Remote sensing contributions to the scale issue

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Abstract
During the last decade, *the scale issue* has increasingly attracted the attention of a number of scientists in different disciplines, culminating with strong recommendations for establishing a *science of scale*. While it is widely acknowledged that remote sensing can provide significant contributions in that field, very few attempts have been made to synthesize the work already done, and suggest future research directions. This paper proposes a coherent framework within which the main contributions of remote sensing in relation to scale are reviewed. Remote sensing is presented as a particular case of the modifiable areal unit problem (MAUP). Then a description follows of how solutions to the MAUP have been and could further be applied in a remote sensing context to address the different components of the scale issue. Finally, it is advocated that remote sensing has and will continue to play a major role in the development of a science of scale.

Keywords: Scale, scaling, remote sensing, modifiable areal unit problem (MAUP)

Résumé
Au cours de la dernière décennie, le problème d'échelle a attiré l'attention d'un nombre croissant de chercheurs de diverses disciplines. Il a été fortement suggéré qu'une science de l'échelle soit établie. Alors qu'il est largement reconnu que la télédétection peut apporter une contribution significative au problème d'échelle, très peu d'études ont été menées dans le but de synthétiser le travail déjà accompli et suggérer de futures directions de recherche. Cet article propose un cadre conceptuel à travers lequel les principales contributions de la télédétection au problème d'échelle sont revues. Les données de télédétection sont présentées comme un cas particulier du problème des unités spatiales modifiables. Il est ensuite décrit comment les solutions proposées au problème des unités spatiales modifiables ont été et peuvent être appliquées dans le contexte de la télédétection afin d'investiguer les différentes composantes du problème d'échelle. Finalement, le rôle important de la télédétection dans le développement d'une science de l'échelle est souligné.

Mots-clés: Échelle, changement d’échelle, télédétection, problème des unités spatiales modifiables

Introduction

The existence of natural or preferred spatial scales and the necessity to find appropriate linkages between different scales was recognized in the social and natural sciences more than forty years ago [for an exhaustive review, see Marceau (1999)]. More recently, issues of scale have shown a widespread resurgence in scientific literature as manifest in books (Rosswall *et al.*, 1988; Ehleringer and Field, 1993; Schneider, 1994; Quattrochi and Goodchild, 1997), and specialized workshops in ecology (Turner *et al.*, 1989), environmental modeling and remote sensing (Raffy, 1993), hydrology (Sivapalan and Kalma, 1995; Stewart *et al.*, 1996), and forestry, remote sensing and geographic information systems (GIS) (Marceau and Hay, 1998). It has been strongly suggested that a science of scale be established. Meentemeyer and Box (1987) indicate that such a science must include scale as an explicitly stated variable in the analysis and strongly recommend the use of remote sensing and GIS as powerful tools for studying scale effects. In a complementary framework, Marceau (1992) suggested that a spatial theory be developed in remote sensing to take into account scale and the intrinsic spatial attributes of the geographic entities under study. Recently, Goodchild and Quattrochi (1997) noted that a full science of scale should seek answers to the following interrelated questions that can be regarded as the basic components of the scale issue:

- the role of scale in the detection of patterns and processes, and its impact on modeling,
- the identification of domains of scale (invariance of scale) and scale thresholds,
- scaling, and the implementation of multiscale approaches for analysis and modeling.

While a ubiquitous definition of scale does not exist (Schneider, 1994), several useful definitions have been provided in the literature. Cao and Lam (1997) describe four meanings of scale, namely the cartographic, the geographic, the operational and the measurement scale, while others have defined scale in relation to the absolute and relative representations of space (Meentemeyer, 1989; Marceau, 1999). Conceptually, scale represents the *window of perception*, the filter, or the measuring tool through which a landscape may be viewed or perceived (Levin, 1992). Thus, changing the scale changes the patterns of reality, which has obvious implications for understanding the dynamics of any environmental system. In the context of remote sensing, scale corresponds to *spatial resolution* (Woodcock and Strahler, 1987) which refers to the ability of a sensor to record and display fine spatial detail as separated by its surroundings. More correctly, remote sensing scale is a function of the instantaneous field of view (IFOV) of the system, which represents the ground area viewed by the sensor at a given instant in time, convolved by the optics of the sensor (Forshaw *et al.*, 1983). Remote sensing imagery also encapsulates two important aspects of scale: grain and extent. *Grain* represents the finest distinction that can be made in an observation set (i.e. spatial resolution), while *extent* corresponds to the span of all detected entities (Allen and Hoeskstra, 1991) (i.e. the total area covered within an image swath).

Despite the fact that an increasing number of scientists recognize that remote sensing can provide a significant contribution to the scale issue, there have been very few attempts to synthesize the work already achieved and to propose future research directions. Therefore, the primary goal of this paper is to present a coherent framework within which major contributions of remote sensing in relation to scale are reviewed. More specifically, the objectives are:

- to describe the contributions of remote sensing to the scale issue by emphasizing that remote sensing represents a particular case of the modifiable areal unit problem (MAUP),
- to describe how solutions to MAUP have been, and could further be applied within a remote sensing context to address the key components of the scale issue, and
- to advocate the role of remote sensing in pursuing empirical studies to deepen the understanding of the scale issue, and in developing a coherent theoretical framework for spatial scale.

The appropriate scale for a given geographical environment

Initial interest on the importance of scale in remote sensing begun in the mid seventies, through a series of empirical studies conducted on airborne and satellite multispectral data. As analysis proceeded, scientists became concerned over the choice of spatial resolution and data processing techniques that were producing poor automated classification results. Furthermore, a premise was made that finer spatial resolution imagery (than the currently available 80 m Landsat MSS) would improve feature extraction results. Consequently, a series of studies were conducted to assess the effects of spatial resolution on the ability to classify land-cover/land-use types using digital classification techniques (Sadowski and Sarno, 1976; Sadowski *et al.*, 1977; Latty and Hoffer, 1981; Markham and Townshend, 1981; Ahern *et al.*, 1983; Irons *et al.*, 1985; Cushnie, 1987). Their prime conclusions were that a change in spatial resolution could significantly affect classification accuracies, and that in many cases, the use of successively higher spatial resolution data resulted in lower overall classification accuracy. This was due to an increase in within-class spectral variability which confused per-pixel classifiers.

Following these results, several researchers began formally addressing the importance of spatial scale in remote sensing. In a central paper, Woodcock and Strahler (1987) developed a measure of local image variance to help in selecting an appropriate scale for three different geographical environments. They concluded that the choice of an appropriate scale depends on three main factors: the output information desired about the ground scene, the methods used to extract the information from the imagery, and the spatial structure of the scene itself. Additionally, Woodcock *et al.* (1988a, b) tested the use of variograms as a measure of spatial variation to improve the understanding of the relationships between ground scenes and the information content in remote sensing imagery. In 1988, Townshend and Justice applied Fourier analysis to investigate the required spatial resolution for global monitoring of land transformations.

Scale and individual geographical entities

In the previous studies, scientists were focused on a specific geographical environment (a scene), such as a forest, an urban zone, or an agricultural area. They were searching for the most appropriate unique spatial resolution for their particular application. It was rarely considered that the scene was composed of different sized real-world entities, and that a single resolution might not be appropriate to discriminate all classes within the image.

On the basis of these ideas, Marceau (1992) undertook a review encompassing two decades of thematic mapping studies involving remotely sensed imagery, and revealed this basic observation: within a given classification producing several land-cover/land-use types, there were often considerable inconsistencies in the results obtained from one class to another. For example, in a multispectral classification of SPOT images in a rural-urban environment using a conventional per-pixel classifier, Gong *et al.* (1992) reported 21% correct classification for new crops, 38% for cleared land, 49% for rangeland, 64% for old urban residential, 80% for mature crops, and 84% for industrial areas. In attempts to improve per-class accuracies, they performed texture analysis on their data. Their results showed that, for some classes, the classification accuracy increased with the addition of a texture channel, while for other classes, the accuracy did not change or even decreased. Similar observations were apparent in other studies involving texture analysis (Pultz and Brown, 1987; Peddle and Franklin, 1990; Coulombe *et al.*, 1991). In an exhaustive study conducted to evaluate which factors were responsible for the classification accuracies of nine land covers, using the grey-level-cooccurrence matrix method, it was found that 90% of the variability in the classification results was explained by the window size employed for the cooccurrence computation. Furthermore, the best classification accuracy for each class was achieved with different window sizes (Marceau *et al.*, 1990).

Remote sensing: a particular case of the modifiable areal unit problem

Searching for a broad framework to link scale and automated feature extraction results, Marceau (1992) hypothesized that a parallel existed between inconsistency in the results obtained when classifying remote sensing data and the major problems involving the manipulation of arbitrarily defined areal data known as the modifiable areal unit problem (MAUP) [(Openshaw, 1984; for a comprehensive review, see Marceau (1999)]. The MAUP originates from the fact that an enormous number of different ways exist by which a study area can be divided into non-overlapping areal units for the purpose of spatial analysis. Essentially, it represents the sensitivity of analytical results to the definition of data collection units, and is illustrated by two related but distinct components: the *scale problem* and the *aggregation problem*. The former is the variation in results that can be obtained when data collected for one set of areal units are progressively aggregated into fewer, larger units for analysis, while the latter is the variation in results generated by the use of alternative combinations of areal units at similar scales.

In a latter study, Marceau *et al.* (1994a) formulated that the acquisition of remote sensing data is a particular case of an arbitrary uniform spatial sampling grid used to obtain measurements about geographical entities that induces the scale and aggregation effect responsible for haphazard analysis results. To confirm this, they conducted an empirical investigation to verify the impact of spatial resolution and aggregation level on classification accuracy of forest data. Their results indicated that per-class accuracies were considerably affected by changing scale and aggregation level, which led to the conclusion that remote sensing data are not independent of the sampling grid used for their acquisition, and that neglecting the scale and aggregation level can produce haphazard results having little correspondence with the geographical entities of the scene. They also noted that there is no unique spatial resolution appropriate for the detection and discrimination of all geographical entities composing a complex natural scene, and advocated that classification based on the use of a unique spatial resolution should be replaced by a multi-scale approach.

Further studies also acknowledged the importance of the MAUP when interpreting remote sensing data. For example, Arbia *et al.* (1996) confirmed the effects of the MAUP on the accuracy of maximum-likelihood image classification. Jelinski and Wu (1996) stated that in remote sensing, the modifiable units are the pixels of the image; when different sensors are used or when pixels are aggregated, these areal units are modified. Consequently, substantive errors may be introduced during such aggregation procedures if close attention is not paid to the aggregation rules.

Solutions to the MAUP applied in the context of remote sensing

Since the MAUP was well documented in the social sciences, possible ways to overcome its effects had already been proposed. In particular, Fotheringham (1989) listed five different solutions:

- the derivation of optimal zoning systems,
- the identification of basic entities,
- abandonment of traditional statistical statistics,
- sensitivity analysis, and
- the search for fluctuations in variables and relationships with scale.

Though seldom undertaken directly to test theses solutions, several remote sensing studies addressing scale issues provide interesting methods and results that fit these criteria. In the following sections, examples will be provided where solutions to MAUP have been applied, or could further be investigated, within a remote sensing context to address the main components of the scale issue. First, the *optimal spatial resolution* approach, which has been initially inspired by the search of optimal zoning systems in the social sciences, will be described. Second, attention will be given to an emerging trend in remote sensing where the focus is on the extraction of individual entities from the imagery, and the development of entity-based approaches. Such methodologies are under rapid progress in forestry, particularly for individual tree recognition. Examples will also be presented to illustrate the use of spatial statistics in remote sensing in order to take explicitly into account the spatial properties of these data. Finally, the last section will be devoted to a series a studies illustrating sensitivity analysis to changes of scale when detecting patterns and processes, for modeling, as well as the potential of remote sensing to derive appropriate rules for scaling, and implementing multiscale approaches.

The main contributions of these studies are twofold. First, emphasis is placed on the inherent spatial nature of remote sensing data. The fundamental relationship between spatial resolution and the information content of the image, in terms of meaningful geographical entities and patterns, is formally addressed. The development of entity-based approaches is particularly promising because it simulates the human vision system where individual entities are resolved from a background by zooming in or zooming out until the appropriate scale of observation is reached corresponding to the inherent spatial characteristics (size, shape, texture, structure) of these entities. The application of spatial statistics in remote sensing allows to capture the richness of the information that lies within this unique type of spatial data. On the other hand, remote sensing is increasingly used to investigate the impact of scale on pattern detection and to relate them to ecological processes.

The optimal spatial resolution (OSR) approach

In attempts to solve the MAUP, several techniques to derive optimal zoning systems have been developed in the social sciences [see Marceau (1999) for a review]. In particular, Openshaw (1977, 1978, 1984) proposed an approach where the selection of areal units becomes an integral part of the goal of a particular spatial analysis. His methodology starts by formulating an hypothesis concerning the expected result for a given model or method of analysis, and then aggregating areal units to the point where the target result is attained. The richness of this approach is that the spatial units are not only defined to fulfill the particular needs of the analysis, but also to be geographically meaningful.

Such an approach was applied in the context of remote sensing to identify optimal spatial resolutions for detection and discrimination of coniferous classes in a temperate forested environment (Marceau *et al.*, 1994b). *Optimal spatial resolution* was defined as the spatial sampling unit corresponding to the scale and aggregation level characteristic of the geographical entity of interest. The methodology implies the following steps:

- *a priori* define the geographical entities under investigation,
- determine an optimization criterion for the choice of a sampling system,
- progressively aggregate data acquired from a fine spatial sampling grid,
- apply the optimization criterion on the series of spatially aggregated data, and
- verify the validity of the results obtained in relation to the goal of the study.

Internal variance for each forest class was calculated in relation to a series of spatial resolutions. Minimum variance was used as the indicator of the spatial resolution capturing in the best case the intrinsic characteristics of each forest class. Profiles of spectral separability between classes were produced, provided by the ratio of the intra- and inter-class variances, for the range of spatial resolutions. Results showed that, for all forest classes and spectral bands considered in the study, there is a minimal value in intraclass variance indicating the optimal spatial resolution for each class. The profiles of spectral separability revealed that forest classes, viewed in particular spectral bands, could be discriminated only within a specific range of spatial resolutions, and that the separability of the classes was maximized at their respective optimal spatial resolution.

The OSR approach was extended by Dionne *et al.* (1996) to incorporate topography in the analysis. Hyppänen (1996) also conducted a study to identify the optimal spatial resolution in a forested landscape. He used a similar approach to Woodcock and Strahler (1987) and reported a clear peak of local variance for different tree species. Atkinson (1997) performed a similar study to determine a suitable spatial resolution for agricultural mapping. Franklin *et al.* (1996) derived semivariograms to generate *geographic windows* corresponding to the scale of observation to provide forest inventory, forest structure characteristics, and land-cover classes. Atkinson and Curran (1995) also used semivariograms and kriging to define an optimal size of resolution for various remote sensing applications. Costanza and Maxwell (1994) conducted a study to find the optimal resolution for a particular modeling problem that balances the benefit of increasing data predictability with the cost of decreasing model predictability with the change of scale.

An important consideration related to the optimal spatial resolution approach is that optimality will change based on the questions under investigation. A resolution that is optimal for one variable may not be optimal for another. It may therefore be difficult to identify a unique optimal resolution in geographical modeling where several variables are used, each of which may possess distinctive spatial characteristics. However, the contribution of this approach is to emphasize that each geographical entity possesses intrinsic spatial attributes, which can only be observed and measured at a specific range of scales. This new way of thinking, coupled with the accessibility of very fine spatial resolution imagery and high-performance computers, opens the way to the development of entity-based approaches in remote sensing.

The development of entity-based approaches

As another solution for MAUP, Fotheringham (1989) and Visvalingam (1991) suggested the identification of basic geographical entities, and the use of basic spatial units that define the primitives of the phenomenon under study, for which information could be collected and analyzed. One of the difficulties with this approach is that it is not always easy to define the basic entity of concern, and not always possible to collect data at the required level. Recently, several studies in remote sensing addressed the problem of extracting individual entities from the imagery, particularly in the field of forestry.

In a novel structural approach to quantify the three dimensional image-texture of a forest canopy, Hay (1993), and Hay and Niemann (1994) incorporated location-specific primitives, and an object-specific variable sized and shaped moving kernel to regularize images based on objects spatial characteristics. This approach was then applied to a high resolution airborne scene, where individual tree crowns were automatically located within the image, and variance reduced texture primitives were generated from them (Hay *et al.*, 1996). The importance of this work is its introduction of varying sized and shaped object-specific filters to extract individual entities from remote sensing imagery. Gougeon (1995) also developed a method to automatically delineate tree crowns using an image processing program that follows valleys of shaded material between crowns. Dubé *et al.* (1998) applied a *theft* interpolation method combined with fuzzy logic for individual crown recognition in a mixed forest cover. Interest for individual tree recognition is becoming accelerated as illustrated by an international workshop devoted to the automated interpretation of high spatial resolution imagery for forestry (Leckie and Gougeon, 1998).

The interest of entity-based approaches is that they directly underline the necessity to work at the appropriate scale, or range of scales, where the entity of concern can be observed and measured. As reported by Fotheringham (1989), the identification of basic entities perhaps provides the clearest way out of the MAUP because it is a product of aggregation. This reasoning certainly applies to remote sensing imagery where each pixel corresponds to the aggregation of various ground features delineated by the spatial resolution of the sensor. However, one difficulty with this approach is that it is not always possible to collect data at the required scale.

The use of spatial statistics

Recent studies indicate that the use of spatial statistics, such as autocorrelation indices, may be very helpful to control and predict the MAUP effects to some extent (Hunt and Boots, 1996; Amrhein and Reynolds, 1996). In remote sensing, it is increasingly acknowledged that traditional statistics have severe limitations since they do not take into account the properties of locational data. Such data are generally spatially autocorrelated, non-stationary, non-normal, irregularly spaced, and discontinuous (Haggett *et al.*, 1977), while standard statistical pattern-recognition techniques assume independent and random data, and a normal distribution. Furthermore, these techniques are not built to handle discontinuous irregularly spaced patterns of geographical phenomena as they often appear in remotely sensed imagery.

Among spatial statistics that are increasingly used in remote sensing are the geostatistic tools and autocorrelation indices. Semivariograms have been applied to study the structure and understand the nature of spatial variation in remote sensing images (Woodcock *et al.*, 1988b; Ramstein and Raffy, 1989). They were also used in forestry to analyze the forest stand structure (Cohen *et al.*, 1990; St-Onge and Cavayas, 1995), and to estimate structural damage in balsam fir stands (Franklin *et al.*, 1992). Recently, Wulder and Boots (1998a and b) investigated the use of spatial autocorrelation indices to characterize remotely sensed forested areas.

The field of spatial analysis and the application of spatial statistics for detecting patterns has grown rapidly over the last two decades (Turner *et al.*, 1991; Fortin, 1999). The interest of these methods is to recognize the rich and unique information that lies within spatial data, rather than treating it as an hindrance as it is considered in conventional statistics. In particular, the application of landscape metrics to remote sensing data can be very helpful to characterize landscape patterns and relate them to ecological processes at different scales (Frohn, 1998).

Sensitivity analysis and the search for fluctuations in variables and relationships with scale

Another solution proposed to overcome the MAUP is to recognize its existence and to report the sensitivity of analytical results to variations in both the scale and level of aggregation. To do so requires that the data used can be aggregated and that results can be obtained for each higher level. One great advantage of remote sensing is the capacity to provide data at various spatial resolutions that can easily be aggregated at intermediate scales. Such a methodology is increasingly used to evaluate the influence of scale on detecting patterns and processes, and on modeling results. It also enables the identification of scale thresholds where significant changes in patterns or in the relationship between variables occur. Furthermore, since many processes do not always behave linearly through scales, its may assist in solving the non-trivial question of deriving appropriate rules for scaling. The next section presents several studies conducted in remote sensing to address these various components of the scale issue.

The influence of scale on detecting patterns and processes

Benson and MacKenzie (1995) examined the effects of increasing spatial resolution from 20 m to 1.1 km, using three sets of satellite data, on landscape parameters characterizing spatial structure. Their results indicated that most measures were sensitive to changes in spatial resolution: some parameters decreased, while others increased, or were invariant with scale. O'Neill *et al.* (1996) calculated landscape indices using AVHRR data and noted that significant patches composing the landscape may be lost when the elements of the landscape pattern are scattered and small compared to the pixel size. In a study to evaluate the effect of spatial resolution on the ability to monitor regional and global changes in agricultural lands, Pax-Lenney and Woodcock (1997) note that an intermediary spatial resolution (250 m) could be used to estimate the areal extent of the agricultural lands, while finer spatial resolution is still required to accurately map the location of the fields. Moody and Woodcock (1995) conducted a multi-regression analysis to assess the relationships between landscape spatial patterns and errors in the estimates of cover-type proportions as land-cover data are aggregated to coarser scales. They showed that the proportion error is governed by the interaction of the spatial characteristics of the landscape and the scale of aggregation. They also underline that the standard linear regression model does not account for the different directions of scale-dependent proportion error, and that understanding the interaction between landscape spatial characteristics and resolution is necessary to develop appropriate scaling methods.

The impact of scale in modeling

Turner *et al.* (1996) conducted a study to determine the effects of spatial scale on the results obtained from a spatially distributed biogeochemical model (Forest-BGC). Model outputs were generated at three spatial resolutions, using original and aggregated AVHRR satellite data. Their results clearly indicated differences in the inputs and outputs as spatial resolution is coarsened. Similarly, McNulty *et al.* (1997) examined the influence of data aggregation on a forest-process model at a stand, an ecosystem and a regional scale. They found that the performance of the model to accurately predict ecosystem variables greatly varied with the scale of measurement. Friedl (1997) reports a series of studies in relation to the FIFE project designed to examine the scale effects in remotely sensed data and how they propagate through biophysical models that use these data as inputs. Their results show that a change of scale may introduce significant bias to modeled land surface fluxes.

The identification of scale thresholds and domains of scale

Bian and Walsh (1993) examined the effects of spatial scale on the relationship between vegetation biomass and three topographic variables. Simple and multiple regression analyses were applied at each scale to explore the relationship between the variables. Semivariance and fractal analysis were used to characterize the effective range of spatial scales and the degree of spatial dependence. They noticed that the relationship between vegetation biomass and topography changes with spatial scales, and identified a *characteristic scale* below which these variables are spatially dependent and above which they become less dependent or independent. Following this work, Walsh *et al.* (1997) conducted an exhaustive study to test the hypotheses that the relationships between NDVI, cover types, and elevation are scale dependent, and that the nature of this scale dependence can provide insights into how biophysical processes are represented through remote sensing data. They showed that the degree of explanation in the variation of NDVI varies with scale. At finer resolutions (30 m to 210 m), the level of explanation in the NDVI increased with the inclusion of slope angle and solar radiation potential, suggesting the importance of local-scale topographic orientation on plant productivity. At coarser scales, elevation emerged as the dominant variable to describe the regional-scale productivity responses of the NDVI.

In 1994, Souriau demonstrated the existence of a threshold at a given scale between two physical distributions of a parameter describing continental topography. In a conceptual paper, Puech (1994) also discusses the existence of homogeneity thresholds of targets composing a landscape, suggesting that they provide important information on the fundamental organization of the landscape. They also note that, as a consequence, each target is only detectable between certain limits that can be defined through the use of remote sensing data.

Scaling and the implementation of multiscale approaches

Scaling means transferring data or information from one scale to another. It requires the identification of the factors operational on a given scale of observation, their congruency with those on the lower and higher scales, and the constraints and feedback's on those factors (Caldwell *et al.*, 1993). As noted by Jarvis (1995), scaling represents a real challenge because of the non-linearity between processes and variables, and heterogeneity in properties that determines the rates of processes. Practically, scaling can be performed from a bottom-up or a top-down approach. Upscaling consists of taking information at smaller scales to derive processes at larger scales, while downscaling consists of decomposing information at one scale into its constituents at smaller scales.

Remote sensing offers great potential for scaling. First, it provides the required data for upscaling or downscaling physical models, and for validating their outputs. In describing the contributions of remote sensing for upscaling in hydrology, Stewart *et al.* (1998) notes that traditionally hydrological models were developed to deal with local water resource problems while they are now required to work at regional and continental scales. Such an extension to much larger areas poses a major challenge in obtaining the necessary data to run the models, and only satellite remote sensing data sources can provide the necessary information. Ustin *et al.* (1993) describes a series of studies where remote sensing is used to acquire ecological measurements at different scales to be integrated in ecosystem models. For example, DeFries *et al.* (1997) used MSS and AVHRR data to investigate the problem of land-cover heterogeneity in a global atmosphere-biosphere model.

Second, remote sensing provides the possibility of conducting empirical studies to understand the behavior of variables when changing scale, and derive appropriate rules for scaling. Friedl *et al.* (1995) investigated the relationship between a vegetation index (NDVI), the leaf area index (LAI) and the fraction of absorbed photosynthetically active radiation (FPAR). They demonstrated that NDVI is not scale invariant, and that the relationship between LAI and NDVI is distinctly nonlinear and varies with scale. They also noted that while the relationship between NDVI and FPAR is nearly linear, error is introduced when scaling, creating uncertainty in the relationship. Addressing this problem at a theoretical level, Raffy (1992) proposed a spatialized method to reduce the error introduced by a change of scale when linking a ground parameter, such as LAI, to remote sensing measurements. In hydrology, Wood (1995) compared remotely sensed and model-derived soil moisture data and was able to find the threshold scale in relation to the particular catchment under study.

Finally, remote sensing can be used to test the postulates of conceptual frameworks that have been developed so far to describe the hierarchical organization of the landscape, such as hierarchy theory (Allen and Star, 1982; O'Neill *et al.*, 1986), and the hierarchical patch dynamics paradigm (Pickett and White, 1985; Wu and Loucks, 1995). Cullinan *et al.* (1997) investigated the variability in plant cover from field (1 m^2) to remotely sensed data (30 m^2) to test some hypothesis formulated by hierarchy theory. They compare different models to determine how vegetative patterns of individual species combine to produce community patterns observable at a lower scale. Similarly, Franklin and Woodcock (1997) tested a premise often made in the literature on hierarchy theory that stand-based maps would nest, spatially and taxonomically, within coarser-grained landscape mapping units. They produced a digital vegetation map at the stand and landscape levels, and compared the spatial and categorical information in these two databases to evaluate concepts of hierarchical landscape organization. They found that the two databases were spatially nested, but not taxonomically nested.

In an attempt to determine the most appropriate upscaling technique to represent a remote sensing signal at different scales, Hay *et al.* (1997) describe a scaling technique applied to remotely sensed data that employs object-specific kernels to analyze and incorporate the influence of different sized, shaped, and spatially distributed objects within the upscale image. Originating from observations that the human hand, and lens of the eye dynamically change shape to resolve objects multiscale spatial characteristics (Hay, 1993), this technique identifies spatial properties of individual entities (i.e., image-objects) based on optimal zoning, or threshold factors, that are ecologically meaningful and not modifiable. Consequently, this object-specific approach encompasses many of the solutions to MAUP listed by Fotheringham (1989), and even incorporates several of the MAUP caveats as logic rules. By considering that landscapes are hierarchical structures, and extending their analysis to incorporate a multi-landscape level approach, Hay and Marceau (1998) theorize that these object-specific upscaling ideas may provide a new framework for examining, and potentially solving a series of difficult scale issues, in particular: defining critical landscape thresholds, domains of scale, and appropriately linking data between scales.

The last point regarding the contribution of remote sensing to the scale issue is the possibility it provides for the implementation of multiscale data structures. Csillag (1997) provides a description of procedures that have been developed over the last three decades for hierarchical data representation, mainly in image analysis. In particular, quadtrees offer a structure that effectively manages the complexity of a scene by decomposing it into a series of hierarchical levels. Algorithms have also been developed to classify and/or segment remote sensing imagery to capture the different levels of information embedded within the data (Burt *et al.*, 1981; Kusaka and Kawata, 1991; Tilton, 1991; Bénié and Thomson, 1992). The interest of such approaches is to overcome the fixed-scale paradigm, and to consider the multiple levels of perception that are inherent in a landscape and that can be revealed through the use of multiscale structures.

Conclusion

The severity of the modifiable areal unit problem (MAUP) was recognized by social scientists more than forty years ago (see Marceau, 1999). In 1984, Openshaw stated that the MAUP was one of the most important unresolved problems left in spatial analysis, and a major conceptual challenge central to many aspects of geographical study. He also pointed out that once the existence of the MAUP is known, it is no longer possible to continue using the same science paradigm. Since spatial data and the results obtained from them are not independent of the areal units used to collect them, the selection of any zoning system must be considered an integral part of the analytical purpose, and cannot be based solely on convenience.

Recently, scientists have demonstrated that remote sensing is a particular case of the MAUP (Marceau *et al*., 1994a; Arbia *et al*., 1996). This explains many of the inconsistencies in results when remote sensing data are used to produce thematic maps or as inputs into physical models, without explicitly taken into account the impact of scale. As noted by Raffy (1992), remote sensing models are often based on a relationship between a soil-level parameter and the sensor reflectance at a given wavelength. The general practice is to apply these models without making any correction to compensate for the change of scale; this practice can be completely wrong. Therefore, it is of considerable importance that the effects of the MAUP in remote sensing be fully understood to avoid arbitrary and erroneous analytical results.

This paper reviewed the work of many scientists who tested different techniques to improve feature extraction, detect spatial structures, and understand the nature of spatial variation in remote sensing imagery. While these approaches were not explicitly used to solve the MAUP, they were in fact providing effective ways to cope with the problem. Furthermore, many contributions have been made by scientists who have taken advantage of remote sensing to investigate the impact of scale in modeling, to derive appropriate rules for scaling, and to test the postulates of theories developed to describe the hierarchical organization of the landscape. These contributions represent necessary steps in the development of a science of scale. It is advocated in this paper that remote sensing has, and will continue to play a major role in the achievement of such a goal.

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References

Ahern, F.J., D.N.N. Horler, J. Cihlar, W.J. Bennett, and E. MacAulay. 1983. Digital processing to improve classification results at resolutions of 5 to 50 meters. In *Proceedings of the SPIE Symposium on Techniques for Extraction from Remotely Sensed Images*, Rochester, NY, 16-19 August, pp. 153-170.

Allen, T.F.H., and T.W. Hoekstra. 1991. Role of heterogeneity in scaling of ecological systems under analysis. In *Ecological Studies 86: Ecological Heterogeneity*, J. Kolasa, and S.T.A. Pickett, eds, Springer-Verlag, pp. 47-68.

Allen, T.F.H., and T.B. Starr. 1982. *Hierarchy Perspective for Ecological Complexity*. University of Chicago Press, Chicago, 310 pp.

Amrhein, C., and H. Reynolds. 1996. "Using spatial statistics to assess aggregation effects", *Geographical Systems*, Vol. 3, pp. 143-158.

Arbia, G., R. Benedetti, and G. Espa. 1996. "Effects of the MAUP on image classification", *Geographical Systems*, Vol. 3, pp. 123-141.

Atkinson, P.M., 1997. "Selecting the spatial resolution of airborne MSS imagery for small-scale agricultural mapping", *International Journal of Remote Sensing*, Vol. 18, No. 9, pp. 1903-1917.

Atkinson, P.M., and P.J. Curran. 1995. "Defining an optimal size of support for remote sensing investigations", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 33, No. 3, pp. 768-776.

Bénié, G.B., and K.P.B. Thomson. 1992. "Hierarchical image segmentation using local and adaptive similarity rules", *International Journal of Remote Sensing*, Vol. 13, No. 8, pp. 1559-1570.

Benson, B.J., and M.D. MacKenzie. 1995. "Effects of sensor spatial resolution on landscape structure parameters", *Landscape Ecology*, Vol. 10, No. 2, pp. 113-120.

Bian, L., and S.J. Walsh. 1993. "Scale dependencies of vegetation and topography in a mountainous environment of Montana", *The Professional Geographer*, Vol. 45, No. 1, pp. 1-11.

Burt, P.J., T.-H. Hong, and A. Rosenfeld. 1981. "Segmentation and estimation of image region properties through cooperative hierarchical computation", *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-11, No. 12, pp. 802-809.

Caldwell, M.M., P.A. Matson, C. Wessman, and J. Gamon . 1993. Prospects for scaling. In *Scaling Physiological Processes: Leaf to Globe*, Ehleringer, J.R. and C.B. Field, eds, Academic Press, pp. 223-230.

Cao, C., and N.S.-N. Lam. 1997. Understanding the scale and resolution effects in remote sensing and GIS. In *Scale in Remote Sensing and GIS*, Quattrochi, D.A. and M.F. Goodchild, eds., pp. 57-72.

Cohen, W.B., T.A. Spies, and G.A. Bradshaw. 1990. "Semivariograms of digital imagery for analysis of conifer canopy structure", *Remote Sensing of Environment*, Vol. 34, pp. 167-178.

Costanza, R., and T. Maxwell. 1994. "Resolution and predictability: An approach to the scaling problem", *Landscape Ecology*, Vol. 9, No. 1, pp. 47-57.

Coulombe, A., L. Charbonneau, R. Brochu et D. Morin. 1991. "L'apport de l'analyse texturale dans la définition de l'utilisation du sol en milieu urbain", *Journal canadien de télédétection*, Vol. 7, No. 1, pp. 46-55.

Csillag, F., 1997. Quadtrees: hierarchical multiresolution data structures for analysis of digital images. In *Scale in Remote Sensing and GIS*, Quattrochi, D.A. and M.F. Goodchild, eds, pp. 247-271.

Cullinan, V.I., M.A. Simmons, and J.M. Thomas. 1997. "A bayesian test of hierarchy theory: scaling up variability in plant cover from field to remotely sensed data", *Landscape Ecology*, Vol. 12, pp. 273-285.

Cushnie, J.L., 1987. "The interactive effect of spatial resolution and degree of internal variability within land-cover types on classification accuracies", *International Journal of Remote Sensing*, Vol. 8, No. 1, pp. 15-29.

DeFries, R.S., J.R. Townshend, and S.O. Los. 1997. Scaling land cover heterogeneity for global atmosphere-biosphere models. In *Scale in Remote Sensing and GIS*, Quattrochi, D.A., and M.F. Goodchild, eds, pp. 231-246.

Dionne, D., J.G. Boureau, M. Deshayes, D. Gratton et D. J. Marceau. 1996. "Étude de la résolution spatiale optimale dans un milieu forestier de moyenne montagne", *Bulletin de la Société française de photogrammétrie et télédétection*, Vol. 141, 1996-1, pp. 51-55.

Dubé, P., G. J. Hay, and D. J. Marceau. 1998. Voronoi diagrams, extended area-stealing interpolation, and tree-crown recognition: A fuzzy approach. *Proceedings of the Workshop on Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry*. February 10-12, Victoria, British Columbia, Canada.

Ehleringer, J.R., and C. B. Field. 1993. *Scaling Physiological Processes. Leaf to Globe*. Academic Press, 388 pp.

Forshaw, M.R.B., A. Haskell, P.F. Miller, D.J. Stanley, and J.R.G. Townshend. 1983. "Spatial resolution of remotely sensed imagery. A review paper", *International Journal of Remote Sensing*, Vol. 4, No. 3, pp. 497-520.

Fortin, M.J., 1999. Spatial statistics in Landscape Ecology. In *Landscape Ecological Analysis: Issues and Applications*, Klopatek, J.M., and Gardner, R.H., eds, Springer-Verlag, pp. 253-279.

Fotheringham, A.S., 1989. Scale-independent spatial analysis. In *Accuracy of Spatial Databases*, Goodchild, M., S. Gopal, Eds, Taylor and Francis, pp. 221-228.

Franklin, J., and C.E. Woodcoock. 1997. Multiscale vegetation data for the mountains of southern California: spatial and categorical resolution. In *Scale in Remote Sensing and GIS*, Quattrochi, D.A. and M.F. Goodchild, eds, pp. 141-168.

Franklin, S.E., M.A. Wulder, and M.B. Lavigne. 1996. "Automated derivation of geographic window sizes for use in remote sensing digital image texture analysis", *Computers and Geosciences*, Vol. 22, No. 6, pp. 665-673.

Franklin, S.E., W. Bowers, J. Hudack, and G. McDermid. 1992. Estimating structural damage in balsam fir stands using semivariance. *Proceedings of the 15th Canadian Symposium on Remote Sensing*, June, Vancouver, British Columbia, pp. 96-99.

Franklin, S.E., and D.R. Peddle. 1990. "Classification of SPOT HRV Imagery and Texture Features", *International Journal of Remote Sensing*, Vol. 11, No. 3, pp. 551-556.

Friedl, M.A., 1997. Examining the effects of sensor resolution and sub-pixel heterogeneity on spectral vegetation indices: implications for biophysical modeling. In *Scale in Remote Sensing and GIS*, Quattrochi, D.A., and M.F. Goodchild, eds, pp. 113-139.

Friedl, M.A., F.W. Davis, J. Michaelsen, and M.A. Moritz. 1995. "Scaling and uncertainty in the relationship between the NDVI and land surface biophysical variables: An analysis using a scene simulation model and data from FIFE", *Remote Sensing of Environment*, Vol. 54, pp. 233-246.

Frohn, R.C., 1998. *Remote Sensing for Landscape Ecology*. Lewis Publishers, 99 p.

Gong, P., D.J. Marceau, and P.J. Howarth. 1992. "A comparison of spatial feature extraction algorithms for land-use classification with SPOT HRV data", *Remote Sensing of Environment*, Vol. 40, pp. 137-151.

Goodchild, M.F., and D.A. Quattrochi. 1997. Scale, multiscaling, remote sensing, and GIS. In *Scale in Remote Sensing and GIS*, Quattrochi, D.A. and M.F. Goodchild, eds., pp. 1-11.

Gougeon, F.A., 1995. "A crown-following approach to the automatic delineation of individual tree crowns in high spatial resolution aerial images", *Canadian Journal of Remote Sensing*, Vol. 21, No. 3, pp. 274-284.

Haggett, P., A.D. Cliff, and A. Frey. 1977. *Locational Analysis in Human Geography. Locational Models*. Edward Arnold, 605 p.

Hay, G.J., 1993. *Visualizing 3-D texture: A three Dimensional Structural Approach To Model Forest Texture*. Unpublished M.Sc. Thesis, Department of Geography, University of Victoria, 81 p.

Hay, G.J., and K.O. Niemann. 1994. "Visualizing 3-D texture: A three-dimensional structural approach to model forest texture", *Canadian Journal of Remote Sensing*, Vol. 20, No. 2, pp. 90-101.

Hay, G.J., K.O. Niemann, and G.F. McLean. 1996. "An object-specific image-texture analysis of H-resolution forest imagery", *Remote Sensing of Environment*, Vol. 55, pp. 108-122.

Hay, G.J., D.G. Goodenough, and K.O. Niemann, 1997. "Spatial thresholds, image-objects, and upscaling: A multi-scale evaluation", *Remote Sensing of Environment*, Vol. 62, No. 1, pp. 1-19.

Hay, G.J., and D.J. Marceau. 1998. "*Are image-objects the key for upscaling remotely sensed data?*" Proceedings of the Modeling Complex Systems Conference, July 12-17, New Orleans, Louisiana.

Hunt, L., and B. Boots. 1996. "MAUP effects in the principal axis factoring technique", *Geographical Systems*, Vol. 3, pp. 101-121.

Hyppänen, H., 1996. "Spatial autocorrelation and optimal spatial resolution of optical remote sensing data in boreal forest environment", *International Journal of Remote Sensing*, Vol. 17, No. 17, pp. 3441-3452.

Irons, J.R., B.L. Markham, R.F. Nelson, D.L. Toll, D.L. Williams, R.S. Latty, and M.L. Stauffer. 1985. "The effects of spatial resolution on the classification of Thematic Mapper data", *International Journal of Remote Sensing*, Vol. 6, No. 8, pp. 1385-1403.

Jarvis, P.G., 1995. "Scaling processes and problems", *Plant, Cell, and Environment*, Vol. 18, pp. 1079-1089.

Jelinski, D.E., and J. Wu. 1996. "The modifiable areal unit problem and implications for landscape ecology", *Landscape Ecology*, Vol. 11, No. 3, pp. 129-140.

Kusaka, T., and Y. Kawata. 1991. Hierarchical classification of Landsat TM image using spectral and spatial information. *Proceedings of IGARSS*, June 3-6, Espoo, Finland, pp. 2187-2190.

Latty, R.S., and R.M. Hoffer. 1981. Computer-based classification accuracy due to the spatial resolution using per-point versus per-field classification techniques. *Symposium of Machine Processing of Remotely Sensed Data*, pp. 384-392.

Leckie, D., and F. Gougeon. 1998. *International Workshop on Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry*, February 10-12, Victoria, British Columbia, Canada.

Levin, S.A., 1992. "The problem of pattern and scale in ecology", *Ecology*, Vol. 73, pp. 1943-1967.

Marceau, D.J. 1999. "The scale issue in social and natural sciences", *Canadian Journal of Remote Sensing*, this issue.

Marceau, D.J., 1992. *The Problem of Scale and Spatial Aggregation in Remote Sensing: An Empirical Investigation Using Forestry Data*. Unpublished Ph.D. Thesis, Department of Geography, University of Waterloo, 180 p.

Marceau, D.J., and G.J. Hay. 1998. *Proceedings of the International Workshop on Scaling and Modeling in Forestry: Applications in Remote Sensing and GIS*, March 19-21, Montréal, Canada, Department of Geography, University of Montreal, 180 p.

Marceau, D.J., P.J. Howarth, and D.J. Gratton. 1994a. "Remote sensing and the measurement of geographical entities in a forested environment; Part 1: The scale and spatial aggregation problem", *Remote Sensing of Environment*, Vol. 49, No. 2, pp. 93-104.

Marceau, D.J., D.J. Gratton, R. Fournier, and J.P. Fortin. 1994b. "Remote sensing and the measurement of geographical entities in a forested environment; Part 2: The optimal spatial resolution", *Remote Sensing of Environment*, Vol. 49, No. 2, pp. 105-117.

Marceau, D.J., P.J. Howarth, J.M.M. Dubois, and D.J. Gratton. 1990. "Evaluation of the gray-level cooccurrence matrix (GLCM) method for land-cover classification using SPOT imagery", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 28, No. 4, pp. 513-519.

Markham, B.L., and J.R.G. Townshend. 1981. Land cover classification accuracy as a function of sensor spatial resolution. *Proceedings of the Fifteenth International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, pp. 1075-1090.

McNulty, S.G., J.M. Vose, and W.T. Swank . 1997. Scaling predicted pine forest hydrology and productivity across the southern United States. In *Scale in Remote Sensing and GIS*, Quattrochi, D.A., and M.F. Goodchild, eds., pp. 187-209.

Meentemeyer, V., 1989. "Geographical perspectives of space, time, and scale", *Landscape Ecology*, Vol. 3, Nos. 3/4, pp. 163-173.

Meentemeyer, V., and E.O. Box. 1987. Scale effects in landscape studies. In *Landscape Heterogeneity and Disturbance*, M.G. Turner, ed., Springer-Verlag, pp. 15-34.

Moody, A., and C.E. Woodcock. 1995. "The influence of scale and the spatial characteristics of landscapes on land-cover mapping using remote sensing", *Landscape Ecology*, Vol. 10, No. 6, pp. 363-379.

O'Neill, R.V., C.T. Hunsaker, S.P. Timmins, B.L. Jackson, K.B. Jones, K.H. Ritters, and J.D. Wickham. 1996. "Scale problems in reporting landscape pattern at the regional scale", *Landscape Ecology*, Vol. 11, No. 3, pp. 169-180.

O'Neill, R.V., D.L. De Angelis, J.B. Waide, and T.F.H. Allen. 1986. *A Hierarchical Concept of Ecosystems*. Princeton University Press, Princeton, New Jersey.

Openshaw, S., 1977. *A Geographical Solution to Scale and Aggregation Problems in Region-Building, Partitioning and Spatial Modeling*. Institute of British Geographers, Transactions, New Series, Vol. 2, No. 1, pp. 459-472.

Openshaw, S., 1978. "An empirical study of some zone-design criteria", *Environment and Planning A*, Vol. 10, pp. 781-794.

Openshaw, S., 1984. *The Modifiable Areal Unit Problem.* Concepts and Techniques in Modern Geography (CATMOG), No. 38, 40 p.

Pax-Lenney, M., and C.E. Woodcock. 1997. "The effect of spatial resolution on the ability to monitor the status of agricultural lands", *Remote Sensing of Environment*, Vol. 61, pp. 210-220.

Peddle, D.R., and S.E. Franklin. 1989. High resolution satellite image texture for moderate relief terrain analysis. *Proceedings of IGARSS/12th Canadian Symposium on Remote Sensing*, Vol. 2, pp. 653-655.

Pickett, S.T.A., and P.S. White. 1985. *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, 472 p.

Puech, C., 1994. "Thresholds of homogeneity in targets in the landscape. Relationship with remote sensing", *International Journal of Remote Sensing*, Vol. 15, No. 12, pp. 2421-2435.

Pultz, T.J., and R.J. Brown. 1987. "SAR image classification of agricultural targets using first- and second-order statistics", *Canadian Journal of Remote Sensing*, Vol. 13, No. 2, pp. 85-91.

Quattrochi, D.A., and M.F. Goodchild. 1997. *Scale in Remote Sensing and GIS*. Lewis Publishers, 406 p.

Raffy, M., 1992. "Change of scale in models of remote sensing: A general method for spatialization of models", *Remote Sensing of Environment*, Vol. 40, pp. 101-112.

Raffy, M., 1993. *Deuxième réunion sur les changements d'échelle dans les modèles de l'environnement et de la télédétection*. Strasbourg, 17-19 mai. Groupement scientifique de télédétection spatiale, Strasbourg, France.

Ramstein, G., and M. Raffy. 1989. "Analysis of the structure of radiometric remotely sensed images", *International Journal of Remote Sensing*, Vol. 10, No. 6, pp. 1049-1073.

Rosswall, T., G. Woodmansee, and P.G. Risser. 1988. *Scales and Global Change*. John Wiley and Sons, New York.

Sadowski, F. G., and J. E. Sarno. 1976. *Additional Studies of Forest Classification Accuracy as Influenced by Multispectral Scanner Spatial Resolution*. ERIM 122700-4-R, Environmental Research Institute of Michigan, Ann Arbor, Michigan, 49 p.

Sadowski, F.G., W.A. Malila, J.E. Sarno, and R.F. Nalepka . 1977. The influence of multispectral scanner spatial resolution on forest feature classification. *Proceedings of the 11th International Symposium on Remote Sensing of Environment*, 25-29 April, Ann Arbor, pp. 1279-1288.

Schneider, D.C. 1994. *Quantitative Ecology. Spatial and Temporal Scaling*. Academic Press, 395 p.

Sivapalan, M., and J.D. Kalma. 1995. "Scale problems in hydrology: contributions of the Robertson workshop", *Hydrological Processes*, Vol. 9, pp. 243-250.

Souriau, M., 1994. "Scaling and physical thresholds: The case of continental topography", *International Journal of Remote Sensing*, Vol. 15, No. 12, pp. 2403-2408.

St-Onge, B.A., and F. Cavayas. 1995. "Estimating forest stand structure from high resolution imagery using the directional variogram", *International Journal of Remote Sensing*, Vol. 16, No. 11, pp. 1999-2021.

Stewart, J.B., E.T. Engman, R.A. Feddes, and Y. Kerr. 1996. *Scaling Up in Hydrology Using Remote Sensing*. John Wiley and Sons.

Stewart, J.B., E.T., Engman, R.A. Feddes, and Y.H. Kerr. 1998. "Scaling up in hydrology using remote sensing: summary of a Workshop", *International Journal of Remote Sensing*, Vol. 19, No. 1, pp. 181-194.

Tilton, J.C., 1991. A tool for interactive exploration of hierarchical segmentation. *Proceedings of IGARSS*, June 3-6, Espoo, Finland, pp. 1099-1101.

Townshend, J.R.G., and C.O. Justice. 1988. "Selecting the spatial resolution of satellite sensors required for global monitoring of land transformations", *International Journal of Remote Sensing*, Vol. 9, No. 2, pp. 187-236.

Turner, D.P., R. Dodson, and D. Marks. 1996. "Comparison of alternative spatial resolutions in the application of a spatially distributed biogeochemical model over complex terrain", *Ecological Modeling*, Vol. 90, pp. 53-67.

Turner, M.G., V.H. Dale, and R.H. Gardner. 1989. "Predicting across scales: Theory development and testing", *Landscape Ecology*, Vol. 3, No. 3/4, pp. 245-252.

Turner, S.J., R.V. O'Neill, W. Conley, M.R. Conley, and H.C. Humphries. 1991. Pattern and Scale: Statistics for Landscape Ecology. In *Quantitative Methods in Landscape Ecology*, M.G. Turner and R.H. Gardner, eds, Springer-Verlag, pp. 17-49.

Ustin, S.L., M.O. Smith, and J.B. Adams. 1993. Remote sensing of ecological processes: A strategy for developing and testing ecological models using spectral mixture analysis. In *Scaling Physiological Processes: Leaf to Globe*, Ehleringer, J.R. and C.B. Field, eds, Academic Press, pp. 339-357.

Visvalingam, M., 1991. Areal units and the linking of data: Some conceptual issues. In *Spatial Analysis and Spatial Policy using Geographic Information Systems*, L. Worrall, ed., Belhaven Press, pp. 12-37.

Walsh, S.J., A. Moody, T.R. Allen, and D.G. Brown. 1997. Scale dependence of NDVI and its relationship to mountainous terrain. In *Scale in Remote Sensing and GIS*, Quattrochi, D.A. and Goodchild, M.F., eds, Lewis Publishers, pp. 27-55.

Wood, E.F., 1995. "Scaling behavior of hydrological fluxes and variables: empirical studies using a hydrological model and remote sensing data", *Hydrological Processes*, Vol. 9, pp. 331-346.

Woodcock, C.E., A.H. Strahler, and D.L.B. Jupp. 1988a. "The use of variograms in remote sensing: Part I. Scene models and simulated images", *Remote Sensing of Environment*, Vol. 25, pp. 323-348.

Woodcock, C.E., A.H. Strahler, and D.L.B. Jupp. 1988b. "The use of variograms in remote sensing: Part II. Real digital images", *Remote Sensing of Environment*, Vol. 25, pp. 349-379.

Woodcock, C.E., and A.H. Strahler. 1987. "The factor of scale in remote sensing", *Remote Sensing of Environment*, Vol. 21, pp. 311-332.

Wu, J., and O.L. Loucks. 1995. "From balance of nature to hierarchical patch dynamics: A paradigm shift in ecology", *The Quaterly Review of Biology*, Vol. 70, pp. 439-466.

Wulder, M., and B. Boots. 1998a. "Local spatial autocorrelation characteristics of Landsat TM imagery of a managed forest area", *Canadian Journal of Remote Sensing*, under revision.

Wulder, M., and B. Boots. 1998b. "Local spatial autocorrelation characteristics of remotely sensed imagery assessed with the Getis statistic", *International Journal of Remote Sensing*, vol. 19, no. 11, pp. 2223-2231.