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## *Editorial*

### **Spatially explicit landscape modelling: current practices and challenges**

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### **Abstract**

In the past 30 years, the notion of landscape has emerged in ecology as a result of both theoretical strategies and practical aspects of land use. This has generated a variety of computerized models addressing both objectives and techniques. Scientists model landscapes for at least two reasons: to better understand the landscape dynamics themselves (called intrinsic needs) and to offer a realistic frame to support other ecological processes (extrinsic needs). This special issue concerns both needs and illustrates the way socioeconomic and/or ecological mechanisms of various landscapes have been understood through modelling approaches. It outlines the links between landscape and model concepts, focusing on one hand on several landscape types (agricultural, forested and aquatic) and on the other hand on several landscape model characteristics (explicit or neutral, dynamic or static, patchy or continuous and multi- or mono-scale). The patterns and processes of each landscape model presented in this issue, in particular, should be analysed in order to highlight the way they are contributing to the landscape ecology discipline. We finally argue that the discipline can now offer a theoretical dimension to landscape dynamics, aiming at understanding the possible mechanism unity underlying this complex object.

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## **1. Context**

The concept of *landscape* has become increasingly widespread in ecology. Separated from, yet complementary to, the ecosystem, this notion encompasses elements of various natures and several scales of perception and analysis (Turner et al., 1991; Forman, 1995; Dungan et al., 2002). The concept emerged from a combination of land planning issues, theoretical approaches and technological progress. Lying between local strategies that focus on management of agricultural and forest areas and urban and suburban zones, and those for whole regions, landscape is often perceived as an intermediate level of organisation, prone to be managed (Shoute et al., 1994; Twery, 2004). In parallel, recent progress in computer science, data and information representation and algorithms, have enabled the development of modelling strategies for these objectives (Coquillard et al., 1997; Blasco et al., 1999). The central paradigm of landscape ecology is that the spatial structures of a landscape have an effect on the movements of individuals and the flow of matter it shelters (Forman, 1995; Burel et al., 2003). Certain properties of the landscape such as heterogeneity, connectivity or fragmentation strongly influence the exchange and flow of organisms, matter and energy between the different components (Ricklef et Miller 2000). Moreover, this branch of ecology insists on the importance of

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scales and integration of processes, suggesting an holistic approach to landscape (Turner et al., 1993; Dungan et al., 2002). Other fields of investigation, sometimes less theoretical, have benefited from landscape analysis. Today, forest management is able to consider a forest landscape (sometimes restricted to a single stand) in order to study its evolution and assist in management (Twery, 2004). Physical geography and remote sensing studies are also a great source of inspiration when considering landscape models (Lambin et al., 2000).

Landscape studies are not concerned with energy or mass balances (e.g. element cycles, trophic networks), with specific ecological processes (e.g. tree growth, sedimentation of a water course) or the closure (i.e. no exchange outside the system) of ecosystems. Landscapes are gathering elements of very different natures (e.g. crop fields, rivers, roads, buildings...) that are continuously interacting at various scales (Burel et al., 2003). Landscape modelling may help to formulate, test and validate a hypothesis, often in spatial and temporal dimensions that are impossible to create and validate with *in situ* experiments. Other models (rarely the same as the preceding ones) can help to manage a system, to visualise it and make forecasts by implementing different scenarios. Several reviews of environmental models can be found in recent literature (Jorgensen et al., 2001; Müller et al., 2003), together with numerical simulations of landscape models where the notion of landscape is more present (Baker, 1989; Sklar et al., 1991; Mladenoff et al., 1999). Although these syntheses insist on specific features of current models such as spatial, temporal, and/or integrated descriptions, but they are not at all exhaustive in terms of landscape properties or model characteristics. We argue that they do not as yet emphasise any landscape properties or model characteristics in order to offer a coherent conceptual framework for landscape dynamics studies.

There are several ways of modelling a landscape: by interpolation, using cartography, with a *process-explicit* model or a *neutral* model. The first two types generally simulate spatial distribution of variables using statistical, multi-scale, geometrical and/or topological properties (through GIS) of their spatial patterns (Mackey, 2000; Kyriakidis, 2003). However, they rarely highlight landscape dynamics. Therefore these models are not known as « landscape models » and concern « spatial models on the scale of landscape », using landscape only as fixed support. Landscape models, in our sense, are mainly those highlighting the changes in land use: vegetation cover (forestry, agronomy, etc.), urbanisation (geography) or natural forms (geomorphology, soil studies, etc.). This temporal aspect, necessary in ecology and in the study of the landscape object, leads us to give details concerning the two last types of models. Process-explicit models reproduce a landscape by implementing one or several specific processes (Gaucherel et al., 2006b). They are complementary to neutral models which simulate landscapes with the patterns and statistical properties expected in the absence of studied processes (Gardner et al., 1991; With et al., 1997). Unlike explicit landscape models that would simulate dynamic functions and relations of landscape elements, these models do not try to reproduce the spatial patterns of any given real landscape. Neutral models deal more particularly with one of the characteristics of composition and configuration of real landscapes (With et al., 1997; Gaucherel et al., 2006a).

The authors for this issue were selected from a panel of authors that participated to the international symposium on "Spatial landscape modelling: from dynamic approaches to functional evaluations" which occurred in Toulouse (France), June 2008 ([http://w3.geode.univ-tlse2.fr/rtp-modelisation/eng\\_index.htm](http://w3.geode.univ-tlse2.fr/rtp-modelisation/eng_index.htm)). Its objective was to give an overview of current practices in the field of spatial landscape modelling, confronting developer and user approaches in order to point out future research challenges on spatial and temporal landscape modelling. This special issue aims at presenting a synthesis that characterizes landscape modelling approaches through the lens of four dimensions discussed below, summarizing main conclusions of this symposium. The resulting papers cover a wide range of theoretical and practical considerations, and together illustrate the diversity of existing spatial landscape models. Saltré et al (2009) present an original algorithm to reconstruct spatial and temporal species dispersion in Europe over thousands of years based on palaeo-environmental data. Such an approach would be useful for palaeo-ecologists and landscape ecologists to better understand how history matters (Gillson, 2009) either as geography (altitude, latitude...). Gomez-Gutierrez & al (2009) have respectively tested and developed models that also deal with DEM (Digital Elevation

100 Model) data. Conversely to Saltré et al (2009), they focus on fine scales and prediction of areas with  
environmental stakes. Indeed, the first paper aims to automatically detect area potentially concerned  
by gully erosion in Spain. Le Ber & al (2009) and Chaput-Bardy & al (2009) illustrate how models  
can contribute to explain how landscapes characteristics and/or dynamics influence gene flow and/or  
105 biodiversity. While dealing with very different landscapes (agricultural and aquatic), these papers  
illustrate that models could be efficient tools to evaluate how human activities / landscape  
configuration influence fluxes of matters and organisms. The last paper (Degenne et al, 2009)  
demonstrates that spatial landscape modelling, whatever the environmental issue, needs to refer to  
theoretical research to improve and facilitate development of such models. Finally, the papers in this  
110 special issue present an overview of the insights available to landscape ecologists, landscape modellers  
and all scientists working on modelling landscape dynamics.

## 2. Discussion

A rapid synthesis of modelled landscapes emerging from the review of the literature and on the models  
of this issue indicates the presence of dimensions (or polarisations) in relation to the design choice.  
The modelled landscapes have (a) a varying degree of landscape discontinuity (raster-vector); (b)  
115 various spatial and temporal dimensions (involving different scales); (c) operations dealing with  
diverse landscape elements; and (d) distinct degrees of specificity and finality.

- a. Firstly, we observe a dichotomy between those landscapes perceived as homogeneous patches and  
those with spatial gradients (continuous fields) which cannot be classified into a particular model  
type. If the component of a studied landscape is continuous, such as topographical elevation,  
120 latitudinal degree or bathymetric areas, physico-chemical equations can generally be used to  
remove segmentation bias and geometrical modifications not easy to avoid in landscapes. Rural  
landscapes are often discontinuous, but can also host continuous types of processes (pollens,  
pesticides, etc.) (Levin et al., 1993; Wu et al., 1997; Saltré et al, 2009). We have mentioned some  
of the works dealing with these discontinuous landscapes made up from uniform patches with  
125 distinct, well defined borders (Forman et al., 1981; Kotliar et al., 1990; Wu et al., 1994). As seen  
from the literature, especially with regard to neutral landscape models (Gaucherel et al., 2006a; Le  
Ber et al, 2009), the continuity or discontinuity of a landscape cannot be modelled in the same  
way.
- b. Undoubtedly the most interesting aspect of landscape models is to try to reproduce the dynamics  
they host. But which dynamics? Those of the first two dimensions  $[x, y, t]$ , that concentrate on the  
130 evolutions in the structure of horizontal landscape. These are the prime dimensions in landscape  
ecology and remote sensing. Are we more interested in vertical dynamics  $[z, t]$ , involving mainly  
digital terrain models (Saltré et al, 2009; Gomez-Gutierrez, 2009) and plant (or building) growth  
(Prusinkiewicz, 1999; Kang et al, 2008)? Hydrology, soil sciences and plant modelling all provide  
135 information for these dynamics, but other, more complex, approaches could be considered,  
involving simultaneously the dynamics of 2D landscape structures and growth in vegetation height  
or land erosion  $[x, y, z, t]$ . Very few attempts to develop functional landscape models in four  
dimensions exist.
- c. Beyond the question of landscape dimensions, there are also marked differences in landscape  
140 evolutions. We have mentioned Land-Use and Land-Cover Changes (LUCC) models which  
essentially take into account the attributes of landscape elements (Lambin et al., 2000; Mackey,  
2000): they modify the dominant type of element (the attribute of a patch, a group of pixels) called  
the landscape composition, but do not change the shape or the spatial arrangements of these  
elements called the landscape configuration. We qualified these latter operations as geometrical  
145 operations and noted that they remain relatively rare amongst landscape models (Le Ber et al,  
2009). Their development and calculation time are costly, but they are now increasingly being  
implemented in landscape studies (With et al., 1997; Gaucherel et al., 2006a). In particular,  
landscape models focusing on linear networks such as road networks or hydrographical networks  
are specifically addressing the question of landscape configuration (Chaput-Bardy et al, 2009).

150 d. Close examination of landscape models shows that objectives may vary. What are the objectives  
of these models? Do we want to check one or several hypotheses, or produce software or business  
packages? In this context, two model structures that have produced promising results for  
155 environmental issues, are in our opinion well adapted to landscape modelling: that of a domain-  
specific language (Fall et al., 2001; Degenne et al, 2009) and that of modelling platform. A  
domain-specific language uses a kernel of data, knowledge and methods surrounded by models  
specific to certain applications (less costly to design). This is situated mid-way between a  
multitude of small, object-specific models that are effective, but costly with, by definition, local  
results, and a universal, utopian model that could provide solutions to all objectives. This concept  
160 is not far away in one sense of other platforms such as SME (Costanza et al., 2004), CAPSIS (De  
Coligny et al., 2004) or L1/DYPAL (Gaucherel et al., 2006b), except that it also provides a  
language to improve modelling ease.

### 3. Conclusion

At present, there is need for landscape modelling to progress in many ecological disciplines. For  
example, different components must be integrated into landscape. Today, closer coupling between fine  
165 and large scale models, between biophysical and socio-economic factors is being implemented into  
landscape dynamics (Palang et al., 2000; Osinski et al., 2003). This coupling is all the more necessary  
today since the effects of man on the environment are becoming increasingly obvious. An integrative  
approach could be considered by coupling with other environmental models simulating atmospheric,  
underground and/or biological components of the landscape. Working in four dimensions and/or using  
170 domain-specific languages may be necessary in ecology (Degenne et al, 2009). These are promising  
strategies since they favour integrating ecological phenomena and provide a holistic view of  
ecosystems too. Landscape models that take into account their possible geometrical evolution, that are  
not limited to random change, and that adopt a patchy description in homogeneous landscape units,  
unlike a raster description, also seem to have a promising future. The small number of modelling  
175 approaches using only mechanistic landscape models, specifically describing how to change landscape  
components, leads us to further research along these lines using recent knowledge on ecological and  
socio-technical functioning of landscape and on fluxes. Landscape is a concept that can federate  
different environmental strategies.

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