On the Definitions of Scale

Recently, it was suggested that the traditional cartographic definition of scale, the ratio of map distance to earth surface distance, should be adopted as the sole definition (Silbernagle 1997). This was in response to the well-known inconsistency between geographic and ecological notions of scale. In describing the same spatial data, a geographer could refer to it as small scale whereas an ecologist could refer to it as large scale. The geographer is describing scale in reference to the ratio of map distance to earth distance. The ecologist is often describing scale in reference to the extent of the phenomenon studied or the spatial resolution that was incorporated in the study. For the ecologist, perhaps the adjectives fine or coarse are more appropriate than large or small, but beyond these semantic issues, there is a fundamental difference between the cartographer's and the ecologist's notion of scale. A contrasting opinion to Silbernagle (1997), on how to treat the terminology of scale, is to adopt pluralistic definitions that describe distinct aspects of the concept (e.g., Peterson and Parker 1999). In this paper we discuss various definitions of scale in the ecological context and explain why multiple meanings of the scale need to be recognized.

Historically, the cartographic definition of scale has been the most widely used. Cartographic scale is necessary for developing maps that describe real-world locations and distances between locations in a useful manner. A small-scale map would have a small map size relative to the earth area being depicted. (For the same size map, a country map is of a larger scale than a continental map.) This usage of the term scale has been sufficient for problems such as map making. Ecology, though, is more interested in describing patterns, understanding the processes responsible for these patterns, and exploring the ecological effect of the patterns. For ecology, knowing the cartographic scale is only one piece of the scale puzzle.

Why should we prefer a variety of scale definitions? What is missing from the cartographic definition of scale? In the engineering sciences, scale effects are those that result from size differences between a model and the real system. Even though a miniature model of a building made of wood is structurally sound, it is not necessarily appropriate to infer that the same process of maintaining structural stability could hold for a full-sized building made of wood. In ecology this concept is relevant because the majority of ecological studies occur for only a short amount of time and at a small plot scale. Understanding ecological scale effects is necessary to incorporate this localized information with processes occurring at regional, continental, and global scales.

These are two fundamentally distinct aspects of scale: accurately comparing a model to the real world and accurately translating a process between different physical or spatial sizes. Ecology, which includes the study of both pattern and process, needs to develop a synthetic understanding of scale. This need has led to the generation of a variety of definitions that partition scale into its various components. The increase in definitions assists the growth of ecology by articulating the different contexts in which scale can be important.

Geographic scale (see Lam and Quattrochi 1992) is defined as the scope of a particular map, which is equivalent to the term "extent" used in landscape ecology. The definition is germane to ecology because it defines the spatial environment within which a question is framed. As the extent of a study increases, the characterization of the environment changes. For example, examinations of the dynamics of nitrogen processing at a regional extent must include the examination of climatic patterns, geologic patterns, and other processes occurring over these large areas. This endeavor is in contrast to the examination of nitrogen dynamics within a cubic meter of soil, which would only consider localized phenomena of soil water content, organic material complexity, and microbial activities. Thus, a change in the extent (scale) for a question changes the relevance of specific environmental variables. Hierarchy theory, in particular, has identified the importance of this in describing patterns and understanding mechanisms in ecology (Allen and Starr 1982, O'Neill et al. 1986, Wu, *in press*).

Operational scale (see Lam and Quattrochi 1992) is defined as the spatial extent of the operation of a particular phenomenon. This is related, although not equivalent, to the geographic concept of the minimal mapping unit (for vector maps), the smallest size of object which is represented by the map, or grain size (for raster maps), the size of the pixels within which heterogeneity is not described. Operational scale is relevant to ecology because it relates to the process that is being addressed by a particular question.

Many of the classical ecological studies have examined questions for which the geographic and operational scales are the same. The Hubbard Brook ecosystem deforestation study is an example (Likens and Bormann 1995). The extent of the ecosystem was defined by the catchment boundary; this ecosystem was also the resolution of all processes; estimates of inputs and exports were made for the entire ecosystem only. Studies such as these, where the geographic and operational scales are equal, do not force an explicit recognition of scale phenomena. The recent development of a spatially explicit orientation in ecology, however, has led to a divergence between the geographic and operational scales. This divergence does necessitate an explicit consideration of scale. If the functioning of multiple watersheds nested within a hydrologic unit is considered, the role of scale should be examined.

Another definition of scale that incorporates the disparity between geographic and operational scale is relative scale. This is defined as the relationship between the smallest distinguishable unit, grain size, and the extent of the map (Meentemeyer 1989). This definition expresses scale as a ratio, in this regard similar to the cartographic definition. Based on this definition of scale, comparisons of scale between studies are possible even if a large absolute difference in the geographic scale exists. An ecological study that examines a single biofilm could be coarser in relative scale than a global study that segregates the biosphere into several distinct units. Specifically, the relationship between the processes under study relative to the environment in which this process exists defines the relative scale.

Two important developments, the theory and application of fractal geometry, and geographic information systems (GIS), have shown the necessity of understanding additional aspects of scale aside from its cartographic notion. These two factors contributed to the realization that the degree of resolution at which a pattern is described influences the analysis of that pattern. One of the classical questions in geography asks, “What is the length of a coastline?” The answer depends on the length of the ruler used to measure it (Mandelbrot 1982). A shorter ruler measures the coastline variability that is smoothed over when a longer ruler is used; thus a smaller ruler results in a longer measure of the coastline than a larger ruler. This phenomenon is not captured by the cartographic definition of scale, but the definition of scale as grain size and extent addresses this issue.

Computing power, which has allowed for the rapid development of GIS, has also increased the importance of understanding scale beyond the cartographic definition. GIS software reduces the restrictions of the cartographic scale. Once a map is entered into a GIS, alterations of the cartographic scale are trivial. Zooming functions can instantaneously change the relationship between the map distance and real world distance. However, other aspects of scale, such as geographic, operational, and relative scale, are not easily adjusted. These aspects of scale depend on the underlying data that cannot be altered without collecting more data or resampling the current data. In principle, downscaling (generating patterns at a resolution below the grain of the data without auxiliary information) is inappropriate, whereas upscaling (aggregating fine-scale information to a coarser scale) should be attainable, although this still represents a challenge in ecology (Wu 1999). How should one aggregate or extrapolate fine-scale information to a coarse scale? One of the problems frequently encountered in translating information across scales is the modifiable areal unit problem (Jelinsky and Wu 1996). To deal with this problem, the definition of scale as grain and extent is imperative.

Clearly, scale has several ecologically meaningful aspects that are not contained in the cartographic definition. We agree with many ecologists that when describing scale, we should be explicit about which aspects are being addressed; it is neither necessary nor possible to restrict the use of scale to its cartographic connotation. Withers and Meentemeyer (1999) reasonably proposed that scale only be used with a context-specific modifier. As ecology progresses, we believe that definitions pertinent to ecological pattern and process will be retained, while others may be relegated to specific instances. Indeed, a quick examination of the literature in different fields such as engineering, physics, meteorology, biology, social sciences, and even geosciences reveals that scientists have long adopted multiple definitions of scale in their studies. Science is dynamic; so is its terminology.

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