by "agent" we mean a computer entity representing a kind of stakeholder (individual) or a group of stakeholders. We stick with that operational definition even when the authors opt for another terminology and propose to characterize each kind of agent by considering two aspects: internal reasoning leading to decision-making and interactions with the other agents (coordination).

19.3.3.1 Internal Reasoning

Decision-making is the internal process that specifies how an agent behaves. It encompasses two dimensions: sophistication (from reactive to cognitive) and adaptiveness (through evaluation). What is called the "behaviour" of an agent refers to a wide range of notions. In some situations, the behaviour of an agent is simply and straightforwardly characterized by the value of a key parameter, as in the theoretical exploration of the tragedy of the commons by Pepper and Smuts (2000) where agents are either restrained (intake rate of resource is set to 50 %) or

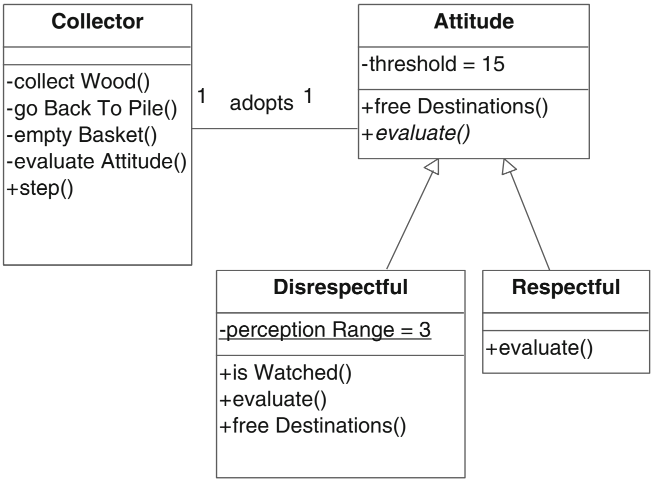

Fig. 19.1 Design pattern of the driftwood collector agents (Thébaud and Locatelli 2001)

unrestrained (intake rate of resource is set to 99 %) in their foraging activity, when all the other biological functions (perception, movement, reproduction, mortality) are the same. In some other cases, the behaviour of a given agent does not only depend on internal characteristics, like the driftwood collector agents proposed by Thébaud and Locatelli (2001) who are stealing wood collected by other agents only when their attitude is still disrespectful (internal property) and when they cannot be observed (no peer pressure). Whatever the factors determining the behaviour of an agent are, this behaviour may or may not change over time. When the behaviour is simply characterized by a value of a key parameter, the adaptiveness can be taken into account without any particular architectural design. For more sophisticated behaviours, it becomes necessary to use a design pattern linking the agent to its behavioural attitude. With such a design pattern, the different behavioural attitudes are made explicit through corresponding subclasses, as shown in Fig. 19.1 with an example taken from the Dricol model (Thébaud and Locatelli 2001). The adoption of a particular attitude is updated according to some evaluation function.

Regarding the degree of sophistication of the decision-making process, the so-called *reactive* agents implement a direct coupling between perception (often related to little instantaneous information) and action. The forager agents of Pepper and Smuts (2000) mentioned above are typical reactive agents. On the opposite side, *cognitive* agents implement more complex decision-making processes by explicitly deliberating about different possibilities of action and by referring to specific representations of their environment, which is of particular importance for applications of ABMS to environmental management (Bousquet and Le Page 2004). An example of such agents is given by Becu et al. (2003): farmer agents evaluate direct observations and messages received from others (social network), update their knowledge base, and evaluate options according to their objectives (see the corresponding architecture in Fig. 19.2).

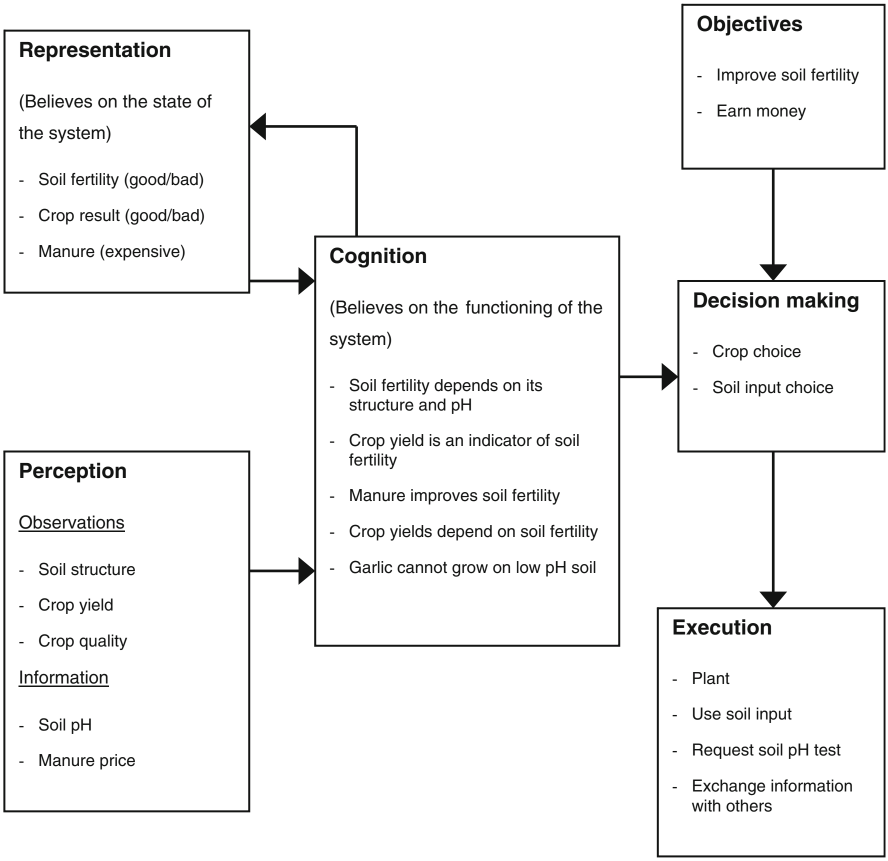

Fig. 19.2 Architecture of farmer agents from the Catchscape model (Becu et al. 2003)

19.3.3.2 Interactions with Other Agents (Coordination)

Bousquet (2001) synthesized his general approach of multi-agent systems to study environmental management issues with a diagram (see Fig. 19.3). We will refer here to the three kinds of interactions depicted in Fig. 19.3 to describe the types of agents implemented in applications of ABMS to environmental management.

The deliberative process of one agent is quite often influenced by some other closely related agents. The proximity may be either spatial (local neighbourhood) or social (acquaintances). In situations like the Dricol model (Thébaud and Locatelli 2001), what matters is just the presence of other agents in the surroundings. When more information about the related agents is needed, then the rules to access this information have to be specified. It is often assumed that the information is directly accessible through browsing the agents belonging to a given network. This corresponds to “Ie” in Fig. 19.3: other agents perceived through the environment are considered as part of the environment of one agent.

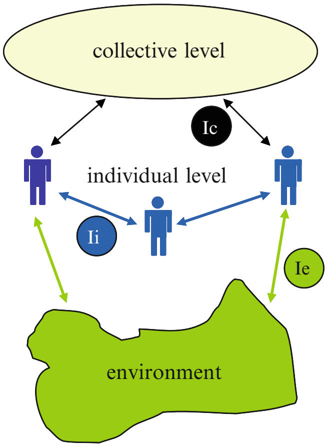

Fig. 19.3 Interactions between agents via the environment (Ie), through peer to peer communication (Ii) and via the collective level (Ic) (Bousquet 2001)

Agents may strictly control the access to their internal information unless they intentionally decide to communicate it ("Ii" in Fig. 19.3). Then the sharing of information has to go through direct exchanges of peer-to-peer messages, with a specified protocol of communication.

Relating agents directly to the collective level ("Ic" in Fig. 19.3) is most often achieved via the notion of *groups* to which they can belong and for which they can be representative to outsiders. Inspired by the Aalaadin meta-model proposed by Ferber and Gutknecht (1998), recent applications of ABMS to agricultural water (Abrami 2004) and waste water (Courdier et al. 2002, described in the next section) management as well as to epidemiology (Muller et al. 2004, described in the next section) illustrate how both notions of *group* and *role* are useful to handle levels of organisation, and behaviours within levels of organisation. Even when «Ic» are not implemented through specific features of the agents' architecture, the mutual influence of both collective and individual levels is fundamental in renewable resources management. On one hand, individuals' behaviours are driven by collective norms and rules; on the other hand, these norms and rules are evolving through agents' interactions. This individuals-society dynamics linkage, introducing the notion of institution, relies on the representation of common referents (Bousquet 2001). Such "mediatory objects" are for instance the water temples involved in the coordination of a complex rice-terraces system in Bali (Lansing and Kremer 1993; Janssen 2007).

19.3.4 Implementation

We believe it is useful to indicate whether a simulation platform was used or not to implement the model. Nowadays, some established generic tools such as Ascape, Cormas, Mason, (Net)(Star)Logo, Repast, or Swarm are being used by large communities of users. Intending to release researchers from low-level technical-operational issues, their development is boosted by their comparisons performed through the implementation of simple benchmark models (Railsback et al. 2006) and the analysis of their abilities to fulfil identified requirements (Marietto et al. 2003). The maintainers and developers of such generic platforms have also taken into consideration some sensitive technical aspects (floating point arithmetic, random numbers generators, etc.) recently pointed out (Polhill et al. 2006), and provide some elements to help users to escape these numerical traps. Additionally to the benefit of not having to re-implement basic functionalities from scratch, it may also happen that a previous model, made available online in the library of existing models, presents some similarities with the new model to be developed.

Nevertheless, using a generic platform is not a panacea. It may incidentally lead to poorer presentation of the developed models if the authors (wrongly) assume that any reader is aware of the platform's general principles. A new research stream (model-to-model comparison) recently emerged from the fact that it is very difficult to replicate simulation models from what is reported in publications (Hales et al. 2003). Reproducing results, however, is a *sine qua non* condition for making ABMS a more rigorous tool for science. It may be achieved through a better description of individual models, but also through the maintenance and development of strong communities of users sharing the same tools for implementation. This kind of stimulating diversity of the simulation platforms may contribute to identify some generic 'shorthand' conventions that could minimize the effort to describe the model rigorously and completely (Grimm et al. 2006).

19.3.5 Simulation Scenarios

Some ABMS platforms like NetLogo, for simplicity purposes, merge in the same (unique) implementation file the definition of the domain entities with the specification of the simulation scenario. In their ODD protocol, Grimm et al. (2006) suggest to state the elements pertaining to the scheduling of a "standard" simulation scenario in the first part (overview) of the sequential protocol, then come back to some specific design concepts characterizing the domain entities (discussed here in Sect. 19.3.3) in the second part (design) of the sequential protocol, and finally to describe the initialization of a standard scenario in the third and last part (details). Yet, a clear separation between model and simulation should be promoted when seeking genericity. At the level of the agents, focusing on the description of their internal structure and potential behaviour may help to identify some modules of their architecture that could be re-used in other contexts. At the level of the initialization and scheduling of the simulation, the same benefit can be expected: for instance, generating parameter values for a population of agents from a statistical distribution, or creating an initial landscape fitting some schematic patterns (Berger and Schreinemachers 2006).

The notion of "standard" scenario is not always very easily recognizable. Some authors prefer to start by presenting what they call "reference" scenarios that correspond to "extreme" situations. For instance, whenever the structure of a given model makes sense to mention it, a "*no agents*" simulation scenario should be available without any modifications, i.e. just initializing the number of agents to zero. These scenarios can be used either as a verification step in the modelling process (to test that the implementation is a faithful translation of the conceptual model), or as a reference to compare the outputs obtained from more plausible simulation scenarios. More generally, simulation scenarios have to address validation by questioning the results through looking back at the system under study. In ABMS, validation is a multi-dimensional notion. Depending on the purpose assigned to the model, the focus will be mainly set on: (1) checking if the simulated data are fitting available real datasets; (2) looking for comparable processes observed in other case studies; (3) evaluating to what extent the stakeholders accept the model and its outputs as a fair representation of their system. For a more detailed discussion of validation see Chap. 8 in this volume (David 2013).

Another essential dimension of simulation scenarios relates to the model output used to observe them. Confronting the interpretations of the same simulated results built from specific stakeholders' viewpoints may be an effective way to share the different opinions and then highlight the need to improve the agents coordination mechanisms, or even to achieve a compromise (Etienne et al. 2003).

19.4 A Review of Recent Applications of ABMS to Environmental Management

To classify the recent applications of ABMS in environmental management is not an easy task, as the range of covered topics is wide: dynamics of land use changes, water, forest and wildlife management, but also agriculture, livestock productions and epidemiology. Some topics like epidemiology can easily be treated separately. Some others are likely to be appearing simultaneously in some case studies, especially for those dealing with multiple uses of the same renewable resource and/or representing landscape with several land-use types. This latter situation frames an entire research field in human geography that is focusing on the dynamics of land-use/cover changes (LUCC). In the classification proposed below, some applications clearly related to LUCC are listed in other subsections (mainly in "agriculture" and in "forest"). Conversely, the "LUCC" subsection contains applications that are related to some other topics specifically addressed later on. Finally, some other topics like biodiversity are multi-dimensional and thus the related case studies can be split into several other topics (for instance, biodiversity related to endangered species are reversed into "wildlife"). Whenever it undoubtedly exists for an application, we are mentioning the relevance to other topics. A specific category has been added to group the examples of ABMS addressing theoretical issues in ecological management.

As the number of publications related to the use of ABMS in ecological management is booming, it is almost impossible to analyze all of them. So for each of the categories presented above, we had to select only a few representative case studies to be briefly described by referring as much as possible to the elements discussed in previous sections (the case studies that were not selected to be analyzed are just mentioned in the introduction paragraph of each category). Following Hare and Deadman (2004) who proposed a taxonomy of ABMS in environmental management as a first step to provoke discussion and feedback, our purpose here is to contribute to the framing of a practical bibliographic survey by proposing some key characteristics useful for comparing applications of ABMS in ecological management. See Appendix for a table recording the key characteristics of the selected case studies.

19.4.1 Theoretical Issues in Environmental Management

Thébaud and Locatelli (2001) have designed a simple model of driftwood collection to study the emergence of resource sharing conventions; Pepper and Smuts (2000) have investigated the evolution of cooperation in an ecological context with simple reactive agents foraging either almost everything or just half of a renewable resource. Schreinemachers and Berger (2006) have compared respective advantages of heuristic and optimizing agent decision architectures; Rouchier et al. (2001) have compared economic and social rationales of nomad herdsmen securing their access to rangelands; Evans and Kelley (2004) have compared experimental economics and ABMS results to explore land-use decision-making dynamics; Soulié and Thébaud (2006) represent a virtual fishery targeting different species in different areas to analyze the effects of spatial fishing bans as management tools.

19.4.2 Dynamics of Land-Use/Cover Changes

Parker et al. (2003) have recently reviewed the application of multi-agent systems to better understand the forces driving land-use/cover change (MAS/LUCC). Their detailed state of the art presents a wide range of explanatory and descriptive applications. Since this authoritative paper has been published, new applications related to LUCC have continued to flourish. For instance, Caplat et al. (2006) have simulated pine encroachment in a Mediterranean upland, Matthews (2006) has proposed a generic tool called PALM (People and Landscape Model) for simulating resource flows in a rural livestock-based subsistence community; LUCITA (Lim et al. 2002), an ABM representing colonist household decision-making and land-use change in the Amazon Rainforest, has been developed further (Deadman et al. 2004); Bonaudo et al. (2005) have designed an ABM to simulate the pioneers fronts in the same Transamazon highway region, but at a lower scale; Manson (2006; 2005) has continued to explore scenarios of population and institutional changes in the Southern Yucatan Peninsular Region of Mexico; Huigen (2004, 2006) has developed MameLuke to simulate settling decisions and behaviours in the San Mariano watershed, the Philippines. Below we describe in more detail a selection of applications that are also characterized in the overview table presented in the Appendix.

19.4.2.1 FEARLUS, Land-Use and Land Ownership Dynamics

FEARLUS, an abstract model of land use and land ownership implemented with Swarm, has been developed to improve the understanding of LUCC in rural Scotland by simulating the relative success of imitative versus non-imitative process of land use selection in different kinds of environment (Polhill et al. 2001). An abstract regional environment is defined as a toroidal raster grid made out of 8-connex land parcels, each being characterized by fixed biophysical conditions. The same external conditions that vary over time apply in the same way to all land parcels. These two factors are determining the economic return of a given land use at a particular time and place. The land manager agents decide about the land uses of the land parcels they own (initially a single one) according to a specific selection algorithm. During the simulation, they can buy and sell land parcels (landless managers leave the simulation; new ones may enter it by buying a land parcel). Simulation scenarios were defined on several grids by pairing selection algorithms from the predefined sets of 5 imitative and 5 non-imitative selection algorithms.

19.4.2.2 Greenbelt to Control Residential Development

This ABM, the simplest version of which being strictly equivalent to a mathematical model, has been developed to investigate the effectiveness of a greenbelt located beside a developed area for delaying residential development outside the greenbelt (Brown et al. 2004). The environment is represented as an abstract cellular lattice where each cell is characterized by two values: a constant one to account for aesthetic quality and a variable one to denote the proximity to service centres. Service centres are called agents but actually they are more passive entities as they do not exhibit any decision making. Residential agents, all equipped with the same aesthetic and service centre preferences, decide their location among a set of randomly selected cells according to a given utility function. The Swarm platform was used for implementation. Scenarios, scheduled with periodic introductions of new agents, are based on the values of residential agents' preferences and on the spatial distribution of aesthetic quality.

19.4.2.3 LUCC in the Northern Mountains of Vietnam

Castella et al. (2005a) developed the SAMBA model under the Cormas simulation platform to simulate the land use changes during the transition period of decollectivisation in a commune of the northern Vietnam uplands (Castella et al. 2005a, b; Castella and Verburg 2007). This simple and adaptable model with heuristic value represented the diversity of land use systems during the 1980s as a function of household demographic composition and paddy field endowment in the lowland areas. The environment in which agents make decisions was made of a 2,500 cell grid, and 6 different land use types could be attributed to each cell, representing a plot of 1,000 m^2, also characterized by its distance to the village. While there were no coordination among farmer agents with reactive behaviour in the early version of the model, interactions among them was added later and the model coupled to a GIS to extrapolate the dynamics to the regional landscape level (Castella et al. 2005b). The simulated scenarios tested the effects of the size of the environment, the overall population and household composition, and the rules for the allocation of the paddy fields on the agricultural dynamics and differentiation among farming households. More recently, this process-oriented model was compared to a spatially explicit statistical regression-based pattern-oriented model (CLUE-s) implemented at the same site. While SAMBA better represented the land use structure related to villages, CLUE-s captured the overall pattern better. Such complementarity supports a pattern-to- process modelling approach to add knowledge of the area to empirically calibrated models (Castella and Verburg 2007).

19.4.2.4 Competing Rangeland and Rice Cropping Land-Uses in Senegal

To test the direct design and use of Role-Playing Games (RPG) and ABMS with farmers and herders competing for land-use in the Senegal River Valley, participatory simulation workshops were organized in several villages (D'Aquino et al. 2003). The ABM used during the last day of the workshops was straightforwardly implemented with the Cormas platform from the characteristics and rules collectively agreed the day before when crafting and testing a RPG representing stakeholders' activities related to agriculture and cattle raising. The environment is set as a raster grid incorporating soil, vegetation and water properties of the village landscape as stated by the stakeholders (a GIS was used only to clear ambiguities). The same crude rules defined and applied during the RPG were used to implement the autonomous reactive farmer agents. After displaying the scenario identified during the RPG, new questions emerged and were investigated by running the corresponding simulation scenarios. The hot debates that emerged demonstrate the potential of these tools for the improvement of collective processes about renewable resources management.

19.4.2.5 Landscape Dynamics in the Méjan Plateau, Massif Central, France

Etienne et al. (2003) developed a multi-agent system in order to support a companion modelling approach on landscape dynamics in the Méjan plateau of the Massif Central, the mountain range of central France (Etienne et al. 2003). The purpose of the model is to support the coordination process among stakeholders concerned with pine encroachment. The environment is a cellular automaton coming from the rasterisation of a vector map. Several procedures account for vegetation changes due to pine encroachment according to natural succession trends and range, timber or conservation management decisions. The three agents types (sheep farmers, foresters and the National Park) are concerned by this global biological process but it affects their management goals in a very different way (sheep production, timber production, nature conservation). The model is used to simulate and compare collectively contrasting management scenarios arising from different agreements. Simulation results were used to support the emergence of collective projects leading to a jointly agreed management plan.

19.4.2.6 GEMACE: Multiple Uses of the Rhone River Delta, Southern France

This ABM developed with the Cormas platform simulates the socio-economic dynamic between hunting managers and farmers in the Camargue (Rhone river delta, southern France), through the market of the wildfowling leasing system, in interaction with ecological and spatial dynamics (Mathevet et al. 2003a). A CA represents an archetypal region based on a spatial representation of the main types of estates, distributed around a nature reserve. Each cell is characterized by water and salt levels through land relief, land-use history, infrastructure, spatial neighbourhood, and current land use. A wintering duck population, heterogeneously distributed in its habitats, is affected by various factors such as land-use changes, wetland management, hunting harvest, and disturbance. Land-use decisions are made at farmland level by farmers and hunting managers that are communicating agents. Their strategy, farming or hunting oriented, is based on crop rotation, allocation of land use and water management, and may change according to some specific representations and values related to farming and hunting. Scenario runs allowed discussing the structuring of the waterfowl hunting area resulting from the individual functioning of farms in conjunction with a nature reserve and other hunting units and the conservation policy.

19.4.3 Water Management

In the field of sustainable development, water management resources are an issue of major importance. ABMS dealing with water management are used to simulating the management of irrigated ecosystems, to represent the interactions among stakeholders by capturing their views and formalizing the decision-making mechanisms (especially negotiation processes), to capture the socioeconomic aspects of potable water management and evaluate scenarios based on alternative control measures, etc. For instance, Haffner and Gramel (2001) have investigated strategies for water supply companies to deal with nitrate pollution; Janssen (2001) has simulated the effects of tax rates related to the intensive use of phosphorus on lake eutrophication; Becu et al. (2003) have developed CATCHSCAPE to simulate the impact of upstream irrigation management on downstream agricultural viability in a small catchment of Northern Thailand; Krywkow et al. (2002) have simulated the effects of river engineering alternatives on the water balance of the Meuse river in the Netherlands, and have related this hydrological module to stakeholders' negotiations and decisions. Below we describe in more detail a selection of applications that are also characterized in the table presented in the Appendix.

19.4.3.1 SHADOC: Viability of Irrigated Systems in the Senegal River Valley

To examine how existing social networks affect the viability of irrigated systems in the Senegal River Valley, the SHADOC ABM focuses on rules used for credit assignment, water allocation and cropping season assessment, as well as on organization and coordination of farmers in an irrigation scheme represented as a place of acquisition and distribution of two resources: water and credit (Barreteau and Bousquet 2000; Barreteau et al. 2004). The model used a spatially non-explicit representation: all plots are subject to the same hydrological cycle regardless of their exact geographical position. The societal model is structured with three types of group agents in charge of credit management, watercourse and pumping station management. As far as individual agents (farmers) are concerned, the model employs a four-level social categorization with different types of farmers according to their own cultivation objective. Each agent acts according to a set of rules local to him. Each agent also has its own point of view about the state of the system and especially its potential relations with other agents. SHADOC was first designed as a tool for simulating scenarios of collective rules and individual behaviours.

19.4.3.2 MANGA: Collective Rules of Water Allocation in a Watershed

MANGA has been developed to test the economics, environmental, and ethical consequences of particular water rules in order to improve the collective management of water resources according to agricultural constraints, different actors' behaviours, and confrontation of decision rules of each actor (Le Bars et al. 2005). Their modelling approach takes into account cognitive agents (farmers or water supplier) trying to obtain the water they need via negotiation with the others as a result of its individual preferences, rationality, and objectives. The MANGA model used a spatially non-explicit representation for coupling social and environmental models. To implement the decision-making process of the cognitive agents, the authors used the BDI formalism and more particularly the PRS architecture. During simulations, MANGA allows to test several water allocation rules based on water request, irrigated corn area or behaviour evolution.

19.4.3.3 SINUSE: Water Demand Management in Tunisia

Sinuse is a simulator conceived to simulate the interactions between a water table and the decisions of farmers in Tunisia (Feuillette et al. 2003). The farmers' decisions are driven by economic objectives, but the dynamics of the system is mainly dependent on the interactions among agents. The agents interact through message sending to exchange land, and to team up to build wells. They also interact through imitation and influence on the land price. They interact through the environment as they share a common resource, the water table which has its own dynamics and depends on the number of active wells. The model was developed with Cormas platform. Simulations study the influence of various policies such as subsidies for improved irrigation equipment.

19.4.3.4 Water Management and Water Temple Networks in Bali

Do irrigation systems necessarily need a centralized authority to solve complex coordination problems? An ancestral Balinese system of coordination based on villages of organized rice farmers (subaks) linked via irrigation canals has served as a case study to investigate this question (Janssen 2007; Lansing and Kremer 1993). Actions to be done on each specific date for each subak are traditionally related to offerings to temples. The original model was recently re-implemented to deeper investigate why the temple level would be the best level for coordination. The environment is set as a network of 172 subaks, together with a network of 12 dams allocating the water to the subaks. Each subak has up to 4 neighbouring subaks. It selects one cropping plan out of 49 predefined ones. The corresponding water demand is affecting the runoff between dams. Harvests are affected by water stresses and pest outbreaks. The densities of pest in subaks are changing due to local growth (related to the presence of rice) and migration (based on a diffusion process). Six simulation scenarios based on the level of social coordination were explored by Lansing and Kremer. Additionally, to the two extreme scenarios defined with a single group of all 172 subaks (full synchronization) and 172 separate groups (no synchronization), 4 intermediate scenarios were tested, based on groups defined from the existing system of temples.

19.4.3.5 Sharing Irrigation Water in the Lingmuteychu Watershed, Bhutan

Raj Gurung and colleagues used ABMS, following the companion modelling approach, to facilitate water management negotiations in Bhutan (Gurung et al. 2006). A conceptual model was first implemented as a role-playing game to validate the proposed environment, the behavioural rules, and the emergent properties of the game. It was then translated into a computerized multi-agent system under the Cormas platform, which allowed different scenarios to be explored. Communicating farmer-agents exchanged water and labour, either within a kinship network or among an acquaintance network. Different modes of communication (intra-village and inter-village) were simulated and a communication observer displayed the exchange of water among farmers.

19.4.4 Forestry

Applications of ABMS in forestry are either focusing on LUCC issues or on management issues. For instance, Moreno et al. (2007) have simulated social and environmental aspects of deforestation in the Caparo Forest Reserve of Venezuela; Nute et al. (2004) have developed NED-2, an agent-based decision support system that integrates vegetation growth, wildlife and silvi-culture modules to simulate forest ecosystem management plans and perform goal analysis on different views of the management unit. Below we describe in more detail a selection of applications that are also characterized in the table presented in the Appendix.

19.4.4.1 Deforestation and Afforestation in South-Central Indiana

Hoffmann et al. (2002) propose an original way of using ABMS to improve scientific knowledge on the interactions between human activities and forest patterns in Indiana, during the last 200 years (Hoffmann et al. 2002). The environment is a raster artificial landscape randomly generated from the 1820's land-cover ratio between crops, fallows and forests, and randomly calculated slopes. Farmer is the only type of agent identified but they can behave differently according to two potential goals (utility maximizing or learning reinforcement) and two actions: deforestation or afforestation. Simulations are used to check through statistical analysis of a high number of runs, the impact of ecological (slope), social (stakeholders goals) or economic (agricultural prices, returns) factors in changing land-use patterns.

19.4.4.2 Forest Plantation Co-management

This ABMS modeling approach links social, economic and biophysical dynamics to explore scenarios of co-management of forest resources in Indonesia (Purnomo and Guizol 2006; Purnomo et al. 2005). The purpose is to create a common dynamic representation to facilitate negotiations between stakeholders for growing trees. The environment is a simplified forest landscape (forest plots, road, agricultural land) represented on a cellular automaton. Each stakeholder has explicit communication capacities, behaviours and rationales from which emerge specific actions that impact landscape dynamics. The model is used to simulate different types of collaboration between stakeholders and both biophysical and economic indicators are provided to measure the impact of each scenario on forest landscape and smallholders incomes. Simulations results are supposed to support the selection of the system of governance providing the best pathway to accelerate plantation development, local community poverty alleviation and forest landscape improvement.

19.4.5 Wildlife

Understanding how human activities impact on the population of animals in the wild is a concern shared by conservationists, by external harvesters (hunters, fishermen) and by local people. Viewed as a source of food or as an emblem of biodiversity, management schemes first have to ensure the viability of the population. Viewed as competitors for the living space of local people, management schemes have to control the population. For instance, Zunga et al. (1998) have simulated conflicts between elephants and people in the Mid-Zambezi Valley; Galvin et al. (2006) have used ABMS to analyse how the situation in the Ngorongoro Conservation Area (NCA) in northern Tanzania could be modified to improve human welfare without compromising wildlife conservation value; Jepsen et al. (2005) have investigated the ecological impacts of pesticide use in Denmark. Below we describe in more detail a selection of applications that are also characterized in the table presented in the Appendix.

19.4.5.1 Water Management in Mediterranean Reedbeds

Using the Cormas platform, the authors have developed an ABM to be used in environmental planning and to support collective decision-making by allowing evaluation of the long-term impact of several water management scenarios on the habitat and its fauna of large Mediterranean reedbeds (Mathevet et al. 2003b). A hydro-ecological module (water level, reedbed, fish, common and rare bird populations) is linked to a socio-economic module (reed market and management). Each cell was assigned a type of land use, land tenure and topography from a GIS to create a virtual reedbed similar to the studied wetland. Five types of interacting agents represent the users of the wetland. They are characterized by specific attributes (satisfaction, cash amount, estates etc.) and exploit several hydro-functional units. The behaviour of the agents depends on their utility function based on their evaluation of the access cost to the reedbed and on their beliefs. The ecological and socio-economic consequences of individual management decisions go beyond the estates, and relate to the whole system at a different time scale.

19.4.5.2 Giant Pandas in China

Using data from Wolong Nature Reserve for giant pandas (China), this ABM simulates the impact of the growing rural population on the forests and panda habitat (An et al. 2005). The model was implemented using Java-Swarm 2.1.1 and IMSHED that provides a graphical interface to set parameters and run the program. It has three major components: household development, fuelwood demand, and fuelwood growth and harvesting. The simulated landscape was built from GIS data. Two resolutions were identified for sub-models requiring extensive human demographic factors and for landscape sub-models. Both person and household are cognitive agents that were defined from socioeconomic survey. They allowed simulating the demographic and household dynamics. Agents interact with each other and their environment through their activities according to a set of rules. The main interaction between humans and the environment is realized through fuelwood collection according to demand. This model was used to test several scenarios and particular features of complexity, to understand the roles of socioeconomic and demographic factors, identifying particular areas of special concern, and conservation policy.

19.4.5.3 Traditional Hunting of Small Antelopes in Cameroon

To investigate the viability of populations of blue duikers, a small antelope traditionally hunted by villagers in the forests of Eastern Cameroon, an ABM has been developed with the Cormas platform (Bousquet et al. 2001). The raster spatial grid was defined by reading data from a GIS map corresponding to a village that was surveyed during several months. Each cell represents 4 ha (the size of the blue duiker habitat) and is characterized by a cover (river, road or village) and a reference to a hunting locality. The population dynamics of the blue duiker is simulated through the implementation of biological functions (growth, age-dependent natural mortality, migration, reproduction) applied to all the individual antelope agents. Hunter agents decide on the location of their traps by selecting one hunting locality out of the four they use. A first set of simulation scenarios was based on unilateral decisions of hunter agents, all of them following the same general rule. Coordination among kinship groups of hunters was introduced in a second set of experiences.

19.4.5.4 Whale-Watching in Canada

To investigate the interactions between whale-watching boats and marine mammals in the Saguenay St. Lawrence Marine Park and the adjacent Marine Protected Area in the St. Lawrence estuary, in Quebec, this ABM was implemented with the RePast platform (Anwar et al. 2007). A raster grid defined from a GIS database represents the landscape of the studied area. The boats are cognitive agents and whales are simple reactive agents. Several simulations were run to explore various decision strategies of the boat agents and how these strategies can impact on whales. For each simulation, the happiness factor was used as an indicator of how successful the boat agents were in achieving their goals. Results showed that cooperative behaviour that involves a combination of innovator and imitator strategies based on information sharing yields a higher average happiness factor over non-cooperative and purely innovators behaviours. However, this cooperative behaviour creates increased risk for the whale population in the estuary.

19.4.6 Agriculture

ABMS applied to agriculture is mainly focussing on decision-making processes at the farm level (typically, agents represent households). Economic aspects usually play a pivotal role and standard procedures like linear programming are often used to represent individual choices among available production, investment, marketing alternatives, etc. This economic module is then embedded into a more integrated framework to explicitly represent spatial and social aspects. For instance, to investigate technology diffusion, resource use changes and policy analysis in a Chilean region, Berger (2001) has connected an economic sub-model based on recursive linear programming to an hydrological sub-model; Ziervogel et al. (2005) have used ABMS to assess the impact of using seasonal forecasts among smallholder farmers in Lesotho; Sulistyawati et al. (2005) have analyzed the consequence at the landscape level of swidden cultivation of rice and the planting and tapping of rubber by Indonesian households whose demography and economic welfare are simulated. Below we describe in more detail a selection of applications that are also characterized in the table presented in the Appendix.

19.4.6.1 Agricultural Pest and Disease Incursions in Australia

To analyse the effectiveness and regional economic implications of alternative management strategies for a range of different scenarios of a disease incursion in the agricultural sector, an ABM has been developed with the Cormas platform and applied to the case of the wheat disease Karnal bunt in a region of south eastern Queensland, Australia (Elliston and Beare 2006). A cellular spatial grid allows representing the spread of the pest across neighbouring paddocks and a range of potential transmission pathways including the wind, farm inputs and agents (farmers, contractors and quarantine officers) through their movement over the spatial grid. Farmers make cropping decisions about planting, spraying for weeds, harvesting and the use of contract labour. They can directly identify and report signs of a Karnal bunt incursion on their property. The incursion can also be detected from quality inspection when farm production reaches the collective storage unit. Then a quarantine response, based on a recursive checking in the neighbourhood of infected farms, is implemented by officer agents. Simulation scenarios are based on one hand on levels of farmer detection and reporting and on the other hand on the way the disease was first introduced into the system (limited and slowly expanding incursion versus potentially rapid expansion from a wide use of contaminated fertiliser).

19.4.6.2 AgriPolis: Policy Impact on Farms Structural Changes in Western Europe

Agripolis is the evolution of a model developed by Balmann (1997). It describes the dynamics of an agricultural region composed of farms managed by farmers (an agent represents both of these concepts) (Happe et al. 2006). The Landscape and the Market are the other agents. The farm agent has a cognitive decision-making process: this process corresponds to the traditional modelling in agricultural economics, where agents try to maximise their income. The land market is the central interaction institution between agents in Agripolis. Farm agents extend their land by renting land from farm landowners. The allocation of land is done through auctions. The Agripolis model was used to study a region in southwest Germany. A sensitivity analysis is done to analyze the relationship between policy change and determinants of structural changes such as the interest rate, managerial abilities and technical change.

19.4.6.3 Adaptive Watershed Management in the Mountains of Northern Thailand

This companion modelling experiment aims at facilitating a learning process among Akha highlanders about the socio-economic aspects (i.e. allocation of formal & informal credit, on & off-farm employment) of the expansion of plantation crops to mitigate soil erosion risk on steep land (Barnaud et al. 2007). Farmers' individual decision-making regarding investment in perennial crops, assignment of family labour to off-farm wage earning activities and search for credit were modelled. The simulated scenarios looked at the effects of the duration of the grace period of the loans, the distribution of formal credit amongst the 3 types of farms, and different structures of the networks of acquaintances for informal credit. Two main indicators were used to analyze the results of the simulations for each type of farm: (1) the total area under plantation crops (ecological indicator) and (2) the proportion of bankrupt farms leaving the agricultural sector (socio-economic indicator).

19.4.7 Livestock Management

Janssen et al. (2000) have used adaptive agents to study the co-evolution of management and policies in a complex rangeland system; another work lead by Janssen (2002) has investigated the implications of spatial heterogeneity of grazing pressure on the resilience of rangelands; Bah et al. (2006) have simulated the multiple uses of land and resources around drillings in Sahel under variable rainfall patterns; Milner-Gulland et al. (2006) have built an ABM of livestock owners' decision-making, based on data collected over 2 years in five villages in southeast Kazakhstan. Below we describe in more detail a selection of applications that are also characterized in the table presented in the Appendix.

19.4.7.1 Rangeland Patterns in Australia

To evaluate general behaviours of rangeland systems in Australia, this ABM represents a landscape made of enterprises, which are cognitive agents that represent a commercial grazing property (Gross et al. 2006). Each property is defined by an area, the quality of land in each patch, and its livestock. Behaviours of the enterprise agents are defined by a strategy set comprised of a set of rules, which evolves over time to represent learning. A government agent has an institutional strategy set that also varies through time. Its main roles are to collect taxes and deliver drought relief in the form of interest payment subsidies. The biophysical sub-models allow simulating plant and livestock dynamics. Pastoral decisions are made by the enterprise agents according to a set of rules. The variation in the level of financial weakness leads to the adoption of a new strategy by an enterprise. Each one is randomly associated with a rate of learning. Implemented in the C++ programming language, the model is fed by inputs of historical data. The simulations emphasize consequences of interactions between environmental heterogeneity and learning rate.

19.4.7.2 Collective Management of Animal Wastes in La Reunion

To investigate the collective management of livestock farming wastes on La Reunion Island, an ABM called Biomas has been developed with the Geamas platform (Courdier et al. 2002). Biomas simulates the organization of transfers of organic materials between two kinds of agents: surplus-producing farms (i.e. farms where livestock raising activity dominates) and deficit farms (i.e. predominantly crop production). The environment is represented as a network of "situated objects". Their association with the Geamas agents enable the agents to act on the environment (e.g. "crop" agents are linked to "plot" situated objects). Some situated objects like "road sections" are only related to other situated objects.

Graphs of connected situated objects allow representing itineraries. The agents in Biomas are interacting through direct exchanges of messages; they are also linked to a "Group" agent through a membership process. The "Group" agent is responsible for imposing the management constraints on all its members or individual agents by means of contracts, and implements a penalty system in the case of disregard of the regulations. The simulation scenarios are based on the constraints and regulations defined at this "Group" level.

19.4.8 Epidemiology

Models developed for the spread of infectious diseases in human populations are typically implemented assuming homogeneous population mixing, without a spatial dimension, social (and network) dimension, or symptom-based behaviour. ABMS offers great potential to challenge these assumptions. Recently Ling Bian (2004) proposed a conceptual framework for individual-based spatially explicit epidemiological modelling, discussing four aspects: (1) population segments or unique individuals as the modelling unit, (2) continuous process or discrete events for disease development through time, (3) travelling wave or network dispersion for transmission of diseases in space, and (4) interactions within and between night time (at home) and day time (at work) groups. As an illustration, she compares a simple population-based model of influenza to an equivalent schematic individual-based one. This abstract model has been utilised by Dunham (2005) to develop a generic ABMS tool. Recently, the fear of bioterrorism has also stimulated intensive studies in the USA, see for instance BioWar, developed by Carley et al. (2006) to simulate Anthrax and smallpox attacks on the scale of a city.

19.4.8.1 Bovine Leukemia

Two methodologies (system dynamics and agent-based) used to simulate the spread of a viral disease (Bovine Leukemia) are compared (Bagni et al. 2002). The purpose is, through "what-if" analysis, to assess the system's behaviour under various conditions and to evaluate alternative sanitary policies. Based from the same set of Unified Modelling Language (UML) diagrams, Vensim and Swarm are the two platforms that have been used to implement the conceptual model. The environment represents in an abstract way a dairy farm segmented into sectors. "Cow" and "Farm sector" are the two types of autonomous agents in this model. The integration at the farm level is directly achieved through the "model swarm". Scenarios focus particularly on the number of cows detected as positive at sanitary controls (as opposed to the total number of infected cows).

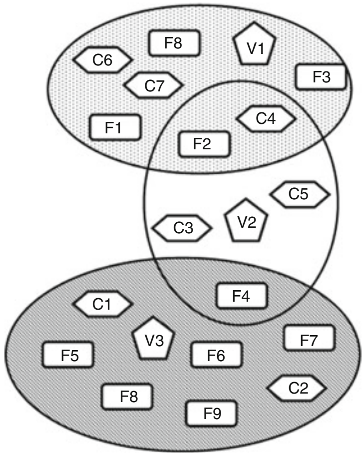

Fig. 19.4 The representation of space as clustering of three kinds of "location" agents: village (*pentagons*), cocoa plantations (*hexagons*) and forest (*rectangles*) (Muller et al. 2004)

19.4.8.2 Malaria in Haiti

To assess the impact of education on malaria healthcare in Haiti, an ABM with a realistic representation of Haiti has been designed (Rateb et al. 2005). The environment is set as a raster-grid with cells characterized by land-covers (sea, road, land, mountain, city, school, and hospital) associated with specific contamination probabilities (this is how mosquitoes are represented in the model). Apart from an epidemiological status, autonomous agents (representing individual people) are characterized by a mobility capability and an education score which value corresponds to the time agents take to attribute existing symptoms to malaria and therefore to go to hospital. Implemented in StarLogo, three scenarios based on the number of schools and hospitals have been discussed.

19.4.8.3 Sleeping Sickness in Cameroon

To understand the spread of Human African Trypanosomiasis, and ultimately to elaborate a tool to evaluate risk and test control strategies, an ABM has been developed with the MadKit platform and tested with data from one village in Southern Cameroon (Muller et al. 2004). The space is not explicitly represented in this model. This is due to the meta-model associated with the MadKit platform: the system under study has to be described through "agent-group-role" interactions (Ferber and Gutknecht 1998). Hence, surprisingly, locations can only be depicted as agents here (see Fig. 19.4). They are characterized by a proportional surface area and a number of animals.

Location agents, as "groups", are responsible for "enrolling" tsetse and human agents that will, as members of the same group, be able to interact through the sending of "bite" messages. The probability for a human agent to be bitten is inversely proportional to the number of animals. Simulation scenarios are based on the organisation of space, to investigate the effect of the size and number of transmission areas.

19.4.9 General Considerations

To fill in the table presented in the Appendix from the description of the models found in publications was not always easy. This is partly due to the fact that the elements to be detailed in the columns of the table require further refinements and more precise definitions. But this can also be attributed to the heterogeneity in the way model contents are detailed by the authors. The lack of a general framework to document such kind of models is patent, and all designers of ABM should become aware and refer to the framework proposed by Grimm et al. (2006). Even when the code of the implemented model is published (in appendices of articles or on a website), it is quite challenging and time-consuming to dive into it to retrieve specific information. This difficulty has triggered a bias: we have tended to select the applications we know better. As the co-authors of this chapter all belong to the same scientific network, the representativeness of the selected case studies may be questioned. This kind of task – a systematic survey based on a set of unambiguously defined characteristics – should be undertaken at the whole scientific community level, in a continuous way. Ideally, it should use an effective tool for mass collaborative authoring like wiki.

The environment, abstract or realistic, is most often represented as a raster grid. The spatial resolution, when it makes sense to define it precisely (for realistic simulated landscapes), is always clearly related to a key-characteristic of one of the model's components.

The number of applications with interactions involving the collective level is rather low. This does not necessarily imply cognitive agents. In the model of Bousquet et al. (2001), for instance, the collective level is related to the kinship structure of the small antelopes' population; when a young individual becomes mature, it leaves the parental habitat territory and starts to move around to look for a potential partner to establish a new family group in an unoccupied habitat. The group left by the young adult is affected in such a way that the reproduction can be activated again.

In our review, theoretical case studies are less numerous than empirical case studies. The prevalence of theoretical case studies is only significant for the LUCC category. It suggests that the proportion of empirical applications of ABMS is gaining ground compared to theoretical and abstract contributions. As analyzed by Janssen and Ostrom (2006), this could be explained by the fact that theoretical models, more frequent at the beginning, have demonstrated that ABMS can provide novel insights to scientific inquiry. The increased availability of more and more relevant ecological and socio-economics data then paved the way to the rise of empirically-based ABMS.

19.5 Why ABMS Is More and More Applied to Environmental Management

If ABMS is becoming more and more popular in environmental modelling, it is mainly because it demonstrates a potential to overcome the limitations of other kinds of models to take into account elements and processes that can hardly be ignored to consider the underlying research questions. Another aspect has to be stressed: ABMS is structurally an integrative modelling approach. It can easily be expressed with other modelling formalisms and tools. Additionally, to the evidential use of CA as a way to represent the space in ABMS applications dealing with environmental management, several other fruitful associations with complementary tools (GIS to handle spatial requests, Linear Programming modules directly used by agents to perform maximization of utility functions, etc.) have already been explored. Beyond technical aspects, ABMS can also be seen as a methodological step of a wider approach, like in companion modelling when it is jointly used with role-playing games to allow stakeholders' participation in the design of the tools used during participatory simulation workshops (Bousquet et al. 2002).

19.5.1 Getting Rid of Empirically Implausible Assumptions

In ecology, traditional general population models are assuming that: (1) individuals are identical; (2) the interaction between individuals is global; (3) the spatial distribution of individuals is uniform. Required to ensure analytical tractability, these overly simplified assumptions significantly limit the usefulness of such population-based approaches. The assumption of "perfect mixing" on which population-based modelling approaches rely (two individuals randomly picked can be inter-changed) is only valid when the environment is homogeneous or when all individuals facing the same environmental conditions react in exactly the same way. One way to account for heterogeneity is to define subpopulations as classes of similar individuals (for instance based on their age). Then a distribution function of the individual states is sufficient. But when interactions between individuals are depending on the local configuration of the environment (including the other individuals), the spatial heterogeneity and the inter-individual variability (two key drivers of evolution) can not be left out anymore. Spatially-explicit individual-based models (IBM) allow representing any kind of details critical to the system under study, thus relaxing assumptions distorting the reality in an unacceptable manner. This is the main reason why for more than two decades now (DeAngelis and Gross 1992; Huston et al. 1988; Judson 1994; Kawata and Toquenaga 1994), IBM has been more and more widely used in ecological modelling (for a recent guideline to make IBM more coherent and effective, see Grimm and Railsback 2005).

When it comes to include human decision-making processes into models, the standard way consists in assuming that all individuals equally informed (perfect information sharing) exhibit a standard behaviour based on rationality to achieve optimization. It is well known that renewable resources management addresses self-referential situations. The success of an individual strategy highly depends on the ability to "best-guess" what the other individuals may do over time (Batten 2007). This is closely related to the notion of "representation" defined by Rouchier et al. (2000) as the understanding an agent has of what it perceives, and that enables it to evaluate and then to choose the actions it can undertake on its environment. Do all agents agree, or do they have very different approaches to the same object or agent? One of the main interests of ABMS is to offer the possibility to explore the second option.

More generally, ABMS is a valid technical methodology to take into account heterogeneity in parameter values and in behaviours. In abstract and theoretical ABMS, standard statistical distribution functions can be used to assign particular parameter values to the different instances of agents created from the same class. Railsback et al. (2006) have compared how the main generic ABMS simulation platforms handle the initialization of one attribute of a population of agents from a random normal distribution (see version #14 of their benchmark "StupidModel"). For more realistic applications of ABMS, Berger and Schreinemachers (2006) recently introduced a straightforward approach to empirical parameterization using a common sampling frame to randomly select observation units for both biophysical measurements and socioeconomic surveys. The heterogeneity in behaviours is usually considered with each agent having to select one behavioural module from a set of existing ones. From a conceptual design point of view, heterogeneity of behaviours is easier to represent with a hierarchy of classes. Subclasses of a generic agent class are a proper design when a given agent does not update its behaviour over time. To account for such an adaptive ability, the agent class has to be linked to a hierarchy of behaviours, as shown in Fig. 19.1. Beyond selecting an alternative out of a predefined set of options, it is even possible to define innovative agents equipped with some evolutionary programming to drive the creation of new behavioural patterns by recombining elementary behavioural components.

19.5.2 Dealing with Multiple Nested Levels

The seminal paper of Simon (1973) envisions hierarchical organizations as adaptive structures and not only as top-down sequences of authoritative control. This view was instilled in ecology by Allen and Starr (1982), who promoted the idea that biotic and abiotic processes at work in ecosystems are developing mutually reinforcing relationships over distinct ranges of scales. Each level, made from components interacting at the same time scale, communicates some information to the next higher and slower level. Reciprocally, any level can contribute to maintain the stability of faster and smaller levels. In the field of environmental management, both social and biophysical systems are characterized by hierarchical, nested structures. For example, family members interact to form a household, which may interact with other households in a village through political and economic institutions. Populations formed of individual species members aggregate to form communities, which, in turn, collectively define ecosystems. Holling (2001) nicely illustrates this with two mirroring examples: on one side the components of the boreal forest represented over time and space scales (from needle to landscape); on the other side the institutional hierarchy of rule sets (from the decisions of small groups of individuals to constitution and culture) represented along dimensions of the number of people involved and the turnover times.

These ideas have been conceptualized to frame the emerging paradigm of "panarchy" (Gunderson and Holling 2002): the hierarchical structure of socio-ecological systems is exhibiting never-ending cycles of growth, accumulation, restructuring and renewal. The key-concepts of this heuristic model are undoubtedly expanding the theoretical understanding of environmental management. What is their concrete contribution to the evolution of ecological modelling? To what extent can ABMS claim to represent them in a better way than other kinds of models?

The aggregation between hierarchical levels is very difficult to model in a purely analytical or statistical framework. In ecology, aggregation methods are applicable for models involving two levels of organisation (individual and population) and their corresponding time scales (fast and slow) to reduce the dimension of the initial dynamical system to an aggregated one governing few global variables evolving at the slow time scale (Auger et al. 2000). The reverse way is much more difficult to integrate to models. How to account for the influence of changes at the global level on transitions at the microscopic level? Moreover, how to simulate both ways simultaneously at work? The main challenge deals with the coordination and scheduling of the different processes running at different levels: at the collective level, explicit decisions about temporarily giving back the control to lower-level component entities, and conversely decisions from lower-level entities to create a group and to give the control to it. In the scientific community of ABMS, these ideas have directly inspired the production of conceptual organizational meta-models like Aalaadin (Ferber and Gutknecht 1998), specific features in generic simulation platforms like the threaded scheduling of agents in Swarm, as well as applications like simulating hydrological processes (runoff, erosion and infiltration on heterogeneous soil surfaces) with "waterball", pond and river agents (Servat et al. 1998).

19.5.3 Beyond Decision Support Systems: Exploring New Dimensions in the Way to Use Models

As they represent complex adaptive systems which are unpredictable as a whole, ABMS applied to environmental management should caution about the large uncertainties related to their predictive abilities (Bradbury 2002). Still, empirically-based ABMS can be used as a decision-support system, for instance to assist policymakers in prioritizing and targeting alternative policy interventions, as Berger et al. (2006) did in Uganda and Chile. Nevertheless, when multiple perceptions of the reality coexist, the statement “everything is defined by the reality of the observed phenomena” can be questioned. Therefore, ABMS in the field of ecological management should take some distance with the positivist posture that designates the scientific knowledge as the only authentic one. Relating empirical observations of phenomena to each other, in a way which is consistent with fundamental theory, phenomenological modelling is a means to represent the phenomena in a formalized and synthetic way. Descriptive rather than explanatory, this approach does not truly gain understanding of the phenomena, but can claim, in simple cases, to predict them. Parker et al. (2003) refer to these two distinct explanatory and descriptive approaches to clarify the potential roles of ABMS in LUCC. Anyway, the general rule “the more realistic the application, the more descriptive the approach” may not necessarily always apply. Explanatory goals can be assigned to models closely related to a real situation as well.

In contrast to the positivist approach, the constructivist approach refers to “constructed” knowledge, contingent on human perception and social experience and not necessarily reflecting any external “transcendent” realities. Starting “from scratch” to collectively design a model is a straightforward implementation of the constructivist approach. Among scientists, it will integrate within and between disciplines. By involving stakeholders, instead of showing them a simplification of their knowledge, the collective design of the model is seeking a mutual recognition of everyone’s representation. In such a context, ABMS is more a communication platform to facilitate collective learning than a turnkey itinerary for piloting renewable resources management (Bousquet et al. 1999; ComMod 2003; Etienne et al. 2003; Gurung et al. 2006).

19.6 Drawbacks, Pitfalls, and Remaining Challenges

19.6.1 Verification and Validation of ABMS

This is a problem challenging ABMS in general that is addressed in Chaps. 6 (Galán et al. 2013) and 8 (David 2013) of this book. In the field of ecological management, as in other fields of applications, some authors claim to intentionally bridle the development of their agent-based model to design a strict equivalent to a mathematical equations-based model, as a means to verify it (Brown et al. 2004). The same process has been tested with mathematical representations of discrete distributed systems like Petri nets (Bakam et al. 2001).

19.6.2 Capturing the Meta-rules Governing the Adoption of Alternative Strategies

Nowadays, a set of tested and reliable tools and methods is available to better understand decision rules of actors and integrate them in computer agents (Janssen and Ostrom 2006). What remains much more challenging is to capture the rules governing the changes in agents' behaviours. An example of such a kind of "meta-rule" is the "evaluateAttitude" of the Collector agent (see Fig. 19.1) defined by (Thébaud and Locatelli 2001). In such a stylized model, the meta-rule is simply based on a threshold value of a specific parameter (the size of the pile of collected driftwood). When it comes to making the rules explicit to governing the changes of behavioural rules of human beings in real situations, methods are still weak. The meta-rules, if they exist, that control changes of strategies are difficult to grasp and elicit, and by consequence to implement in an empirical-based ABM. One reason is the time scale which is greater for these meta-rules than for decision rules, and which makes direct observation and verification harder to carry.

19.6.3 Improving the Representation of Space

Representing space with a CA, by far the most frequent way in current applications of ABMS in environmental management, is easy. But, as recently pointed out by Bithell and Macmillan (2007), imposition of a fixed grid upon the dynamics may cause important phenomena to be misrepresented when interactions between individuals are mediated by their size, and may become too consumed by computer resources when the system scale exceeds the size of individuals by a large factor. How to handle discrete spatial data that is potentially completely unstructured, and how to discover patterns of neighbourhood relationships between the discrete individuals within it? New directions like particle-in-cell are suggested.

In the next few years, we can also expect more applications based on autonomous agents moving over a GIS-based model of the landscape, with rendering algorithms determining what an individual agent is able to "see". Already used to simulate recreational activities (see for instance Bishop and Gimblett 2000), behavioural responses to 3D virtual landscape may become more common.

Further Reading

1. The special issue of JASSS in 2001[1] on "ABM, Game Theory and Natural Resource Management issues" presents a set of papers selected from a workshop held in Montpellier in March 2000, most of them dealing with collective decision-making processes in the field of natural resource management and environment.
2. Gimblett (2002) is a book on integrating GIS and ABM, derived from a workshop held in March 1998 at the Santa Fe Institute. It provides contributions from computer scientists, geographers, landscape architects, biologists, anthropologists, social scientists and ecologists focusing on spatially explicit simulation modelling with agents.
3. Janssen (2002) provides a state-of-the-art review of the theory and application of multi-agent systems for ecosystem management and addresses a number of important topics including the participatory use of models. For a detailed review of this book see Terna (2005).
4. Paredes and Iglesias (2008) advocate why agent based simulations provide a new and exciting avenue for natural resource planning and management: researches and advisers can compare and explore alternative scenarios and institutional arrangements to evaluate the consequences of policy actions in terms of economic, social and ecological impacts. But as a new field it demands from the modellers a great deal of creativeness, expertise and "wise choice", as the papers collected in this book show.

Appendix

Topic and Issue

When multiple topics are covered by a case study, the first in the list indicates the one we used to classify it. Within each topic we have tried to order the case studies from the more abstract and theoretical ones to the more realistic ones. This information can be retrieved from the issue: only case studies representing a real system mention a geographical location.

[1] http://jasss.soc.surrey.ac.uk/4/2/contents.html

Publications	Model name	Topic	Issue	Environment	Agents	Software
Polhill et al. 2001	FEARLUS	LUCC	Land-use and land ownership dynamics	Raster 7,7 region	Land manager (*49*) HeB (10) Ie	Swarm
Brown et al. 2004		LUCC	Greenbelt to control residential development	Raster *X*,80 suburb	Resident (*10*) Ho Ie R	Swarm
Castella et al. 2005a	SAMBA (Generic)	LUCC	LU changes under decollectivization in north Vietnam	Raster 50,50 (25 Ha) commune level (Abstract)	Household (50) HeP Ie R	Cormas
Castella et al. 2005b	SAMBA-GIS (More realistic)	LUCC	LU changes under decollectivization in north Vietnam	Raster regional level (More realistic)	Household (x) HeP Ie R (x = nb household in each village)	Cormas ArcView
D'Aquino et al. 2003	SelfCormas	LUCC; agriculture; livestock	Competing rangeland and rice cropping land-uses in Senegal	Raster 20,20 (5Ha) village	Farmer (20) *HeB*(2) Ie R	Cormas
Etienne et al. 2003	Mejan	LUCC; livestock; forestry; wildlife	Pine encroachment on original landscapes in France	Raster 23793 (1 ha) plateau	Farmer (40) *HeB* Ie,Ii,Ic C forester (2) HeB Ie,Ii,Ic R national park (1) Ho Ie,Ii,Ic C	Cormas MapInfo
Mathevet et al. 2003a	GEMACE	LUCC; agriculture; wildlife	Competing hunting and hunting activities in Camargue (South of France)	Raster region	Farmer Ie, Ii hunting manager Ie, Ii	Cormas
Barreteau and Bousquet 2000; Barreteau et al. 2004	SHADOC	Water; agriculture	Viability of irrigated systems in the Senegal river valley		Farmer	
Le Bars et al. 2005	Manga	Water			Farmer (n) Ie,Ii C water supplier (1) Ic C	
Feuillette et al. 2003	Sinuse	Water; agriculture	Water table level	Raster 2400 (1Ha) watershed	Farmer HeP Ie,Ii,Ic	Cormas
Lansing and Kremer 1993; Janssen 2007		Water; agriculture	Water management and water temple networks in Bali	Network 172 watershed	Village (172) HeB(49) Ie,Ic R	
Raj Gurung et al. 2006	Limbukha	Water management	Negotiation of irrigation water sharing between two Bhutanese communities	Grid 8,13 (10.4 Ha) (Abstract) Village	Farmer (12) *HeB* Ii	Cormas
Hoffmann et al. 2002	LUCIM	Forestry; LUCC	Deforestation and afforestation in Indiana USA	Raster 100 state	Farmer (10) HeB Ie R	
Purnomo and Guizol 2006		Forestry	Forest plantation comanagement in Indonesia	Raster 50,50 () Forest massif	Developer Ie,Ii,Ic Smallholder Ie,Ii,Ic C Broker Ie,Ii,Ic government Ie,Ii,Ic	

Mathevet et al. 2003b	ReedSim	Wildlife	Water management in Mediterranean reedbeds			Cormas
An et al. 2005		Wildlife	Impact of the growing rural population on the forests and panda habitat in China			
Bousquet et al. 2001	Djemiong	Wildlife	Traditional hunting of small antelopes in Cameroon	Raster 2042 (4Ha) village	Hunter (90) HeP Ie,Ic R antelop *(7350)* *HeB*(3) Ie,Ic R	Cormas
Anwar et al. 2007		Wildlife	Interactions between whale-watching boats and whales in the St. Lawrence estuary	Raster	Boat C whale R	Repast
Elliston and Beare 2006		Agriculture; epidemiology	Agricultural pest and disease incursions in Australia			Cormas
Happe et al. 2006	AgriPolis	Agriculture; lifestock	Policy impact on structural changes of W. Europe farms	Raster 73439 (1Ha) region	Farms (2869) HeP Ic	
Barnaud et al. (forthcoming)	MaeSalaep 2.2	Agriculture; LUCC	LU strategies in transitional swidden agricultural systems, Thailand	Raster (300 Ha) (Realistic) village catchment	Farmer (12) HeP Ii R credit sources (3)	Cormas
Gross et al. 2006		Lifestock	Evaluation of behaviours of rangeland systems in Australia		Entreprise C government	
Courdier et al. 2002	Biomas	Livestock; agriculture	Collective management of animal wastes in La Reunion	Network region	Livestock farm (48) HeP Ie, Ii,Ic crop farm (59) HeP Ie,Ii,Ic shipping agent (34) HeP Ii	Geamas
Bagni et al. 2002		Epidemiology; livestock	Evaluation of sanitary policies to control the spread of a viral pathology of bovines	Abstract farm	Farm sector Cow	Swarm
Rateb et al. 2005		Epidemiology	Impact of education on malaria healthcare in Haiti	Raster country	Inhabitant *HeP* R	StarLogo
Muller et al. 2004		Epidemiology; agriculture; livestock	Risk and control strategies of African Trypanosomiasis in Southern Cameroon	Network village	Villager Ic R	MadKit

Environment

- First line: mode of representation, with the general following pattern:

$$[\text{none; network; raster, vector}]\ N(x)$$

  N indicates the number of elementary spatial entities (nodes of network, cells or polygons), when raster mode, N is given as number of lines *x* number of columns, unless some cells have been discarded from the rectangular grid because they were out of bound (then only the total number is given), and (x) indicates the spatial resolution.
- Second line: level of organization at which the issue is considered (for instance village; biophysical entity (watershed, forest massif, plateau, etc.); city; conurbation; province, country, etc.)

Agents

One line per type of agent (the practical definition given in this paper applies, regardless of the terminology used by the authors). The general pattern of information looks like:

$$\text{name}(x)[\text{Ho}; \text{HeP}; \text{HeB}(y)][\text{Ie}; \text{Ii}; \text{Ic}]\ [\text{R}; \text{C}]$$

- (x) indicates the number of instances defined when initializing a standard scenario, italic mentions that this initial number change during simulation.
- When $x > 1$, to account for the heterogeneity of the population of agents, we propose the following coding: "Ho" stands for a homogeneous population (identical agents), "He" stands for a heterogeneous population. "HeP" indicates that the heterogeneity lies only in parameter values, while "HeB" indicates that the heterogeneity lies in behaviours. In such a case, each agent is equipped with one behavioural module selected from a set of (y) existing ones. Italic points out adaptive agents updating either parameter value (*HeP*) or behaviour (*HeB*) during simulation.
- [Ie, Ii, Ic] indicates the nature of relationships as defined in the text and shown in Fig. 19.3.
- [R; C] indicates if agents are clearly either reactive or cognitive

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