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Decision Support for Forest Fire Risk Evaluation: Dynamic Modelling and Spatio-Temporal Integration

Eric Maillé
Cemagref, Aix-en-Provence Group
Mediterranean Ecosystems and Risk Research Unit
CS40061, Le Tholonet
F-13182 Aix-en-Provence Cedex 5, France
eric.maille@cemagref.fr

Bernard Espinasse
LSIS – UMR CNRS 6168
Univeristé Paul Cézanne
Domaine Universitaire de Saint-Jérôme
F-13397 Marseille Cedex 20, France
Bernard.espinasse@lsis.org

Abstract – Land cover quickly changes in the Mediterranean area: forest progress on agricultural abandoned lands when scattered urban zone progress into forest areas. As forest fire risk in linked to spatial arrangements, land cover change implies quick changes in forest fire risk level. Cartographic fire risk models elaborated by research for engineering are usually static, and do not take into account this temporal dimension. However, decision-makers need risk change previews for judicious land management planning. A framework to integrate time in spatial risk models is proposed. It is funded on integration of land cover change (vegetation and urbanisation) dynamic models, and forest fire risk models in order to design an environmental decision support system (EDSS). Such a system has to integrate geographical information systems (GIS) with modelling and simulation softwares of land cover changes (vegetation, urbanisation). This spatio-temporal integration can take different forms, from weak coupling up to intelligent integration. Two integration strategies are studied.

I. INTRODUCTION

The recent great economical development of many European Mediterranean local territories has leaded to important land use changes. Agricultural and pastoral activities have often decreased when industrial and touristy activities were highly developed. This has involved rapid demographic improvement. As a consequence, most of Mediterranean areas show great land cover changes. While many agricultural lands are abandoned, more and more rural territories get urbanised. According to a common model, towns and scattered building areas on one hand, and forest areas on the other hand progress one towards the other.

This long-term land transformation is a key factor of forest fire risk. First because when forest is in contact with urban areas or even is mixed with scattered urbanised areas, forest fire threatens directly people and goods. Secondly, because of urban infrastructures are well known factors of forest fire ignition. In the Mediterranean area, where most of forest fires have a human origin, the proximity of urban zones increases dramatically the number of forest fire starting points.

Some land management plans are elaborated to protect urban and suburban zones as well as the forest itself against forest fire risk. General plans aim to control land cover evolution, in particular the urbanisation process. As the risk evolves, fire risk maps used to make protection plans are only valid during a short period. The validity period is often shorter than the plan duration. Decision makers need decision support tools able to represent and simulate forseen land cover changes and risk level changes during the plan.

Such systems are necessarily funded on long-term fire risk model, i.e. on land cover changes modelling. The paper proposes to design a spatial decision support tool for risk evolution management, funded on land cover change models. This system will be designed to assist two kinds of users: decision-makers in charge of local spatial planning on one hand, fire risk and land management researchers on the other hand. For the first users, it would be a spatial decision support tools. For the second one, it would be a spatio-dynamic modelling tool.

In section II are analysed solutions to model land cover change dynamics with the aim to assess forest fire risk evolution. Two types of land cover change models have to be integrated: ecological models, used to simulate changes in vegetal cover, and geographical models, used to simulate the (scattered) urbanisation process. These dynamic models are the foundations of time introduction into forest fire risk modelling. In section III is presented a typology of spatial forest fire risk models to be integrated, and their limits. Then, in section IV, two spatio-temporal integration solutions are proposed: one wrappers-based, and one spatial agents-based in a GIS environment.

II. LAND COVER CHANGE DYNAMIC MODELLING FOR FOREST FIRE RISK VARIATION PREVISION

It does not exist integrated domain models able to represent global land cover changes at the origin of fire risk variation. Global land cover change modelling should necessarily be based on domain models integration. First is exposed the general assumption of the integration approach, then are inventoried a few domain models, from ecology on one hand and from geography on the other hand, that should be integrated in an environmental decision support system (EDSS) dedicated to fire risk management.

A. General assumption

One assumption of this research work is that land cover dynamics related to forest fire risk changes are of two main types: the urbanisation process and the ecosystem spontaneous dynamics. In the Mediterranean area, long term land cover changes have always their origin in changes of land uses. Land use changes result from human decisions, either individual (agricultural land abandonment, for example), or collective land management decisions (allowing buildings in one given rural zone, for example). In general, human decisions are very complex process, which modelling and simulation are often difficult. However, numerous individual decisions are also often modelised with aggregated models, analytical, statistical or even spatial models. The decision process itself is then not really modelised, but only its observable effects. Land cover changes due to numerous individual decisions, such as house building in a forest building zone, can be considered as "spontaneous dynamics" determined by a reduced number of factors.

Following the collective land use change decisions (in particular land management decisions), some spontaneous land cover changes occur. Two main dynamics that have great impacts on forest fire risk level are to be considered "Fig. 1":

1) ecosystem changes: these are changes in vegetal groups formation, structure and spatial distribution, evolving from grass lands up to climax forest. Relatively to forest fire risk, ecosystem changes represent the dynamic of the fuel spatial distribution.

2) house spreading dynamic in building zones: this is the physical discontinuous urbanisation process. Relatively to forest fire risk, the urbanisation process represents changes in space vulnerability.

The knowledge of these land cover changes is necessary to make judicious land management decisions taking into account forest fire risk. The decision support tool that is expected in this research work aims to represent spatial dynamics, in relation with different land management decision scenarios.

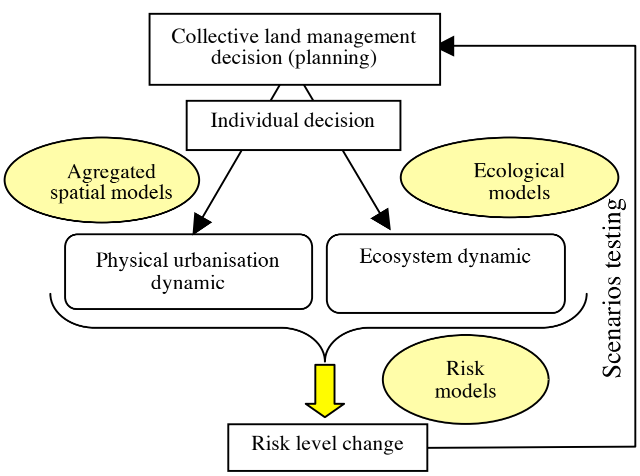

Fig. 1. The indirect relationship between land management planning decisions and risk level change and the required models

Some kinds of domain models available to represent these two dynamics are now examined in order to design such an EDSS.

B. Modelling the vegetal cover change dynamics

Ecological models are usable to represent vegetation changes dynamics. Such land cover changes are particularly important in fire risk evolution. First the role of the main types of vegetation lands in relation with forest fire risk is exposed. Then two different kinds of ecological models usable to represent their dynamic are presented.

In most of cases, agricultural lands are supposed to be efficient fuel breaks able to protect vulnerable zones (in particular building lands) against forest fire. In some cases, dry cereal crops are a factor of ignition danger, during a short period, in the beginning of summer time. However, yearly changes of agricultural managed land cover are not supposed to be factors of risk change.

On the other hand, abandoned agricultural lands represent high risk of ignition zones, as they are usually dry grassy and/or bushy lands. After some years, abandoned agricultural lands evolve towards forest. Abandoned lands are often in contact with forest lands, what makes the forest to progress on agricultural lands, and then to reach building lands closer and closer.

So called "opened natural lands", that is to say rocky, grassy or bushy natural lands, are usually former pastoral areas in the Mediterranean area. When such poor pastures are abandoned by breeders, they also evolve slowly towards forest, what still increases the surface of lands covered with forest, and then forest fire risk.

Forest advance on former agricultural or pastoral lands is one of the most important land cover change that increase forest fire risk. It can be described using ecological models.

After a given land use change decision like agricultural land abandonment, the ecosystem evolve spontaneously towards its climax state. This dynamic has two dimensions: the vertical one, that is to say vegetation growth and changes in formation and structure, and the horizontal one, which means the spatial spread of different spieces. Biologists produce numerous domain models able to describe both vertical and horizontal ecosystem dynamics. Two kinds of ecological models are necessary to simulate vegetation changes:

1) The structural vegetation models: they describe changes in vegetation structure, form grass stage up to forest stage, on a given ecological place, characterised by its environmental conditions. Such ecological models are well known as vegetation series models. They can easily be implemented, by describing the series in the database of a GIS, and then making successive queries on the database. Time step calibration is however a serious problem to solve.

2) The "spatio-dynamic" ecological models: they describe forest advance on former agricultural lands. Three groups of models are distinguished in relation with their "explanatory" levels:

- Simple spatial diffusion models. These models are funded on proximity relationship. Such models are well implemented using the cellular automata paradigm. They are sometimes completed by geographical information layers that representing environment conditions (notably edaphic conditions) or human infrastructures (forest exploitation, fuel break, etc.).
- Reproduction based models. These models take into account seed production and transportation (by the wind, by animals, etc.). Such models usually concern only one tree specie. As a case study, the AFFORSIM model [13] will be used, which is designed to simulate the pine *(Pinus sylvestis)* spread on abandoned agricultural lands.
- Physiological models. These models are complex models based on physiological functioning of plants. Such models are rarely used to simulate spatial dynamics of vegetation.

Ecological models have more or less advanced level of formalisation. Some keep being literal when others are already implemented. Because of the complexity of the biological processes that have to be taken into account, such ecological models are rarely totally analytical. Individual based modelling (IBM) is often well adapted to represent ecological dynamics [2]. Operationalisation of this approach uses different paradigms, for example the object paradigm (case of the AFFORSIM model), cellular automata or multi-agents systems (MAS) paradigm. These paradigms can also be used to formalize geographical models, i.e. spatial analysis dynamic models, used to represent the urbanisation process.

C. Modelling the urbanisation dynamic

In the Mediterranean area, the urbanisation process is rarely spatially continuous. On the contrary, the urban zone usually progress discontinuously, making scattered building zones, where houses, forest and agricultural patches are mixed. These scattered urbanised areas have high forest fire ignition risk as well as high vulnerability level. That is why this particular way of urbanisation should be modelled, in order to better manage forest fire risk planning.

At the local scale, the urbanisation can be seen as a kind of spontaneous dynamic after the land use change decision. The starting point of the urbanisation process is a land management decision, which allows buildings in a rural, and may be forest, zone. The actual precise location of each new building in the building zone is unpredictable individual human decision. But globally, the urbanisation process at large scale responds to quite simple rules that can be represented by simple spatial dynamic model, produced by geographers. Individual decisions are aggregated into simple spatial model, able to represent the physical spatial spread of houses on the building zones.

These models use the spatial relationships (proximity, contiguity) and influence (attraction, repulsion…) between geographic entities [3]. Among them, Markov gravity models are well adapted to represent spatial spread of houses form particular attraction points or lines. Attraction points or lines represent specific equipment such as water supply equipment or way of access.

Even if gravity models are analytical, individual based formalisms are also well adapted to describe scattered urbanisation process. Each building (generally dwelling houses) can be considered as an "individual", having a (simple) location behaviour in relation with its environment, and its neighbouring buildings. In any cases, the spatial relationship between different geographical objects is the key factor of the system dynamic. Geographical information systems (GIS) are specialised in processing such spatial relationships.

To assess the impact of land cover changes on the forest fire risk level, the EDSS should as well allow integrating forest fire risks models.

III. FOREST FIRE RISK MODELS

The relationship between forest fire risk evolution, and spatial dynamics, is described by forest fire risk models themselves. These are generally spatial models, funded on spatial feature attributes and/or arrangements. Four types of fire risk models can be distinguished [8].

A. Analytical attribute models

The risk is calculated in any point of the geographical space, by combining spatial attributes of the point itself. The risk is decomposed in its two main components, hazard and vulnerability, relatively to the two main stages of forest fire phenomenon, ignition and propagation. These different components are assessed by characterising vegetation, as well as local climatic conditions (average wind, for example). The calculated risk indicator has no absolute meaning. It only allows organizing into hierarchy different geographical places. The risk indicator values are usually classified into a few simple groups of risk levels: strong, medium, low, none, for example. These levels are sometimes called indices, and the models are often called indices models.

B. Aggregated spatial models

This type of model assesses the risk level by evaluating the spatial relationship between hazardous objects (as roads, for example), and vulnerable objects (as forest). Many spatial objects, buildings in particular, are both hazardous and vulnerable objects. This is the reason why such models assess a global risk, aggregating both of its components. Risk level is then directly related to spatial arrangements. Particularly high level of risk is located in the "interface area" between forest areas and building areas.

C. Analytical spatial models

This type of model distinguishes inducted risk and undergone risk, taking into account the propagation process. The undergone risk in one zone is calculated relatively to the inducted risk of the whole surrounding hazardous areas. Such model should take into account fire potential trajectory between inducted risk zones and undergone risks zones. So it is necessary to well know the fire propagation process.

D. Multi-simulation statistical models

This type of model is funded on fire dynamic propagation models. By repeating fire simulation many times it is possible to assess the risk level of any geographical point with statistical analysis of the simulations' results. This method is well adapted to assess the risk inducted by a particular punctual object (an industrial installation, for example).

All these risk models are static, even if the last type is funded on dynamic fire simulators. They do not allow previewing long-term risk changes, due to land cover changes. An EDSS has to be funded on dynamic modelling to be able to fill this deficiency. In some cases, the fire risk models are not much formalised. However, they quickly evolve, with the progress of the applied research. This justifies the necessity of an opened modelling support tool, intended to researchers implied in forest fire risk modelling. The EDSS to be designed should facilitate implementation of these different types of forest fire risk models, and finally to integrate those into one unique tool together with land cover change models, ecological and geographical ones. This requires a spatio-temporal integration approach.

IV. SPATIO-TEMPORAL INTEGRATION STRATEGIES

A modelling framework dedicated to spatial dynamic simulations should offer spatial analysis and spatial data processing functionalities, available in GIS, to the dynamic modelling framework, specialised in temporal process simulation [6]. To do so, integration solutions have to be implemented. Many strategies exist, from systems coupling to intelligent integration [9].

GIS are archetypes of generic EDSS. Land managers are now used to use this kind of tools, which are part of their working environment [15]. One of the most important factors of such tool appropriation by the users, is its ability to give spatial representation of one user's particular territory, in a very usual form for him (geographical maps in particular). However, even if time can be represented in some GIS, this tool is specialised in static spatial representations and spatial analysis. Because of this lack in time representation, direct implementation of dynamic models in common GIS environment is unusual [19].

On the other hand, dynamic simulation frameworks are usually not end-user tools, and are still rarely directly used by decision makers. They are not specialised in graphic spatial representations, and sometimes have poor capabilities in spatial analysis and in making simulations on real geographical information layers related to a given actual territory.

An efficient spatial decision support tool dedicated to fire risk dynamic management should associate usability together with advanced spatial analysis and dynamic simulation capabilities. Most of the needed functionalities are already implemented in GIS and in individual based simulation systems or frameworks. The proposed EDSS will be based on integration of GIS and individual based dynamic simulation systems (MAS in particular) [6]. The spatio-temporal integration can be more or less sophisticated, from syntactic weak coupling, up to intelligent agents-based semantic integration [7]. First are examined different kinds of possible couplings, and then are compared two possible strategies of agents-based integration.

A. Coupling strategies

Mandl [12] proposes a typology of links between GIS and MAS that distinguishes four types of couplings:

1) Weak coupling: both systems remain independent, only data is exchanged. This is usually a static coupling, because of the complexity of the two systems, which allows only poor performance of dynamic exchanges. Lieurain [10] proposes to use the Dynamic Data Exchange (DDE) standard to improve exchange performances. But weak coupling is mainly useful to fix initial state and to represent final state. Some intermediate interesting states can also be memorised and represented on the GIS using static links [4].

2) Tight coupling: spatial information processing functionalities are implemented in a MAS, or symmetrically, simulation functionalities are implemented in GIS. This is an archetype of dynamic coupling. However, new functionalities implemented in one or the other system, are necessarily limited, in a not really adapted software environment. Moreover, developments are redundant. It is only applicable to solve simple problems that do not need advanced spatial analysis functionalities nor elaborated agents or communication system between them.

3) Direct cooperative coupling: both systems remain independent, and communicate through a client/server link. They keep their whole capabilities, and are dynamically coupled thanks to the client/server link. However, this coupling requires a good interoperability between the data model of each system.

4) Indirect cooperative coupling: this is the same as the previous one, except there is a third system dedicated to data model adapting. The adapting system holds the (graphical) user interface (GUI). This last coupling requires quite heavy software developments.

All these types of coupling are syntactic, and do not take into account semantic aspects. In some intelligent couplings [5], information exchanges are ensured by specific agents of a MAS: the mediator agents [16]. As these agents are able to manipulate spatial information, they are spatial agents [14]. Spatial coupling agents are able to select and transfer the right information at the right time. To do so, they need semantic capabilities, so that they are able to act in relation with the informational context of the moment. This way of coupling, close to a total integration of both systems, allows good performances and maximises the global functional capabilities of the resulting integrated system. Several architecture solutions are available for such integration systems implementation.

B. Agents-based integration strategies

Two different possible agents-based integrations are considered in relation to their ability in implementing land cover change models for forest fire risk dynamic prevision: a “wrappers-based” solution on one hand, and a “spatial agents-based” architecture in GIS environment on the other hand. These two solutions differ notably in their level of genericity.:

1) A wrappers-based architecture: Serment & al. [17] propose an agents-based integration architecture able to integrate the different functional modules required for EDSS, including modelling and simulation modules. This architecture is inspired of the HLA (high level architecture) for simulation system integration. This proposed architecture distinguishes three major components: the wrappers, which encapsulate the software tools and ensure their integration to the system, the mediator, which ensure the interoperability between the different software tools, and the interfaces, which link the wrappers to the mediator. All these components are agents-based. This is a very generic architecture usable to integrate any existing or to be designed EDSS.

2) Spatial agents-based architecture in GIS environment: an architecture, more specific to land cover change modelling and simulation, is proposed [11], based on making agents with spatial entities in a GIS environment [1]. This solution is close to tight coupling, but it uses only one data model for both spatial objects and dynamic entities. The spatial agent paradigm is use as unique paradigm, although some GIS entities remain simple spatial objects and some agents have no spatial capabilities. A three phases integration demarche is proposed for the implementation of this integration architecture:

- The first phase aims to integrate into GIS the different models, in particular ecological individual based models that are not implemented in a GIS environment (for the studied application, this is the case of the AFFORSIM model).
- The second phase aims to make agents with some GIS entities that should become dynamic spatial entities. To do so, it is necessary to have an agent language functioning into the GIS environment. Ecological entities such as trees have to become agents, as well as some geographical dynamic objects like houses and land cover polygons.
- The third phase aims to implement the spatial relationship between agents and between agents and spatial objects as factors of the spatial agents’ behaviour. Spatial relationships between entities will be evaluated in order to minimize fire risk level, through integrated fire risk models, in relation to user, defined scenarios. Interactions between the spatial analysis engine of the GIS and spatial-agents have to be defined, as well as spatial task distribution between agents and between agents and the GIS.

The second solution is more dependent on software environment. It is more usual for end users, as they are used to standard (although often commercial) GIS environment. It is also functionally more specific, specialised in spatial dynamic modelling and simulation, when other functionalities, are directly ensured by the GIS software (in particular spatial graphical representations, spatial database management, etc.). However, both architectures are not strictly incompatible: the in-GIS integration approach can use the wrappers, interfaces and mediation layers architecture in order integrate pre-implemented models which are not yet integrated into GIS.

V. CONCLUSION

Land cover changes modelling for forest fire risk evolution assessment requires both model and system integration approaches in order to design an operative EDSS dedicated to land management decision-makers. Domain models elaborated by researchers in the different involved disciplines (ecology, quantitative geography and risk science) progress quickly: the designed tool has to keep being opened and to easily allow the implementation of new models. An open integration standard architecture like HLA appears well adapted to such a progressive modelling approach. On the other hand, usability require familiar software environment for end users. GIS are common environment used by land management decision makers. The proposed tool will be implemented in a GIS environment, by using an HLA architecture where the GIS can have a specific role in the mediation layer. This solution is domain specific, but keeps being opened enough to allow important evolutions in domain models.

IV. ACKNOWLEDGMENT

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