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On the Limits and Extensions of the Definition of Scale

Ecologists' increased interest in issues of scale and scaling is clearly illustrated by the terminological confusion targeted by a recent *ESA Bulletin* contribution (Jenerette and Wu 2000). The prime stimulus for us to respond here to the definition(s) of scale is that their suggestion for "recognizing . . . multiple meanings" is partially misleading, as a rigorous scientific attempt to clarify the reasons for and the possible solutions to the confusion. The potential for misinterpretation is always high when the same word means many things, particularly when those things are directly contradictory, as in cartographic scale, ecological scale, and geographic scale.

We strongly believe that the complementarity of two sizes, that of the observations and that of the study area, cannot be well expressed by one term, such as scale. It is important to note that, in this context, we strictly discriminate the size of observations (such as the sampling unit) from the size of the ecologically meaningful entities (e.g., a bird, a tree, or other agents), as well as the size of the study area, from the size of the area over which those ecological entities exhibit relevant spatial characteristics. The former elements of these two pairs characterize the data; the latter ones characterize processes about which we would like to make inferences. Therefore, we suggest that operative terms must be used for: (1) the characterization of the size and shape of the observation, (2) the size and shape of the study area, (3) the characterization of agents, and (4) the process area (Fig. 1). The first pair (1 and 2)

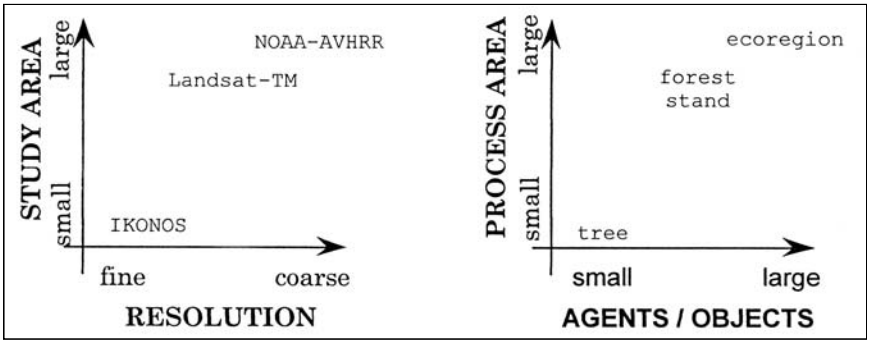

Fig. 1. Relationships between observational and ecological characteristics related to "scale." Assuming that the size of the study area is 10 x 10 km, it would be imaged by 100 1000 x 1000 m (e.g., NOAA-AVHRR) pixels, approximately 10,000 30 x 30 m (e.g., Landsat TM) pixels, and approximately 100,000,000 1 x 1 m (e.g., IKONOS) pixels. The corresponding process-area and agents/objects that we would want to observe are trees, forest stands, and ecoregions/landscapes. Clearly, there should be a reasonably good match between these two sets of parameters. For example, deer habitat should not be mapped at 1000-m resolution, nor should biomes be monitored at 1-m resolution, because the discrepancy between the observation resolution and the ecological entities and processes comes at a very high price in terms of uncertainty.

provide the technical characteristics; the second pair (3 and 4) provide the context. Finally, the conceptual linkages between the pairs should be clearly and critically evaluated. Hence, instead of one expression of spatial property (such as scale), at least four separate characteristics should be reported in every study, as well as a discussion about their relationships, in order to avoid contradictory conclusions due to incompatible observations and/or context.

It is possible that geographers are as much responsible for the confusion (e.g., Tobler [1988], which practically equates cartographic scale and operational resolution) as in some other related disciplines that have generated their own terminology, such as remote sensing (Strahler et al. 1986), geostatistics (Olea 1990), and landscape ecology (Forman 1995).

The classical cartographic approach to scaling is usually discussed under *generalization*. Work on this topic (i.e., McMaster 1989) contradicts the assertion that "once a map is entered into a GIS, alterations of cartographic scale are trivial" (Jenerette and Wu 2000). Although the precision of data representation in GIS is limited only by computer memory, the accuracy reduction caused by errors associated with data transformations (such as resampling, for example) and their propagation makes this a worrisome statement (Heuvelink and Goodchild 1998). Rapid advances of geographical information systems exposed the shortcomings of the tradition of Sinton (see Chrisman 1989), which views data models in a strictly three-dimensional Cartesian scheme along the axes of space, time, and attributes. A conceptual model and its data representation cannot be well described as one point in this framework.

Although GIS software is one of the core modern black boxes of spatial data processing, remote sensing is one of the major data sources for landscape environmental studies. For remotely sensed data, resolution is the standard scale-related term, a function of both the spatial area and the value of an observation. Its dependence on value has been largely left by the wayside; current practice is to refer to a nominal resolution as the area represented by a pixel. The relationship of the pixel observation to the size of "meaningful entities" was emphasized by Strahler et al. (1986) in their taxonomy of H-resolution (cases in which pixel observations represent smaller areas than the size of meaningful entities) and L-resolution (cases in which pixel observations are made over larger areas than the size of meaningful entities). Recently, entire volumes have been devoted to the impact of modern remote sensing technologies on scaling studies (Goodchild and Quattrochi 1997, van Gardingen et al. 1997), demonstrating the diversity of concepts related to scale, but falling short of defining an integrated terminology. In the absence of this integrated terminology, clear specifications of spatial aspects of phenomena, their model representation and observations, are needed. This information can be considered metadata or metainformation (Beard, *in press*), which is helpful for reducing uncertainty in the use of spatial data.

In geostatistics, a tool increasingly used by ecologists, scale-related terminology (support, lag, range, regularization) is clear (Olea 1990). However, these geostatistical terms refer only to the observations and the statistical assumptions of geostatistical (stochastic) models, not to the spatial characteristics of processes or phenomena being studied. Geostatistics, therefore, provides useful terms for only two of the four spatial scale characteristics previously listed.

A detailed survey of the concepts and vocabulary of scale in landscape ecology (Withers and Meentemeyer 1999) recently summarized the issues by research foci. Although their study attempted to harmonize the duality of "grain size and extent" with "minimum sampling unit and (broad vs. fine) scale," the dominant usage in the landscape ecological literature is to define scale by grain *and* extent (Turner et al. 1989, Gustafson 1998, Jenerette and Wu 2000). We propose that grain (size) and extent, and their reference to either observation or context, should be used as separate scale characteristics.

The potential problems related to the inequality of *what we measure* and *what we infer about*, enhanced by computerized data representation, gets exposure in some ecological discussions explicitly referring to scaling landscape characteristics (Levin 1992, Li and Reynolds 1995). However, the everyday practice of ecological studies seems to ignore it almost completely. For example, a recent survey of more than 200 productivity–richness research papers (Wade et al. 1999) found that close to 50% of them gave no precise report on one or more of the spatial characteristics listed above.

We agree that science, and therefore its terminology, is dynamic (Jenerette and Wu 2000). We also believe that clear terminology and clear definitions are necessary requirements for scientific progress. The single numerical descriptor known as cartographic scale (the ratio of map distance over real distance) expresses only part of the information that ecologists and other scientists dealing with spatial data need to communicate. We would like to encourage ecologists to include all relevant technical, contextual, and conceptual pieces of information, and journal editors to demand it, in scientific publications.

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Where the Ocean Meets the Sky . . .

. . . you get air deposition. Technically, air deposition happens when the sky—or the pollution in it—comes down to the ocean (or continent), but Rod Stewart had the right idea. Air and water do meet, and not only in poetry and old Irish song lyrics. Air pollution is often a significant source of water quality problems. Furthermore, ecologists have a