生态学的时空特性

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摘要 众所周知,几乎所有的生态学特征和现象都受限于一特定的时间和空间。因此,相应的科学假设和相关的生态学结论也只能基于这些特定的时空尺度范围。我们利用颇为熟知的事例,引用生态学文献中的具体实例,提纲挈领地论述了时空在生态学研究中的重要性。这些实例包括我们在长白山对云、冷杉(*Picea jezoensis*, *Abies nephrolepis*)林冠结构的模拟、在北美应用遥感和气象方法对碳通量的估算,以及测定湿地生态系统对加温的反应等。文中所涉及的所有生态学现象,对时间和空间都有强烈的依赖性。因而,从生态学问题的提出,到科学假设的演绎,以至试验设计和综合数据分析,都必须以时、空为前提,才不至于导致荒谬结论。

关键词 空间 时间 尺度 林冠 景观 生态系统 生态学研究

PLACING OUR HYPOTHESES AND RESULTS IN TIME AND SPACE

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Abstract Virtually all ecological investigations are conducted and constrained within a range of time and space. This suggests that interpretations of the results must be specific and that extrapolations must be made with caution. We present a hypothetical example illustrating temporal and spatial interactions as confounding factors in ecological research. Through a series of case studies, we illustrate the importance of placing our hypotheses, results from testing those hypotheses, and our conclusions in relevant scales of time and space. Our case studies focus on the ecological effects of scale for determining pattern-process relationships in a montane spruce-fir forest in China, modeling forest canopy structure, predicting carbon flux in forests the Pacific Northwest, USA; detecting temporal scales of variation in carbon flux and meteorological data from deciduous forests in Oak Ridge, Tennessee, USA; and formulating conclusions from a long-term soil-warming experiment of peatlands in Minnesota, USA. We recommend additional efforts for examining ecological phenomena across multiple temporal and spatial scales.

Key words Space, Time, Scale, Ecological studies, Canopy, Landscape, Ecosystem

Consider the following hypothetical example illustrating the confounding influences in time and space: suppose two researchers set out to determine the air temperature gradient between a clearcut and a mixed conifer forest. They lay out a 270 m transect across the edge (i.e., 135 m on each side). For the sake of thoroughness, the researchers sample the air temperature every half-meter. They have four dataloggers with temperature sensors that record air temperature each second installed at the clearcut-end of the transect (0 m), at 60 m, at 180 m, and at the forested-end of the transect (270 m). At 06:00, the researchers begin recording temperatures with hand-held thermometers along the transect. One begins in the clearcut and works toward the forest, while the other moves from the interior forest toward the clearcut. Finish-

ing at 15:00, they collect the dataloggers and retire to the field station to enter their data for analysis (Fig. 1).

The researcher who started in the clearcut found that the temperature gradually increased when moving into the forest. Meanwhile, the one who started in the forest found that the temperature gradually decreased approaching the edge of the stand and then rapidly increased when moving deeper into the clearcut (Fig. 1A). The temperatures recorded by the dataloggers indicate that the forest interior was initially warmer than the clearcut and experienced a 7.3 °C increase during the sampling period. The clearcut experienced a 36.7 °C increase over the course of the day; temperature changes at 60 m and 120 m along the transect are intermediate to these extremes (Fig. 1B). While the above hypothetical example is not characteristic

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of modern field studies , it does illustrate how results are misleading because of the confounding effects of time and space. Clearly , the interaction of time and space and temperature disallows direct comparison of those measurements taken at different times and places across the forest edge .

Fig.1 Temperature measurements on a transect across a forest interior-clearcut edge

- A. Measurements taken sequentially every half meter by two researchers. Y-axis indicates temperature, x-axis indicates location along the transect, vertical line indicates the edge between cover types, line weight indicates direction of movement
- B. Temperature profiles from four locations along the transect. X-axis indicates time of day, line weight indicates location on the transect

Along temporal and spatial axes , measurements of an ecosystem 's complexity and variability vary in magnitude. Further , ecosystem structure and function are influenced by its inherent variability and complexity (Fig.2). Since all ecological measurements are taken in predefined times and spaces , conclusions based on these measurements must be made with reference to the temporal and spatial scales of the measurements (Holling , 1992 ; Levin , 1992). The dependence of our measurements and thus conclusions on time and space as seen in the above example(Fig. 1) can also be seen in the question of how species diversity relates to ecosystem productivity/stability. In examining the empirical relationship between species diversity , productivity , and stability , numerous authors have reported a positive relationship , while others have found neutral , negative , and more complex relationships depending on the system of interest , and the temporal and spatial scale of inquiry(Tilman & Kareiva , 1997 ; Peterson *et al.* , 1998 ; Walsh *et al.* , 1998).

Due to its critical role in explorations of ecological

phenomena , scale has become a fundamental concept in ecology. Scale has a long history in the literature , with many texts devoted to its definition and concepts(Allen & Starr , 1982 ; Goodchild & Quattrochi , 1997 ; Tilman & Kareiva , 1997 ; Peterson & Parker , 1998 ; O 'Neill & King , 1998 ; Gardner , 2001). However , one persistent problem in addressing scale is that interpretation of " scale " varies among and between disciplines(Goodchild & Quattrochi , 1997). We adopt O 'Neill and King 's (1998) definition of scale as the physical and temporal dimensions at and over which phenomena or entities are observed. Scale consists of two primary measures : resolution (i. e. , grain size) and extent. Resolution is the smallest sampling unit of our observation and reflects the finest distinction that can be made between two sampling units (Allen & Starr , 1982 ; Goodchild & Quattrochi , 1997). Extent is the total area or time period over which the observations are made(O 'Neill & King , 1998). As such , the sampling regime in time and space determine the resolution and extent , which have specific units (e. g. , square meter , second). We emphasize the quantitative dimension of scale to make clear the distinction between scale of observation and hierarchical level of organization. A level of organization may have a scale , or it may range across multiple scales(Allen , 1998). Changing scales often necessitates that we consider new levels of organization(O 'Neill & King , 1998).

Fig.2 Conceptual model of temporal and spatial scale dynamics in ecological research

Spatial and temporal scale can positively or negatively effect our perceptions of variability in structure and composition and complexity of ecological interactions. Variability and complexity positively or negatively affect ecosystem functions

Observed patterns and processes are dependent on the scale of observation , and are often not generalizable across scales (Platt & Denman , 1975 ; Reed *et al.* , 1993 ; Ricklefs , 1987) because biophysical interactions between the environment and biotic processes occur across scales (Harris , 1980 ; O 'Neill *et al.* , 1986). Further , environmental problems arise through the " propagation of effects across scales "(Schneider , 1994). Consequently , we face the challenge that ecological phenomena are scale dependent. Bian and Walsh (1993) describe scale de-

pendence as occurring when patterns appear different when observed at different scales. They continue, the scale dependence of certain patterns and processes results in our inability to observe them at particular scales. The causal relationships generating the observed patterns vary when we shift scales. Also, methods used to observe causal relationships among variables are scale dependent: they are affected by the scale of observation. Thus, there often is no single or "characteristic" scale for research (Levin, 1992). In examining the spatial relationships between landscape structure and surface temperature, Saunders *et al.* (1998) clearly demonstrated with wavelet analysis that such relationships are scale dependent. Not only do patterns change with spatial resolution, but new information also appears or diminishes across scales. It is important to note that two perspectives exist regarding scale in ecological research: the first proposes that phenomena occur at specific, identifiable scales which should therefore be chosen for scientific investigations (Holling, 1992); and second proposes that studies of phenomena should be conducted across multiple scales (Levin, 1992). We advocate that both perspectives are useful in ecological research, but the applicability of each is dependent upon the phenomenon of interest and therefore the specific hypotheses and objectives of the scientific inquiry.

While ecologists recognize the importance of scale, they rarely examine how processes act across a range of scales (Lertzman & Fall, 1998). Development of testable hypotheses that are scale-dependent is difficult, and design of corresponding experiments is extremely challenging; however, they deserve attention in future research. We are accustomed to studying some processes at small scales and other processes at larger scales. Unfortunately, single-scaled approaches often do not provide as much useful information as those across multiple scales. Gardner (1998) proposes that identifying and understanding scale-dependent changes in patterns and processes is a prerequisite for comprehending and predicting the consequences of changes in ecological systems induced by disturbances and human alterations of the environment; and he proposes that one means to critically test our understanding of complex systems is to apply our formal conceptual and mathematical models across a wide range of scales. The notion is that when discontinuities among model predictions and empirical, multiscale datasets occur, we may find fundamental flaws in our theories (Gardner, 1998). Similarly, Allen (1998) expresses the need for us to stretch or shrink our ecological theories across scales, "so that when they fail, we can learn."

Herein, we present case studies to promote a greater understanding of how scaling issues apply in ecological research. The specific objectives of this paper are to 1) emphasize the effects of scaling-up measurements on our understanding, 2) advocate the use of mathematical model-

ing in research across multiple scales, 3) express the significance of capturing the heterogeneity in our systems when scale is considered, 4) present the importance of detecting appropriate temporal and spatial scales at which we can reveal useful information, and 5) raise a caution against over generalizing our results across scales. We begin by focusing on the changing controls of spatial pattern with changes in scale. Our first two case studies are from canopy/forest structure research in the spruce-fir forest of the Changbaishan Natural Reserve in China (Chen & Bradshaw, 1999; Song *et al.*, 1997). Our third case study stresses the consequences that scaling up has on our predictions (Turner *et al.*, 2000). Our fourth case study focuses on scale detection in trace gas flux data (Baldocchi *et al.*, 2001). Our final study, from a long-term peatland warming experiment, highlights the importance of placing our conclusions in proper scales.

1 Assessing canopy structure in space

Chen and Bradshaw (1999) performed a spatial analysis on both the stems and canopy architecture by dividing the forest into three vertical layers in the Changbaishan Natural Reserve (CNR) of the People's Republic of China. Species consist primarily of old growth spruce (*Picea jezoensis*), fir (*Abies nephrolepis*), and Ermany birch (*Betula ermanii*). They questioned how the tree species were distributed across the stand, how the distributions changed with scale, and how the patterns related to known species functions, life histories, and interspecific interactions. The spatial distributions of trees by species and height classes were examined to detect potential intra- and interspecific size-class interactions with respect to the vertical and horizontal canopy structure.

Tree species, diameter at breast height (DBH), crown cardinal radii, and stems were mapped in a subsectioned rectangular plot (100 m × 200 m). Eight stems of spruce, fir, and birch were randomly selected to generate height-DBH relationships. Stems were divided into three groups based on the height diameter relationships: lower layer (L), intermediate layer (M), and upper (U). Ripley's *K* statistic was applied to quantify the spatial patterns of the stems at multiple spatial scales. The statistic uses the distances between all possible pairs of points, and thus provides information at multiple scales (Moeur, 1993). The Shannon-Wiener diversity index (H') was calculated to quantify compositional heterogeneity for each grid in the rectangular plot. The hierarchical structure of canopy patches at multiple scales was also explored by generating canopy coverages with grid sizes of 12.5, 25, 50, and 100 m.

Chen and Bradshaw (1999) report differential responses to changing scale by species and size-grouping. *Picea* stems were generally randomly distributed except at scales between 28 and 37 m in the lower canopy where they were mildly clustered; as a population they were ag-

gregated. *Abies* were aggregated at all sizes, with larger *Abies* more so. *Betula* (L) exhibited strong clustering patterns, while in the M and L layers they were randomly distributed at larger scales. Only *Betula* (M) were uniformly distributed at scales greater than 50 m. The species' spatial interactions were also scale and size dependent. *Picea* (U) exhibited significant repulsion to *Abies* (M) and *Betula* (L). *Abies* (L) seemed to be attracted to *Betula* (L). The statistically repulsive phenomenon of *Betula* to *Picea* (U) existed at more scales for smaller trees than for intermediate trees. An attraction phenomenon existed among *Abies* and *Betula* at relatively larger scales. Other spatial interactions were mostly independent of scale.

Heterogeneity of canopy composition was also scale dependent. The H' values increased with increasing scale for all but the largest plot. Variability in H' decreased as scale increased. We can conclude from this study that quantification of forest structure needs not only those traditional forestry metrics such as density, composition, size-frequency distribution, and DBH-height relationships; but also, how stems are distributed across a stand. Information of both types of information is needed for multiple spatial scales.

Chen and Bradshaw's (1999) study reveals how fine-scale phenomena translate with scaling, and brings us closer to linking broad- and small-scale structural information. Ecologists often focus on the relationships of small-scale structure with function, but are increasingly focusing on large-scale structure with the help of remote sensing technology. However, few studies have taken a multiple scale approach by integrating both broad- and small-scale aspects of structure. This study illustrates that not only the scale dependence of the pattern-process relationships structuring the stand, but also how processes operating at different scales can act in concert to generate an observable pattern. By understanding the scale dependency of our observations and how factors can act across scales, we can more readily conduct research across multiple scales. Research approaches across multiple scales are needed to more fully quantify the structure of land mosaics and incorporate the information into future studies of structure and function in ecosystems.

2 Modeling canopies at multiple scales

Song *et al.* (1997) simulated the 3-dimensional, hierarchical structure of individual crowns within forest stands and corresponding canopy patches. They used a modeling approach to describe crown shells based on crown ratio, maximum cardinal radii, vertical position and shape. Adding the unique crowns to simulated stem patterns, they generated canopy projections within an ARC/INFO geographic information system (GIS). The stem distributions were generated from tree patterns of known aggregation as measured by Pielou's index. Class-

es based on diameters at breast height (DBH) were simulated using the Weibull function. Different crown shapes and vertical profiles were modeled by modifying published allometric equations, which are flexible for a variety of crown shells. Values of stem aggregation, stand structure and composition, DBH, and crown parameters used in the modeling exercise were collected in a previous field study (Chen, 1986). Model parameters were independently estimated for four species groups: spruce, fir, birch, and others. The study simulated a 300 m × 300 m plot, and provided canopy coverages for five heights above the ground: 2, 6, 10, 14, and 18 m. Scale differences in the canopy characteristics were examined through five grid coverages with grain sizes of 1 024, 256, 64, 16, and 4. They examined the effects of stand density and stem distribution on patch number and canopy size across spatial resolutions and heights. The Shannon-Wiener diversity index (H') was computed to quantify canopy structural diversity.

Song *et al.* (1997) found an increasing, asymptotic trend in diversity of canopy structure with scale (Fig. 3). For example, H' gradually stabilized around 37.5 m, suggesting a possible scale of regeneration or "eco-unit". The authors suspected that the eco-unit includes only one crown type or canopy gap at smaller scales; as the grid size increased, the number of crown types increased until all types were included. Canopy structure changed dramatically at different horizontal and vertical scales, as indicated by a scale dependent canopy area to gap ratio (Song *et al.*, 1997). The ratio and its heterogeneity also stabilized around the 37.5 m scale.

Fig. 3 Shannon-Wiener diversity of the canopy versus scale of inquiry, variation and magnitude of canopy diversity decrease asymptotically with increasing scale (Figure redrawn from Song *et al.* (1997))

Statistical methods and contemporary cross-scale models impart a degree of scale flexibility in ecological research. Geostatistics and GIS allow researchers to analyze canopy and forest structures at different horizontal and vertical scales, thereby analyze scale dependence of canopy structure and composition. Song *et al.*'s (1997) canopy model provides horizontal resolution, so plots can have any size, number of species or size class without los-

ing details in foliage distribution. Scale flexibility enabled them to run the patch models at any spatial scale and negated the problem of interactions among small plots.

The modeling exercise resulted in scale dependency that is similar to what we find in natural systems. Models often require that diverse data sources be integrated, and these data sources are rarely at the same spatial scale (e.g., point ground measurements and remotely sensed observations) and even less often at the desired modeling scale. Using data at a scale other than which they were obtained, is not always a valid approach. By allowing the model to be flexible to scale, we can ensure that data of appropriate scale is used to effectively address our research problems. Similar conclusions to our first case study can be drawn concerning spatial location and scale as key parameters in modeling canopy structure.

3 Scaling-up landscape pattern

Landscape pattern (the distribution of ecosystems in a landscape) significantly influences the response of measurements to changes in space (Turner *et al.*, 1989). Further, the spatial heterogeneity of the landscape limits our ability to transform information from one scale to another since it is often lost when aggregating data from a smaller scale to a broader one (Bian, 1997). Turner *et al.* (2000) examined the importance of resolution when quantifying production at the landscape level. The objective of the study was to evaluate potential influences of spatial resolution on estimates of net primary production (NPP), net ecosystem production (NEP), and biomass.

Predicted NPP and NEP varied significantly depending on the resolution of spatial data used in the analysis. The study was conducted on a highly fragmented forest landscape around the H. J. Andrews Experimental Forest in central of the Cascade Mountains of western Oregon, USA. Roughly half of the area is native western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), and Pacific silver fir (*Abies amabilis*). The remaining landscape has been harvested over the past 50 years mostly with clearcuts of less than 40 hm² (Cohen *et al.*, 1998). Turner *et al.* (2000) used six vegetation cover classes and one water class previously identified using Landsat imagery. The six classes roughly correspond to the successional stages expected in the region: open, semi-closed, closed-mixed, closed-conifer young, closed-conifer mature, and closed-conifer old (Cohen *et al.*, 1996). NPP and NEP were calculated using a 'measure and multiply' approach after Schimel and Potter (1995). Turner *et al.* (2000) used a carbon budget for medium productivity Douglas-fir stands in the West Cascades to estimate biomass and carbon flux (F_c). They used allometric relationships to estimate foliar/fine litter production and fine root production. Within-class variability was not accounted for in estimating class NPP and NEP values.

The original Landsat TM image had a 28 m resolu-

tion; Turner *et al.* (2000) generated new resolutions of 50, 100, 250, 500, and 1 000 m. The resolutions were coarsened using a 3 × 3 moving window technique. The effects of scaling up on land cover, biomass and carbon flux were assessed as the difference between the percent (land cover class) and totals (biomass and F_c) for the study area at the coarsened resolution with that of the 28 m resolution. Using a different image and a comparable approach we have generated similar results (Fig. 4).

As the images were scaled up to 250 m resolution, the fine-scale patch heterogeneity diminished and the patch structure created by harvesting predominated. Clearcut patches merged and the harvesting-induced structure was lost when the resolution is coarsened above 250 m. The maximal error increased rapidly up to the 250 m resolution; errors did not increase as quickly after that scale. At the 500 m resolution the two least-represented vegetation classes (open, and closed-mixed) were no longer represented. Agreement of the 1 000 m resolution was 42% of the 25 m resolution. The estimates for total tree biomass increased by nearly one-third as the resolution was coarsened. This increase was due to an increase in the area of the closed, old conifer class. NPP decreased consistently with coarsening resolution and was 12% lower at the coarsest resolution than at the most fine. NEP did not change as much as NPP since errors canceled each other out: the loss of open, and closed-mixed classes counteracted the effects from over-representation of the closed-conifer old class. Unfortunately land classification errors will not always cancel out on another: errors in land classification can be compounded when determining productivity since estimates of NEP and NPP from remote sensing depend on land cover.

Turner *et al.* (2000) emphasize the role that scale plays in our predictions of carbon flux. The resolution of human disturbance in this study was less than 1 km; and resolutions down to 30 m were critical. The importance of the finer resolutions points to difficulties that may arise when we try to validate global carbon budget models. These models have traditionally had resolutions coarser than the resolution of the landscape. Similar efforts in predicting NPP using various computer models are being made, and recognition of data resolution (e.g., 500 m to 1 degree) in calculating carbon storage and flux is seriously discussed (Zheng *et al.*, 2003; McGuire *et al.*, 1992).

Turner *et al.* (2000) report a loss of heterogeneity with increasing scale, which result in differing predictions for different scales. A loss of heterogeneity necessarily implies loss of information on structure. Loss of this information may be especially critical in landscape studies for which ecosystem position and landscape structure have definite impacts on models of system function. Critical information may be preserved or identified by modifying existing scaling procedures (King, 1991; Jarvis, 1995) or

developing new scaling frameworks and methods (Wu , 1999 ; Hay *et al.* , 2001).

Methods gaining multiscale information can ensure that we also capture the variation across spatial and temporal scales . Moreover , as one scales up from ecosystems to the landscape , new features (e.g. , edges and spatial configuration) are generated , and synthesis at broader scales should not be additive (Turner *et al.* , 1989). Turner *et al.* (2000) also underscore the importance of selecting spatial resolutions that are considerably finer than the scales of relevant heterogeneity in the system . Selecting such a resolution will ensure that cells are homogenous : relatively few cells are comprised of mixtures of classes . However , determining the proper scales that are most appropriate for examining particular phenomena is not always simple or straightforward . Important information can be lost with scaling up , which can undermine the validity of the scaling . Research that explicitly considers scale dependence is a means to understand what information is lost and what information is gained when we examine phenomena at broader perspectives .

4 Detecting temporal scales from trace gas flux

Scale dependencies occur across temporal scales as well as spatial . Baldocchi *et al.* (2001) illustrate the importance of detecting/selecting proper temporal scales and scale relationships with carbon flux data from on micrometeorological methods . Detecting scale of relevant influence on measurements and processes is a good first step that will allow research across multiple scales to become commonplace . Baldocchi *et al.* (2001) examined the temporal variation of CO₂ flux (F_c) and water vapor flux (F_{H_2O}) between a temperate deciduous forest and the atmosphere . The trace gas flux densities were measured by the eddy-covariance method in an approximately 50-year-old mixed-species , broad-leaved forested study site near Oak Ridge , Tennessee , USA . The drivers of F_c change across temporal scales . For example , Baldocchi *et al.* (2001) noted that sub-hourly flux was driven by changes in photosynthesis , stomatal conductance , and respiration . These processes in turn respond at varying rates to sunlight and leaf temperature (e.g. , photosynthesis responds more quickly than leaf respiration) . Diurnal variation was driven by daily cycles of solar radiation , air and soil temperature and humidity . Weekly variation was driven by weather changes associated with passing high and low pressure fronts . Monthly (seasonal) variation was driven by changes in sun position , ecosystem phenology . Inter-annual variation was driven by large-scale climatic features (Baldocchi *et al.* , 2001) .

Baldocchi *et al.* (2001) identified periods of peak variation in meteorological variables , and carbon flux through spectral analysis . They examined co-spectra of the fluxes and meteorological variables to find coherence and phase lags among peaks . They also evaluated the trace gas exchange model CANOAK (Baldocchi , 1997)

Fig.4 Landsat image degradation similar to the technique used by Turner *et al.* (2002)

Coarsening the resolution changes landscape heterogeneity

by comparing the spectrum from model outputs of annual CO₂ exchange with the power spectrum from measured values. Spectra for each year(1995-1998)for five plant and meteorological variables were produced : leaf area(LAI), photosynthetically-active radiation (PAR), air temperature (T_a), wind speed (*u*), and atmospheric pressure (*P*). On the annual time series , PAR and T_a exhibit distinct spectral peaks at 12 : 00 , 24 : 00 (corresponding to diurnal Earth rotation), and 3-6 month time scales (corresponding to distinct seasonal climate differences). The carbon flux exhibits distinct low frequency peaks associated with peaks of LAI , PAR , and T_a . Carbon flux also exhibits multiple-day peaks possibly associated with the passage of high and low pressure fronts and a month-long spectral gap over which no meteorological variables have influence. On a continuous 4-year time series , Baldocchi *et al.* (2001) found spectral peaks at periods of 342 , 120 , 52 , 17 , and 3.7 days (Fig. 5). Interesting scale dependent phenomena arose such that the 120- and 52-day periods arose in the multiyear time series while the longer semi-annual , and quarter-annual peaks were lost. Baldocchi *et al.* (2001) also precisely related the meteorological and F_c spectra by examining phase lags and peak correspondence. They also were able to produce a similar spectrum of F_c under conditions of adequate moisture with CANOAK (Baldocchi *et al.* , 2001).

Fig.5 Temporal scales of carbon flux variation as determined by spectral analysis

Both the general trend and peaks in the spectrum indicate periods of variability (Reprinted from Baldocchi *et al.* (2001))

A spectral analysis of biosphere-atmosphere trace gas flux densities and meteorological variables across hour to multi-year time scales , 14 , 2001 , with permission from Elsevier Science

By determining the scales of peak variation , we can design our studies to best capture that variation. Several statistical and mathematical approaches exist for detecting scale properties of spatial and temporal data (Xia & Clarke , 1997). Sophisticated techniques such as spectral analysis , variograms , wavelet analysis , and fractal geometry would ensure that we identify active scales at which we can conduct our studies. Since processes vary across

both temporal and spatial scales , research must address these cross-scale aspects simultaneously.

5 Conflicting results across scales

Our final case study comes from a peatland mesocosm experiment. The objectives were to examine the effects of heat and water loading on biophysical processes such as net radiation (R_n), reflection , horizontal and vertical heat fluxes , soil heat storage (G), and evapotranspiration (ET) at various temporal scales : hourly , daily , seasonally , and yearly.

Construction of a peatland mesocosm facility in northern Minnesota , USA , began in the autumn of 1993. Twenty-seven peat monoliths each from a bog and fen were extracted and placed in insulated tanks. The study consisted of a factorial design of three water levels and three heat treatments. Focus was on responses of plant community composition , vegetation surface structure and geometry , vertical temperature profile , climatic variables , nutrient fluxes and availability , methane and CO₂ fluxes , whole-system carbon exchange , and energy fluxes. Since 1998 , R_n , G , and vertical soil temperatures (T_s at 5 , 10 , 25 , and 40 cm depths) have been measured every 20 seconds and means stored at 30 minute intervals. Vegetative cover , *Sphagnum* moss cover , and depth were measured during the summer of 1998. Snow depths were recorded weekly during the snow season.

There were large differences in G and T_s between the fen and bog mesocosms. The ecosystems have distinct feedbacks between vegetation and energy. The fens were generally warmer than the bogs at all depths. The bogs ' R_n , G , and T_s responses appeared more sensitive than the fens. Heat loading lengthened the growing season by 10-30 days , with the duration depending on the interaction of heat loading and water level. The heat loading produced the greatest effects during the winter and spring , with lesser effects recorded in the autumn. Perhaps most importantly , peatlands with infrared heat loading were significantly (more than 3 °C) cooler than unheated plots during the winter (Fig. 6). The results suggest that global warming can cause soil cooling during the winter and early spring seasons. However , we must properly constrain our conclusions. These results are not likely to occur over neither the entire season , nor the over entire expanse of the boreal peatlands. Such effects will likely occur at the southern edge of snow zones in temperate areas , or in years when snowfall is significantly lower than average.

When conducting our studies we inevitably arrive at conclusions. Just as we must take care to include scale in our experiments , we must carefully formulate our conclusions to correspond to the scale of inquiry. Allen (1998) noted that as ecological research moves up-scale , there is a need to be more " inclusive and outward looking ". Indeed , modern funding and publishing procedures promote

inclusiveness, with many editors and review boards asking for “greater significance and applicability”. Such an emphasis leads some researchers to improperly generalize from one level of organization or analysis to another. When incorrect, such over generalizations are not helpful to scientific advancement or credibility. Special attention must be made when concluding so as not to over-extend our results.

Fig. 6 Soil temperature (1 cm) in bogs with intermediate water loading and three different infrared head loadings

HT0, HT1, and HT2 represents head loading of 0, 97, and 167 $\text{W} \cdot \text{m}^{-2}$, respectively. Heated plots can have a lower soil temperature, likely because of higher sensible heat loss without snow cover during the winter and early spring

6 Conclusions

Wu and Hobbs (2002) have identified scaling as a key research priority in the theory and practice of landscape ecology. The case studies described herein exemplify several standing questions identified by Wu and Hobbs (2002): how to extrapolate information gained at small scales to broad scales or vice versa, how to scale up or down across heterogeneous landscapes, how to determine appropriate scales for understanding particular phenomena, and how to extrapolate experimental results to real world systems.

Perhaps most challenging question we face is precisely how to formulate and test hypotheses that examine phenomena across appropriate spatial and temporal scales (Caldwell *et al.*, 1993; Ustin *et al.*, 1993; Friedl *et al.*, 1995; Cullinan *et al.*, 1997; Stewart *et al.*, 1998). Like Baldocchi *et al.* (2001), much work has focused on identifying those appropriate scalar thresholds and domains of scale (Bian & Walsh, 1993; Walsh *et al.*, 1997; Soriau, 1994; Grossi *et al.*, 2001). Sophisticated techniques such as spectral analysis, variograms, wavelet analysis and fractal geometry have the potential to detect scales, but may need more rigorous testing in natural systems (Wu, 1999; Wu & Hobbs, 2002). Given the ramifications scale has on our studies, proper scale identification is still needed as a guide for experimental design. As scales are identified sampling schemes need to incorporate them in novel ways (Oline &

Grant, 2002). Approaches that integrate detailed field measurements across multiple scales, scale-flexible modeling, remote sensing and GIS, multiple scaling strategies, and experimental manipulations will likely prove the most effective in future studies of scale.

The processes responsible for the patterns that we measure can act on different temporal and spatial scales. If we do not recognize the cross-scale dynamics, but rather, measure the processes as if they act at the same scale, we could gain conflicting information that complicate our ability to make conclusions. When we identify the scales over which different forces act, we can further examine those scales for other active forces. A perspective including multiple scales is crucial if we are to develop a fuller understanding of complex natural phenomena.

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