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Scaling-up

Places that are near to each other are more alike than those that are further away and the degree of dissimilarity depends on both the environment and the nature of our observations. This view is one that we need to adopt if we wish to move measurements or understanding from the local to the regional or global scale. True, there are some phenomenon that can sometimes be studied in isolation because they show self-similarity with scale (e.g. drainage patterns) or can be considered spatially homogenous (e.g. fresh snow), but in this diverse world of ours these are the exception rather than the rule.

That every place is unique and space is a variable (rather than a parameter) is the essence of geography (Harvey, 1969). This theme echoes backwards to our understanding of measurement uncertainty (Heisenberg, 1932) and fractals (Mandelbrot, 1982) and forwards to landscape ecology (Meentemeyer, 1989) and the needs of Earth System Science (NASA, 1988). However, this understanding of space, time and, thereby, scale sits uneasily with aspatial deterministic models. Assumptions that a relationship at one scale will be the same at another, untested assumptions of spatial homogeneity and limited information on the land cover of our planet limit our ability to address the pressing need to move from a local to a regional or global scale understanding of our environment (IGBP, 1992; Houghton *et al.*, 1996). This confusion over the fundamental importance of scale has been recognised by a number of observers in recent years (Ehleringer & Field 1993; Foody & Curran, 1994a; Stewart *et al.*, 1996). This book intervenes in this debate by exploring first what we know about scale and second by taking that knowledge to scale our local-scale measurements or understanding to larger, particularly regional or global scales, via a mix of models and spatial extrapolation. The dominant voices in this book are those of biologists and geographers but those with relevant viewpoints from the disciplinary vantage points of statistics, hydrology, meteorology and agriculture feature strongly. Fortunately, the only point of contention was semantic and concerned the long running debate over the definition of the word *scale* (Lam & Quattrochi, 1992). In this context scale has two equally valid definitions. The first is *cartographic* and the second is *colloquial* (Foody & Curran, 1994b). Unfortunately what is small scale by one definition is large scale by the other! The cartographic definition of scale relates the distance on a map to the actual distance on the ground via the equation:

$$\text{scale} = \text{distance on map}/\text{actual distance on ground}$$

Consequently, a *small-scale* map (e.g. 1:10 000 000) covers a large area, like a continent, with little detail and a *large-scale* map (e.g. 1:1000) covers a small area, like a building plot, in great detail. The colloquial definition of scale is that it is a synonym of words such as size or area. Consequently, *small scale* is small size and thereby small area (or period of time) and large scale is large size and thereby large area (or period of time). Scale by the colloquial definition has no commonly accepted bounds and so is relative to the observer. One observer may use small scale to mean a leaf (relative to a field) while another may use small scale to mean a field (relative to a region). The cartographic definition is precise and has a long and unambiguous history (Maling, 1989) whereas the colloquial definition is imprecise and contains in-built redundancy (why use the word scale when no word is needed or when size or area would suffice?). However, the colloquial has the most common contemporary usage and underpins the very notion of 'scaling-up' from small to large. Therefore, in this book we have adopted, where possible, the colloquial definition of scale and authors have adhered to the following five guidelines:

- scale relates to size, area or time period
- the unqualified term *scale* should be avoided
- terms such as *small scale* or *large scale* should be replaced with more specific phrases such as *leaf scale*, *field scale*, *regional scale* and *global scale*
- specific phrases such as *scaling from regional to global scales* should be used to avoid vague phrases such as *scaling-up to larger scales*
- *scaling-up* relates to moving from *small* to *larger* area, but where possible the terms small and large should be defined precisely.

This hopefully will enable the reader to understand each author's use of the term scale. This is vital since the results of an investigation and inferences drawn from it are scale dependent. Thus observations and theories derived at one scale may not apply at another. Furthermore, the differences observed between locations at different scales may be enormous, with, for instance, large changes in both the strength and direction of relationships noted when the scale of the study changed. This type of problem is well known in geographical research, perhaps most notably in the guise of the ecological fallacy (Johnston, 1981; Wrigley, 1995), but has only relatively recently been recognised within the ecological community.

Given the significance of the effects of scale, there is an urgent need for scaling issues, both in space and time, to be recognised as being fundamental to ecological research. The recognition of the existence of domains of scale and the development of scaling theories that generate testable scientific hypotheses are urgent priorities. To achieve these, data will be required at a range of spatial and temporal scales. With much ecological research restricted to relatively small areas, through practical constraints as well as the scientific culture of the ecological research community (Wiens, 1989), much of our knowledge and understanding of the environment relates only to relatively local scales. With the growing awareness and concern over regional- to global-scale issues, such as greenhouse warming and ozone depletion, much emphasis has been placed on scaling-up this detailed knowledge acquired at the local scales. Since the effects of changing scale are complex and non-linear, this is not an easy task, hence the need for multiscale analyses and scaling theories. This will require data at a range of scales. The opportunity to study and exploit scaling effects is provided through remote sensing (Golley, 1989). Presently, remote sensing systems enable the Earth's environment to be studied at spatial scales ranging from the local to the global. Furthermore, the data may be available at a temporal frequency measured over a period of days or weeks, supplemented by an archive that already extends over a number of decades. Remotely sensed data, therefore, provide the basis for observing the environment at a range of scales to facilitate our understanding of the environment. Scale, however, exerts a strong influence on the ability to extract environmental information from remotely sensed data and so the data sets require careful specification and analysis within appropriate scene models (Woodcock & Strahler, 1987; Woodcock & Harward, 1992). The information extracted from the remotely sensed data may then be integrated with other spatial data sets within a geographic information system (GIS). This does not eliminate the need for further accommodation of scale effects. While the data within the GIS may have been acquired at a suitable scale using appropriate techniques, an analyst may wish to change the scale of an investigation and so methods for scaling will be required. Therefore, if scale is to be accommodated appropriately within environmental research, there is an urgent need for theoretical and methodological advancements across a range of fields of study.

It is hoped that the growing awareness of the effects of scale in environmental research and closer linkage between the various research communities involved will aid a better understanding of the environment. We hope that this book will provide a small step in this direction.

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Tackling large-scale problems by scaling-up

Introduction

Much of the activity of scientists is described as *analysis*, by which we mean inspection of the whole by examination of the constituent parts and processes. This is evident in the history of science, and the tools of science. Leeuwenhoek (1632–1723) developed the microscope to see small things clearly, but until the development of remote sensing there was no macroscope or equivalent tool to see very large things in their entirety. Yet the difficulty that humans have of perceiving and understanding larger-scale phenomena is widely acknowledged. In the English language we often accuse people of 'being unable to see the wood for the trees' and 'shortsightedness'. It seems that an act of imagination is required to step beyond the scales of time and space that are imposed by human senses, and that the capacity to do this is much cherished (we speak of 'a man of vision' to describe remarkable people who have this capacity). Yet scientists addressing the larger-scale problems have never found it easy to have their ideas accepted, either by fellow scientists or society as a whole. Examples of such ideas include continental drift, evolution by natural selection, population homeostasis, biospheric homeostasis and even climate change. This is because the scientific method works best when the object of study is well defined, can be isolated from extraneous influences and small changes in the conditions can be made at will. Then the classical scientific method of hypothesis testing by experiment is relatively easy. Unfortunately, many of the urgent problems that we face in the world are large-scale problems to do with land and resource utilisation, which, as Waddington (1977) and many others since have pointed out, are not especially amenable to this approach. The recent upsurge of interest in scales of organisation, and scaling-up, is partly a response to the challenge of using science to solve large problems, and partly the need to reconcile the differing world views that we find between scientific disciplines, for example, between population biology and ecosystematics (Levin, 1992; Rowe, 1992; Ehleringer & Field, 1993).

The propositions

The problem of scale is best discussed as a series of propositions, all of which are widely espoused. The first of these represents the reductionist view.

1. The small things are the ones that determine the characteristics of the living world

Examples of small things in this context are genes, ion pumps, stomata and leaves. At first, this proposition seems self-evident and is implicit in many branches of science. However, on reflection, it is clear that matters are less straightforward. For example, taking the case of genes: although each gene codes for a protein, whether or not any specific gene spreads or is extinguished in the species as a whole depends on the process of natural selection. This operates at the population and individual level, and a complete genetic map of, say, *Homo sapiens* would not in itself explain how the species evolved and why differences between individuals occur. Thus, over long (evolutionary) periods the genome is controlled by events operating at a higher level of organisation, and which are subject to their own laws. There are many such examples. A mechanistic understanding of stomatal movement is an important scientific goal but might not help us to model regional scale hydrology, because properties of the leaves, the land cover and the atmosphere have a more dominant role to play than the movement of potassium ions across the plasmalemma of the guard cells. This type of division may be a quite general problem, acute in some cases but less important in others.

2. The small things are the ones most amenable to study by the methods of science

'Small things' fit into test tubes or observation chambers, and they may be subject to experimental manipulations. Not only are they small, but they perform their function over fairly short periods of time and, therefore, may be the subject of experiments several times in a day. The small things are simple, basic, elemental, so we should be able to find out a lot about them in a human lifetime.

For this reason, leaves, stomata and chloroplasts have been studied more than canopies of leaves, which in turn have been studied more than ecosystems. However, even these simple things, in the hands of an experimental scientist with an inquiring spirit, are revealed to be far from simple. Worlds are found to exist inside worlds, and research often generates more questions than answers. Nevertheless, it has been possible to describe their responses to their immediate environment in considerable detail.

3. The large things are the ones that have the most profound effect on humans

Examples of 'large things' are drought, famine and climate change. It is impossible, or at least difficult, to carry out meaningful experiments on them, because the experiments would take too long, or be too expensive or not be ethically acceptable. The best we can do is to gather statistics about them and to construct mathematical models that represent our best guesses about how they work. Small-scale experiments in 'model systems' or 'microcosms' are often attempted but may not be realistic because larger systems have properties of their own, which small-scale experimental systems cannot capture.

4. There is a feeling that we should be able to use our knowledge of small things to predict and manage these large-scale phenomena

The optimist believes that we should be able to use knowledge derived from small things and this is the motivation for scaling-up. Certainly, we need to be able to predict outside our experience, not just by extrapolation but also from a knowledge of processes and mechanisms embodied in physical, chemical and biological disciplines. We may not agree on how far this prediction is possible, but most people would concede that prediction is perfectly possible in principle, although in practice we are limited by lack of knowledge and a shortage of computing power. Here it is useful to distinguish two sorts of scaling-up. The first, we may call it *simple scaling*, is where we want to multiply up a phenomenon observed in a small plot or sample to make a statement about the landscape, the region or the world. An extreme example is the work of Zimmerman *et al.* (1982) on the evolution of methane, a greenhouse gas, by termites. From a study of two termite species *in vitro*, the authors calculated that termites of the world produce 1.5×10^{14} g methane by consuming 33.0×10^{15} g phytomass. However, there are many life forms and species of termite, each with a characteristic metabolism and methane-producing gut flora. They feed at quite different rates. Moreover, much of the methane produced in soil is now known to be oxidised to CO_2 on passage through the soil profile. It is not surprising that the estimate was controversial and has been adjusted downwards (e.g. Collins & Wood (1984) thought the consumption was a mere 3.36×10^{15} g carbon). Analogous scaling-up procedures are inevitably widespread in work on global geochemistry and climate change, though caveats are usually supplied (Grace *et al.*, 1995). The second type of scaling-up is where it becomes necessary or desirable to move between levels of organisation, for example from a knowledge of how stomata behave in relation to light, humidity and CO_2 to a prediction of the hydrology of a region and how this may be affected by climate change (Norman, 1993). We may call this *hierarchical scaling*.

5. In hierarchical systems, information is passed upscale and downscale

Passage of information in a hierarchy is best explained by a diagram (Fig. 1). Hierarchical structure has a horizontal separation that isolates each level from levels above and below, and a vertical separation that segregates the components of any level into groups. A single process operating at any level is the outcome of several lower-level processes that operate more frequently. It should be clear from this that the processes and mechanisms at any one scale, which determine the characteristics of the next largest scale, are subject to feedbacks (Allen & Star,

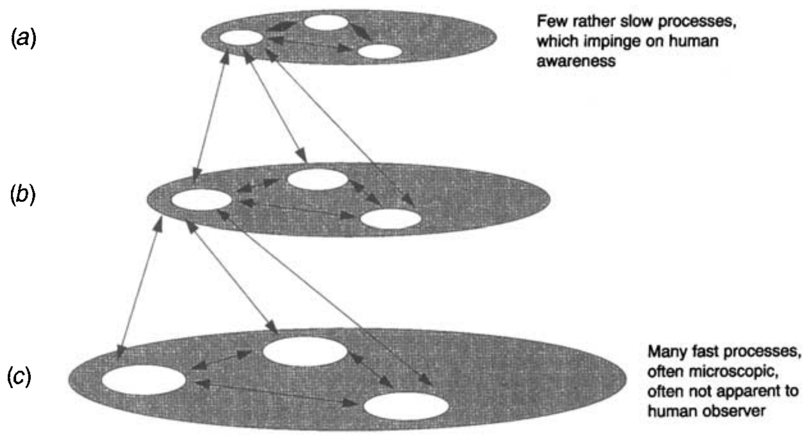

Fig. 1. Scales of organisation, showing feedbacks and feedforwards from the topmost scale (the domain most accessible and familiar to human experience) and the lowermost scale (where structures are microscopic and numerous and processes are fast).

1982). This is the general case of proposition 1. There are several ways this feedback may operate. It may be that the higher level sets the limits for the operation of the processes by a negative feedback. For example, when scaling-up from stomata to a forest region, it is important to realise that the water lost through billions of stomatal pores accumulates in the regional boundary layer, thus decreasing the driving gradient for evaporation (McNaughton & Jarvis, 1991). Therefore, simple scaling of knowledge of evaporation from a population of stomata held at controlled humidity would give the wrong answer, and hierarchical scaling is required. This may be difficult to achieve in practice, as scientific disciplines have evolved to study discrete scales, and scientists may be unaware, or reluctant to assimilate, the wisdom of other disciplines.

A related proposition is that *behaviour at one level cannot always be explained in terms of lower level behaviour simply by adding up the lower level parts*. This is because the parts interact. For example the rate of nutrient supply to a plant cannot be readily predicted from data of nutrient concentrations in the soil; a knowledge of physical chemistry is required to understand how nutrients and toxic ions are made available as the pH and redox potential of the soil changes. The rate will also depend on the distribution of roots and mycorrhizas, as well as on the flux of water through the system, itself a complex function of the vegetational structure and the environment. An example is provided by a study of the impact of elevated CO_2 upon vegetation. Luan (1995) and Luan, Grace & Muetzeldeldt (1996) used a hierarchical model to scale-up the response of leaves to CO_2 in order to predict the response of forest ecosystems to CO_2. The model incorporated many (but by no means all) of the known relationships that act between hierarchical levels. For example, when plants are stimulated to grow fast by elevated supplies of CO_2, then they may become limited by the availability of soil water and nutrients. The study revealed a tendency of the responsiveness to CO_2 to diminish on progressing from leaf scale, through whole plant scale to forest scale. It is too early to say whether this is a general homeostatic principle, essentially the statement of Le Châtelier, which applies to all ecosystems and all perturbations. It seems safer to assume that it is not.

6. Biological systems have evolved bottom-up and tend toward structural stability

In evolution, the lower levels of organisation came first and have been selected for the wider range of environments that they have experienced. This is likely to apply to species and communities. To endure