Scaling and Modelling in Forestry: Applications in Remote Sensing and GIS

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In the book entitled *Scale in Remote Sensing and GIS*, Goodchild and Quattrochi (1997, p. 1) affirm that scale is undoubtedly one of the most fundamental aspects of any research. As it is further described in this Issue, the interest and importance for scale is either new or trivial. We now recognise that the concept of scale is central for understanding the complexity of our geographic world, and that explicitly addressing scale issues is mandatory for all disciplines dealing with anthropic and physical phenomena occurring at the earth's surface.

Over the last forty years, the fundamental role of scale has been revealed through the work achieved by social and natural scientists. From a convergence of ideas developed primarily in economics, ecology and computer sciences, a new theory has emerged that aims at describing the behaviour of human and ecological systems: *complex systems theory*. Complex systems are characterised by a large number of components interacting in a non-linear way and having adaptive properties through time (Waldrop, 1992; Coveney and Highfield, 1995). From this perspective, ecosystems should be regarded as open systems that extract high quality energy from the sun, and respond with the spontaneous emergence of organised behaviour to maintain their structure and function (Kay, 1991; Kay and Schneider, 1995). This mechanism is called *self-organisation* and it is revealed in the form of spatial patterns and temporal rhythms at the macroscopic scale where we can observe them (Nicolis and Prigogine, 1989).

An important characteristic of complex systems is that they take the form of a hierarchy, thus they are composed of interrelated subsystems, each of which in turn is made of smaller subsystems until a lowest level is reached. It has been suggested that complex systems maintain hierarchical structures because such an architecture allows causal relationship to exist, tends to evolve faster, offers more stability, and is therefore favoured by natural selection (Simon, 1962; Salthe, 1985; Wu and Reynolds, 1998). In a hierarchic system, interactions occur among and within subsystems in different orders of magnitude. Interactions are generally stronger and more frequent *within* a level of the hierarchy than *among* levels. This important fact enables scientists to perceive, and describe complex systems by decomposing them into their fundamental parts and interpreting their interactions (Simon, 1962).

The key to understand this hierarchical structure is scale. Actually, scale *is* the fundamental determinant of hierarchical structure. As described by Salthe (1985), if we were an omnipresent observer able to travel through scales in continual gradations, the complexity of the world would appear the same at all scales without discontinuities. But for observers of fixed scale as we are, the world appears as a series of discrete hierarchical levels of organisation. Therefore, scale is the window through which the world is revealed to us. When trying to detect entities, patterns, and processes, and when trying to understand their causal relationships, appropriate scales must be selected. Furthermore, the rules governing the interactions among levels of the hierarchy must be derived. These two aspects are often referred to as the main components of the scale issue.

If scale represents a key factor for deciphering the hierarchical complex structure of our world, two complementary objectives must be achieved to fully understand its role. First, it is necessary to consolidate a theoretical unifying framework from which hypothesis can be tested, and generalisations can be made. The recent integration of hierarchy theory (Allen and Star, 1982) with patch dynamics theory (Pickett and White, 1985) to provide the hierarchical patch dynamics paradigm (Wu and Loucks, 1995) represents a contribution to this goal. Second, quantitative methods must continue to be developed to detect scales and scale thresholds, and to derive appropriate rules for scaling. Models must also be built to investigate and explain the behaviour of ecosystems. Of particular interest is a class of models called distributed simulation models, derived from complex systems theory, where the global behaviour of an ecosystem is described based on spatial interactions at a local scale occurring through time. Technologies for spatial data acquisition and analysis, such as remote sensing and geographic information systems (GIS), can judiciously be used to support empirical investigations about scale and scaling, develop multi-scale analysis techniques (Hay *et al.*, 1999), and test hypothesis about the hierarchical structure of a landscape. Therefore, a positive feedback effect will always be maintained between theoretical and methodological developments to ensure substantial progress in the field. Examples of such interrelated perspectives are presented in this special Issue of this Journal.

Content of this Issue

This special Issue of the *Canadian Journal of Remote Sensing* represents a collection of papers presented at the *International Workshop on Scaling and Modelling in Forestry: Applications of Remote Sensing and GIS*, held at the University of Montreal in March 19-21, 1998. The objective of the Workshop was to gather scientists involved in forestry and vegetation studies where the importance of spatial scale is explicitly recognised and dealt with. Seventy people attended the Workshop originating from Europe, United States, and Canada. Thirty conferences were presented on a series of topics such as scale and scaling, landscape analysis, ecological measurements, and modelling.

The selected papers for this Issue are grouped into three main categories, each of them representing a particular trend of the scientific activities in relation to scale issues. The first group refers to conceptual developments mostly brought in the field of landscape ecology, geography, and spatial analysis. Three papers are presented in that category.

The first article is authored by Danielle Marceau, and represents a comprehensive review of the conceptual and methodological contributions made about scale in the social and natural sciences over the last forty years. Major concepts related to scale are first defined, followed by a description of the key steps involved in the recognition of the importance of the scale issue, and the quantitative solutions proposed to handle it. The paper concludes on a convergence of ideas evolving towards a unifying theoretical framework where scale plays a fundamental role in the understanding of the hierarchical organisation of the geographic world.

The second paper, by Marceau and Hay, describes the substantial contributions of remote sensing to the scale issue within the framework of the modifiable areal unit problem (MAUP). Initial interest on the importance of scale in remote sensing during the seventies is first presented. Then a description of studies is provided demonstrating that remote sensing data represent a particular case of the MAUP, and that its effects on any analytical results made upon these data can introduce considerable errors. A series of studies ranging from the seventies to the present are finally presented, where different solutions to MAUP are investigated within a remote sensing context to address the main components of the scale issue. This paper advocates the important role played by remote sensing in the development of a science of scale.

The third paper, by Jianguo Wu, presents a new theoretical framework, called the hierarchical patch dynamics paradigm (HPDP), which results from the integration of hierarchy theory and patch dynamics. Hierarchy theory focuses on the *vertical* structure of a landscape composed of discrete hierarchical levels, while patch dynamics theory deals with spatial heterogeneity and interactions among system components in a *horizontal* way. The author first explains the complexity of ecological systems and their inherent hierarchical structure. Then, he describes the principles of hierarchy and patch dynamics theory. Finally, he proposes a scaling strategy based on the unifying concepts of HPDP which involves three basic steps: 1) identifying appropriate patch hierarchies, 2) developing models of patterns and processes at their appropriate scale, and 3) extrapolating across scales using a hierarchy of models.

The second group of papers composing this special Issue provides three examples of applications of scale concepts and methodologies for the study of forested environments.

In the first paper, Puech and Viné investigate the relationship between forest structure and the spatial resolution of remote sensing data. They use the concept of *optimal spatial resolution* to describe an homogeneity level that is reached in a remote sensing image when the local variance associated to the elements composing the forest structure is at a minimum. To investigate such a relationship, they make use of high spatial resolution airborne data, and two forest models generated from detailed field data and user defined parameters of forest structure, respectively. The interest of this approach is to identify the appropriate spatial resolution corresponding to specific geographical entities under investigation.

In the second paper, Fleming *et al.* discuss the caveats of upscaling models within the context of evaluating the response of plant and animal populations to different management strategies. They explain that the models used are often based on intensive detailed studies of key factors affecting the reproductivity and survival of individuals, and are then scaled up to the coarser spatial scales at which management decision are taken. Such a process is made without taking into account the scale dependency and the spatial heterogeneity of the model parameters, which may create severe distortion in the resulting output. First, the authors describe the problem of *spatial transmutation*, defined as the process by which the behavior of a populations's dynamics appear to change with the scale of investigation. Then, they assess the impact of spatial transmutation in the context of two models for spruce budworm *(Choristoncura fumiferana)*, a simulation model of population dynamics and an autoregressive time series model. Their results reveal a scale dependency in the parameter estimation of the models, and on the interpretation of the underlying dynamics.

In the third paper of this category, Lett *et al*. describe a spatial model of forest dynamics based on a cellular automata architecture. Cellular automata are a special case of distributed models that enable the observation of large-scale patterns of a forest as they emerge from the local interactions among individual trees. This class of models is derived from complex systems theory (as previously described). The authors begin by describing different forest dynamics models with an emphasis on the *Jabowa gap model* and the *Wissel spatial model*. Then, they present their own approach that includes elements of the two previous models and discuss the results obtained from their simulation.

The last category of papers represent original mathematical developments for taking into account the heterogeneity of pixels when physical model parameters are derived from remote sensing imagery.

Bouguerzaz *et al*. describe a new model, also adapted to heterogeneous pixels, to derive radiative and energy balance from remotely sensed radiance values. The authors explain that the models currently used to estimate energy balance parameters, such as evapotranspiration and albedo, are based on the assumption of homogeneous surface characteristics. However, at large scales and coarse spatial resolutions, the heterogeneity of the landscape can introduce substantial errors in the estimation of the variables of interest. They study the scaling problem related to spatial heterogeneity by simulating spatially heterogeneous landscapes. They show that albedo and fAPAR (the fraction of absorbed photosynthetically active radiation) are nearly insensitive to heterogeneity since they are expressed as quasi-linear functions. However, the error introduced by heterogeneity is large for evapotranspiration and photosynthesis. The authors demonstrate that their approach provides more accurate results in the estimation of these parameters since it explicitly takes into account the scaling problem.

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