The Application of Fractal Geometry to Ecology

New insights into the natural world are just a few of the results from the use of fractal geometry. Examples from population and landscape ecology are used to illustrate the usefulness of fractal geometry to the field of ecology.

The advent of the computer age played an important role in the development and acceptance of fractal geometry as a valid new discipline. New insights gained from the application of fractal geometry to ecology include: understanding the importance of spatial and temporal scales; the relationship between landscape structure and movement pathways; an increased understanding of landscape structures; and the ability to more accurately model landscapes and ecosystems.

Using fractal dimensions allows ecologists to map animal pathways without creating an unmanageable deluge of information. Computer simulations of landscapes provide useful models for gaining new insights into the coexistence of species. Although many ecologists have found fractal geometry to be an extremely useful tool, not all concur. With all the new insights gained through the appropriate application of fractal geometry to natural sciences, it is clear that fractal geometry a useful and valid tool.

New insight into the natural world is just one of the results of the increasing popularity and use of fractal geometry in the last decade.

<u>What are fractals and what are they good for?</u>

Scientists in a variety of disciplines have been trying to answer this question for the last two decades. Physicists, chemists, mathematicians, biologists, computer scientists, and medical researchers are just a few of the scientists that have found uses for fractals and fractal geometry.

Ecologists have found fractal geometry to be an extremely useful tool for describing ecological systems. Many population, community, ecosystem, and landscape ecologists use fractal geometry as a tool to help define and explain the systems in the world around us. As with any scientific field, there has been some dissension in ecology about the appropriate level of study. For example, some organism ecologists think that anything larger than a single organism obscures the reality with too much detail. On the other hand, some ecosystem ecologists believe that looking at anything less than an entire ecosystem will not give meaningful results. In reality, both perspectives are correct. Ecologists must take all levels of organization into account to get the most out of a study. Fractal geometry is a tool that bridges the "gap" between different fields of ecology and provides a common language.

Fractal geometry has provided new insight into many fields of ecology. Examples from population and landscape ecology will be used to illustrate the usefulness of fractal geometry to the field of ecology. Some population ecologists use fractal geometry to correlate the landscape structure with movement pathways of populations or organisms, which greatly influences population and community ecology.

Landscape ecologists tend to use fractal geometry to define, describe, and model the scale-dependent heterogeneity of the landscape structure.

Before exploring applications of fractal geometry in ecology, we must first define fractal geometry. The exact definition of a fractal is difficult to pin down. Even the man who conceived of and developed fractals had a hard time defining them (Voss 1988). Mandelbrot's first published definition of a fractal was in 1977, when he wrote, "A fractal is a set for which the Hausdorff-Besicovitch dimension strictly exceeds the topographical dimension" (Mandelbrot 1977). He later expressed regret for having defined the word at all (Mandelbrot 1982).

Other attempts to capture the essence of a fractal include the following quotes: "Different people use the word fractal in different ways, but all agree that fractal objects contain structures nested within one another like Chinese boxes or Russian dolls." (Kadanoff 1986) "A fractal is a shape made of parts similar to the whole in some way." (Mandelbrot 1982) Fractals are..."geometric forms whose irregular details recur at different scales." (Horgan 1988) Fractals are..."curves and surfaces that live in an unusual realm between the first and second, or between the second and third dimensions." (Thomsen 1982)

One way to define the elusive fractal is to look at its characteristics. A fundamental characteristic of fractals is that they are statistically self-similar; it will look like itself at any scale. A statistically self-similar scale does not have to look exactly like the original, but must look similar. An example of self-similarity is a head of broccoli. Imagine holding a head of broccoli. Now break off a large floret; it looks similar to the whole head. If you continue breaking off smaller and smaller florets, you'll see that each floret is similar to the larger ones and to the original. There is, however, a limit to how small you can go before you lose the self- similarity.

Another identifying characteristic of fractals is they usually have a non- integer dimension. The fractal dimension of an object is a measure of space-filling ability and allows one to compare and categorize fractals (Garcia 1991). A straight line, for example, has the Euclidean dimension of 1; a plane has the dimension of 2. A very jagged line, however, takes up more space than a straight line but less space then a solid plane, so it has a dimension between 1 and 2. For example, 1.56 is a fractal dimension. Most fractal dimensions in nature are about 0.2 to 0.3 greater than the Euclidean dimension (Voss 1988). Euclidean geometry and Newtonian physics have been deeply rooted traditions in the scientific world for hundreds of years. Even though mathematicians as early as 1875 were setting the foundations that Mandelbrot used in his work, early mathematicians resisted the concepts of fractal geometry (Garcia 1991). If a concept did not fit within the boundaries of the accepted theories, it was dismissed as an exception. Much of the early work in fractal geometry by mathematicians met this fate. Even though early scientists could see the irregularity of natural objects in the world around them, they resisted the concept of fractals as a tool to describe the natural world. They tried to force the natural world to fit the model presented by Euclidean geometry and Newtonian physics. Yet we all know that "clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line" (Mandelbrot 1982).

The advent of the computer age, with its sophisticated graphics, played an important role in the development and acceptance of fractal geometry as a valid new discipline in the last two decades. Computer-generated images clearly show the relevance of fractal geometry to nature (Scheuring and Riedi 1994). A computer- generated coastline or mountain range demonstrates this relevance.

Once mathematicians and scientists were able to see graphical representations of fractal objects, they could see that the mathematical theory behind them was not freakish but actually describes natural objects fairly well. When explained and illustrated to most scientists and non-scientists alike, fractal geometry and fractals make sense on an intuitive level. Examples of fractal geometry in nature are coastlines, clouds, plant roots, snowflakes, lightning, and mountain ranges.

Fractal geometry has been used by many sciences in the last two decades; physics, chemistry, meteorology, geology, mathematics, medicine, and biology are just a few. Understanding how landscape ecology influences population ecology has allowed population ecologists to gain new insights into their field. A dominant theme of landscape ecology is that the configuration of spatial mosaics influences a wide array of ecological phenomena (Turner 1989). Fractal geometry can be used to explain connections between populations and the landscape structure.

Interpreting spatial and temporal scales and movement pathways are two areas of population ecology that have benefited from the application of fractal geometry. Different tools are required in population ecology because the resolution or scale with which field data should be gathered is attuned to the study organism (Wiens et al. 1993).

Insect movements, like plant root growth, follow a continuous path that may be punctuated by stops but the tools required to measure this continuous pathway are very different. Plant movement is measured by observing root growth through photographs, insect movement by tracking insects with flag placement, and animal movement by using tracking devices on larger animals (Gautestad and Mysterud 1993, Shibusawa 1994, Wiens et al. 1993).

Spatial and temporal scale are important when measuring the home range of a population and when tracking animal movement (Gautestad and Mysterud 1993, Wiens et al. 1993). Animal paths have local, temporal, and scale-specific fluctuations in tortuosity (Gautestad and Mysterud 1993) that are best described by fractal geometry. The mapping of insect movement also required use of the proper spatial or temporal scale. If too long of a time interval is used to map the insect's progress, the segments will be too long and the intricacies of the insect's movements will be lost. The use of very short intervals may create artificial breaks in behavioral moves and might increase the sampling effort required until it is unmanageable (Wiens et al. 1993).

Movement pathways are one of the main characteristics influenced by the landscape. Movement pathways are influenced by the vegetation patches and patch boundaries (Wiens et al. 1993). Root deflection in a growing plant is similar to an animal pathway being changed by the landscape structure. Paths of animal movement have fractal aspects. In a continuously varying landscape, it is difficult to define the area of a specie's habitat (Palmer 1992).

Application of fractal geometry has given new insights into animal movement pathways. For example, animal movement determines the home range. Because animal movement is greatly influenced by the fractal aspect of the landscape, home range is directly influenced by the landscape structure (Gautestad and Mysterud 1993). Animal movement is not random but greatly influenced by the landscape of the home range of the animal (Gautestad and Mysterud 1993). Structural complexity of the environment results in tortuous animal pathways (Gautestad and Mysterud 1993), which in turn lead to ragged home range boundaries.

Gautestad and Mysterud (1993) found that home range can be more accurately described by its fractal properties than by the traditional area-related approximations. Since demarcation of home range is a difficult task and home range can't be described in traditional units like square meters or square kilometers, they used fractal properties to better describe the home range area as a complex area utilization pattern (Gautestad and Mysterud 1993). Fractals work well to describe home range because as the sample of location observation increases, the overall pattern of the position plots takes the form of a statistical fractal (Gautestad and Mysterud 1993). Fractal dimensions are used to represent the pathways of beetle movement because the fractal dimension of insect movement pathways may provide insights not available from absolute measures of pathway configurations (Wiens et al. 1993).

Using fractal dimensions allowed ecologists to map the pathway without creating an unmanageable deluge of information (Wiens et al. 1993). Insect behavior such as foraging, mating, population distribution, predator- prey interactions or community composition may be mechanisticly determined by the nature of the landscape. The spatial heterogeneity in environmental features or patchiness of a landscape will determine how organisms can move around (Wiens et al. 1993). As a beetle or an other insect walks along the ground, it does not travel in a straight line. The beetle might walk along in a particular direction looking for something to eat. It might continue in one direction until it comes across a bush or shrub. It might go around the bush, or it might turn around and head back the way it came. Its path seems to be random but is really dictated by the structure of the landscape (Wiens et al. 1993).

Another improvement in population ecology through the use of fractal geometry is the modeling of plant root growth. Roots, which also may look random, do not grow randomly. Reproducing the fractal patterns of root systems has greatly improved root growth models (Shibusawa 1994).

Landscape ecologists have used fractal geometry extensively to gain new insights into their field. Landscape ecology explores the effects of the configuration of different kinds of environments on the distribution and movement of organisms (Palmer 1992). Emphasis is on the flow or movement of organism, genes, energy, and resources within complex arrangements of ecosystems (Milne 1988). Landscapes exhibit non-Euclidean density and perimeter-to-area relationships and are thus appropriately described by fractals (Milne 1988).

New insights on scale, increased understanding of landscape structures, and better landscape structure modeling are just some of the gains from applying fractal geometry. Difficulties in describing and modeling spatially distributed ecosystems and landscapes include the natural spatial variability of ecologically important parameters such as biomass, productivity, soil and hydrological characteristics. Natural variability is not constant and depends heavily on spatial scale. Spatial heterogeneity of a system at any scale will prevent the use of simple point models (Vedyushkin 1993).

Most landscapes exhibit patterns intermediate between complete spatial independence and complete spatial dependence. Until the arrival of fractal geometry it was difficult to model this intermediate level of spatial dependence (Palmer 1992, Milne 1988). Landscapes present organisms with heterogeneity occurring at a myriad of length scales. Understanding and predicting the consequences of heterogeneity may be enhanced when scale-dependent heterogeneity is quantified using fractal geometry (Milne 1988).

Landscape ecologists usually assume that environmental heterogeneity can be described by the shape, number, and distribution on homogeneous landscape elements or patches.

Heterogeneity can vary as a function of spatial scale in landscapes. An example of this is a checker board. At a very small scale, a checker board is homogeneous because one would stay in one square. At a slightly larger scale, the checker board would appear to be heterogeneous since one would cross the boundaries of the red and black squares. At an even larger scale, one would return to homogeneity because of the pattern of red and black squares (Palmer 1992).

An increased understanding of the landscape structures results from using the fractal approach in the field of remote sensing of forest vegetation. Specific advantages include the ability to extract information about spatial structure from remotely sensed data and to use it in discrimination of these data; the compression of this information to few values; the ability to interpret fractal dimension values in terms of factors, which determine concrete spatial structure; and sufficient robustness of fractal characteristics (Vedyushkin 1993).

Computer simulations of landscapes provide useful models for gaining new insights into the coexistence of species. Simulated landscapes allow ecologists to explore some of the consequences of the geometrical configuration of environmental variability for species coexistence and richness (Palmer 1992). A statistically self-similar landscape is an abstraction but it allows an ecologist to model variation in spatial dependence (Palmer 1992). Spatial variability in the environment is an important determinant of coexistence of competitors (Palmer 1992). Spatial variability can be modeled by varying the landscape's fractal dimension. The results of this computer simulation of species in a landscape show that an increase in the fractal dimension increases the number of species per microsite and increases species habitat breadth.

Other results show that environmental variability allows the coexistence of species, decreases beta diversity, and increases landscape undersaturation (Palmer 1992). Increasing the fractal dimension of the landscape allows more species to exist in a particular area and in the landscape as a whole; however, extremely high fractal dimensions cause fewer species to coexist on the landscape scale (Palmer 1992).

Although many ecologists have found fractal geometry to be an extremely useful tool, not all concur. Even scientists who have used fractal geometry in their research point out some of its shortcomings. For example, Scheuring and Riedi (1994) state that "the weakness of fractal and multifractal methods in ecological studies is the fact that real objects or their abstract projections (e.g., vegetation maps) contain many different kinds of points, while fractal theory assumes that the natural (or abstract) objects are represented by points of the same kind."

Many scientists agree with Mandelbrot when he said that fractal geometry is the geometry of nature (Voss 1988), while other scientists think fractal geometry has no place outside a computer simulation (Shenker 1994). In 1987, Simberloff et al. argued that fractal geometry is useless for ecology because ecological patterns are not fractals.

In a paper called "Fractal Geometry Is Not the Geometry of Nature," Shenker says that Mandelbrot's theory of fractal geometry is invalid in the spatial realm because natural objects are not self-similar (1994). Further, Shenker states that Mandelbrot's theory is based on wishing and has no scientific basis at all. He conceded however that fractal geometry may work in the temporal region (Shenker 1994).

The criticism that fractal geometry is only applicable to exactly self-similar objects is addressed by Palmer (1982). Palmer (1982) points out that Mandelbrot's early definition

(Mandelbrot 1977) does not mention self-similarity and therefore allows objects that exhibit any sort of variation or irregularity on all spatial scales of interest to be considered fractals. According to Shenker, fractals are endless geometric processes, and not geometrical forms (1994), and are therefore useless in describing natural objects. This view is akin to saying that we can't use Newtonian physics to model the path of a projectile because the projectile's exact mass and velocity are impossible to know at the same time.

Mass and velocity, like fractals, are abstractions that allow us to understand and manipulate the natural and physical world. Even though they are "just" abstractions, they work quite well.

The value of critics such as Shenker and Simberloff is that they force scientists to clearly understand their ideas and assumptions about fractal geometry, but the critics go too far in demanding precision in an imprecise world. With all the new insights and new knowledge that have been gained through the appropriate application of fractal geometry to natural sciences, it is clear that is a useful and valid tool.

The new insights gained from the application of fractal geometry to ecology include: understanding the importance of spatial and temporal scales; the relationship between landscape structure and movement pathways; an increased understanding of landscape structures; and the ability to more accurately model landscapes and ecosystems.

One of the most valuable aspects of fractal geometry, however, is the way that it bridges the gap between ecologists of differing fields. By providing a common language, fractal geometry allows ecologists to communicate and share ideas and concepts. As the information and computer age progress, with better and faster computers, fractal geometry will become an even more important tool for ecologists and biologists. Some future applications of fractal geometry to ecology include climate modeling, weather prediction, land management, and the creation of artificial habitats.

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