Scale

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A note from the authors: This version is static and as such has lost both formatting for viewing ease and important interactive elements like the ability to quiz oneself and click on key terms for hover-box definitions. We highly recommend using this module in it's interactive form by visiting the following link:
https://passel2.unl.edu/view/lesson/ab491bda9f88

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Overview and Objectives

Overview - What Will You Learn in This Lesson?

This lesson discusses what scale is and how it relates to understanding and interpreting natural phenomena.

Objectives

At the completion of this lesson, you should be able to:

1. Explain the meaning of scale in terms of grain and extent in space and time (Q 1-4)
2. Explain why different patterns can emerge from different scales (Q 5)
3. Differentiate between functional and observational scale (Q 6)
4. Explain how processes at broad scales can constrain those at fine scales (Q 7)
5. Explain how fine-scale processes can become broad-scale processes (Q 8)

Correct answers to all questions are highlighted

Introduction - What Is Scale?

Scale refers to the spatial and temporal dimension of natural phenomena and provides context for observations and measurement of objects, time, processes, and other phenomena (Turner and Gardner 2015). All observations have a spatial and temporal scale. Changing scales allow us to zoom in or out in time and space. In time, this is like looking at a day in hour increments and then zooming into an hour with minute increments. In space, this is like zooming in or out of a google map. The two components of scale are grain and extent (Weins 1989). Understanding how to properly apply scale is fundamental to measuring, understanding, and interpreting the world around us.

Grain is the size or duration of the individual units of observation (Weins 1989). Often referring to a plot size, pixel resolution, grid cells or the minimum unit of time from which observations are taken from. Extent is the entire window from which all observations are taken, referring to an area or time span. Extent and grain define the upper and lower limits of resolution, respectively, and are analogous to the total area and mesh size of a fishing net (Weins 1989). Extent is reflected in the total size of the fishing net and grain is reflected in the mesh size.

Consider the importance of using an appropriate net for catching large fish in a study. To capture large fish we need a large enough net (extent) so that a reasonable number of fish will swim into the net. We also need a mesh size (grain) that will allow the large fish to partially pass through and get stuck in the net. If the net is too small not enough fish will encounter the net. If the mesh size is too large the fish will swim through the net and escape. If the mesh size is too small the researchers will only catch small fish. In order to catch large fish, fisheries researchers need to carefully select an appropriate net, otherwise they will not get the results they desire. This illustrates the importance of selecting an appropriate scale to meet an objective. Misleading results and undesirable outcomes occur when scale is misapplied or ignored.

Spatial Scale

Spatial Scale: The entire area over which observation or management occurs (i.e., extent) and the smallest unit of observation or management action (i.e., grain). Spatial scale is changed when either extent or grain, or both are altered. Various spatial scales are shown in Figure 1 and illustrate differences in measurements arising from different scales.

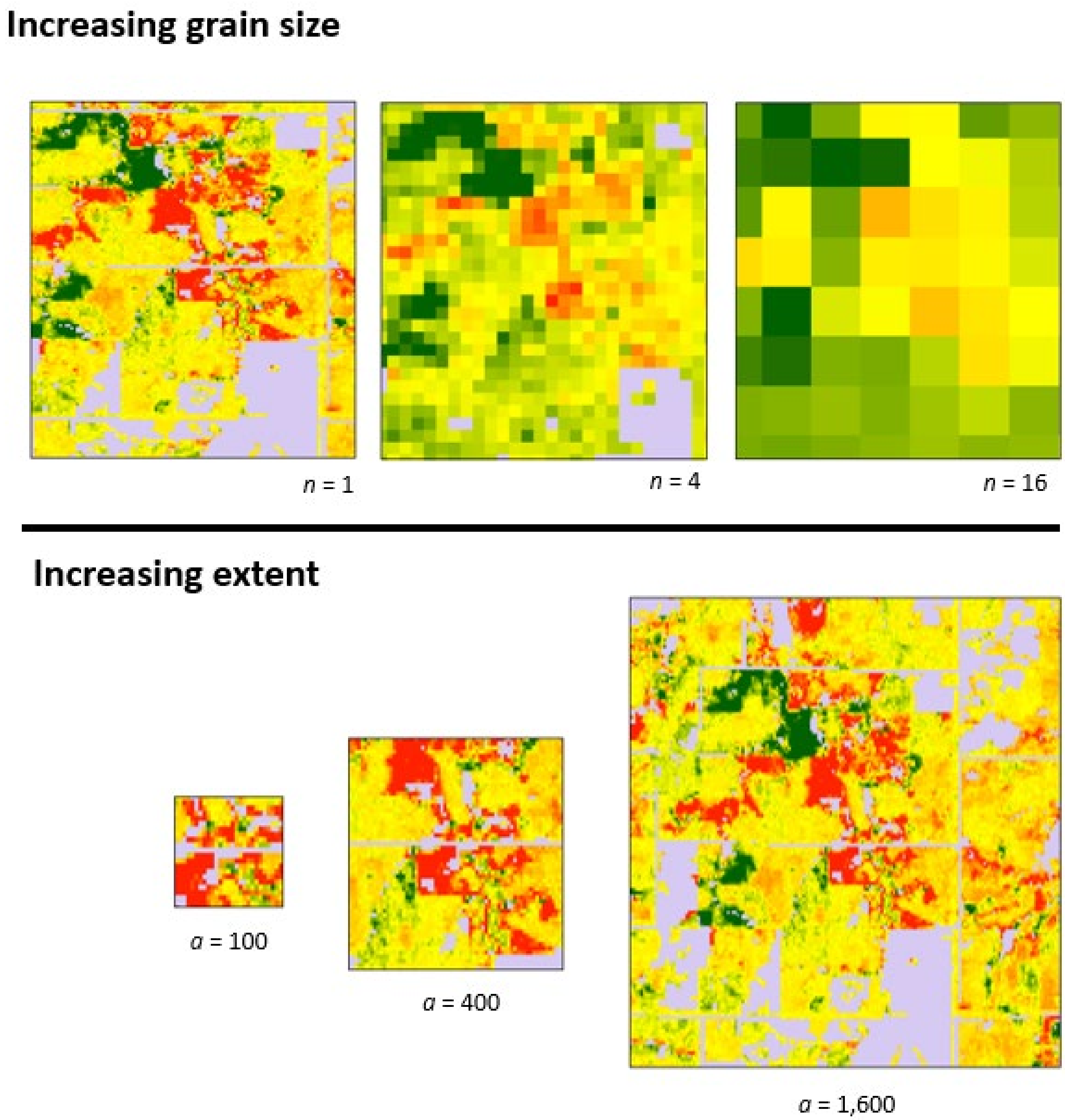


Figure 1. Two components of spatial scale, (a) grain and (b) extent. The number of cells aggregated to form the new data unit (i.e., new grain size) is indicated by n; total area, or extent is indicated by a. Figure is adapted from Turner and Gardner (2015)

Temporal Scale

Temporal Scale: The entire timespan of interest (i.e., extent) and the smallest unit of time over which observations are aggregated (i.e., grain). Temporal scale is changed when either extent or grain, or both are altered. In Figure 2, spatial scale is constant and temporal scale is changed, illustrating how different patterns emerge from different temporal scales.

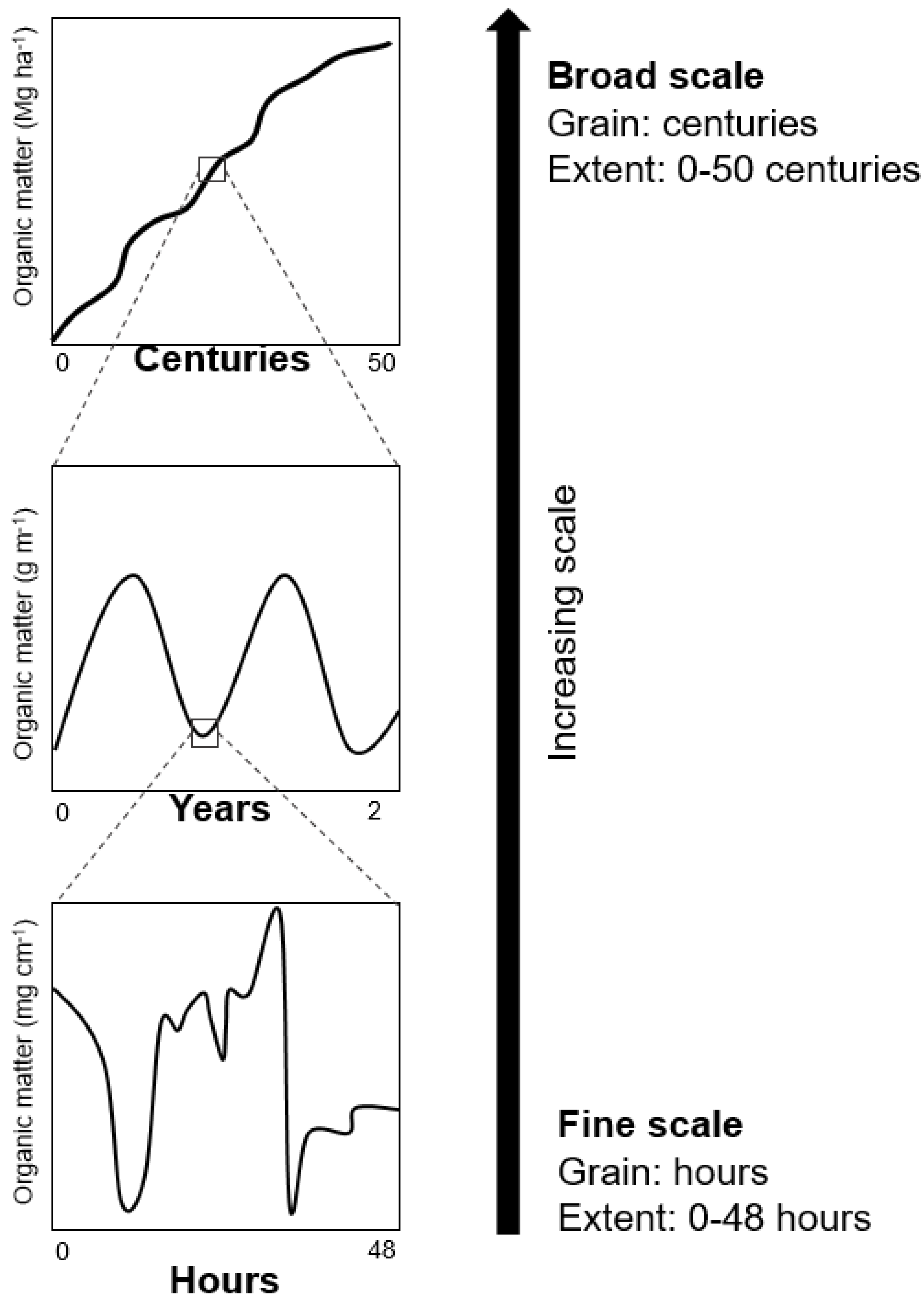
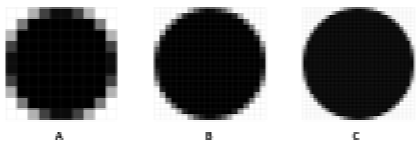


Figure 2. Changes in soil organic matter content viewed from different temporal scales. An extent of days (lower panel) shows rapid fluctuation of soil organic matter from wind and insects. At an extent of years (middle panel), seasonal patterns of organic matter decomposition

become apparent. At an extent of centuries (upper panel), organic matter accumulates with oscillations from changes in the vegetation community. Adapted from Turner and Gardner (2015) and from Sollins et al. (1983).

Question



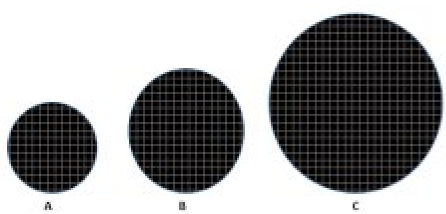
What image depicts the finest grain size?

A

B

C

Question



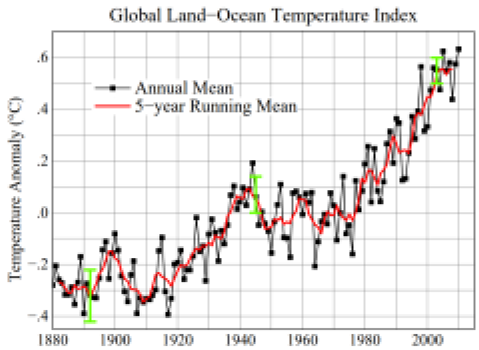
What image depicts the largest extent?

A

B

C

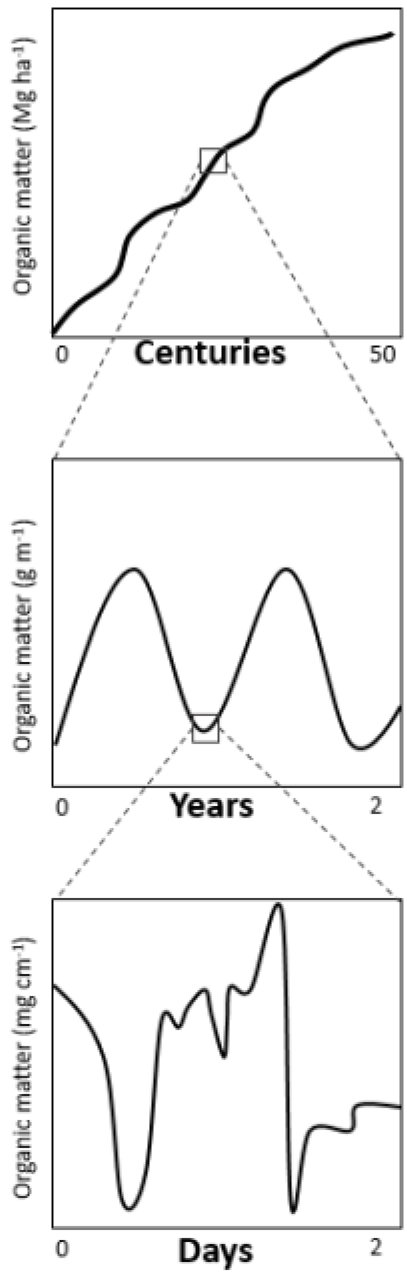
Question



What is the spatial and temporal extent depicted in this figure from NASA?

A. spatial extent is global, temporal extent is global since the beginning of time
B. spatial extent is global, temporal extent is from 1880-2010
C. spatial extent is local, temporal extent is from 1880-2010
D. spatial extent is local, temporal extent is global since the beginning of time

Question



What is the broadest temporal extent depicted in the Figure below?

A. centuries: 0-50
B. years: 0-2
C. days: 0-2
D. Mg ha^-1
E. g m^-1
F. mg cm^-1
G. not enough information provided

Question

Fine-scale events can become broad-scale events when which of the following occurs?

A. They occur randomly
B. They occur at the same time over a broad extent
C. They occur infrequently
D. They occur quickly

Effects of Changing Scale - What Happens When We Look at the Same Location in a Different Way?

What happens when we change grain or extent?

The extent of a scale can be changed independently of grain, that is, a small grain can be maintained as extent increases in size or time (Fig. 1b) (Turner and Gardner 2015). Grain and extent are often positively correlated, in that, as extent increases so does grain size (Wiens 1989; Turner and Gardner 2015). Changing the scale of observation (extent and/or grain) leads to changes in the variability between observations. For example, when extent is held constant, increasing the grain size results in less variability among observations. This is because fine differences are "smoothed" or averaged when large grain size is used to make observations (Weins 1989). When grain is held constant and extent is increased in non-uniform (i.e., heterogeneous) environments the variation between observations (grain) increases because increasing the extent incorporates more variety within the area or time of interest (Weins 1989).

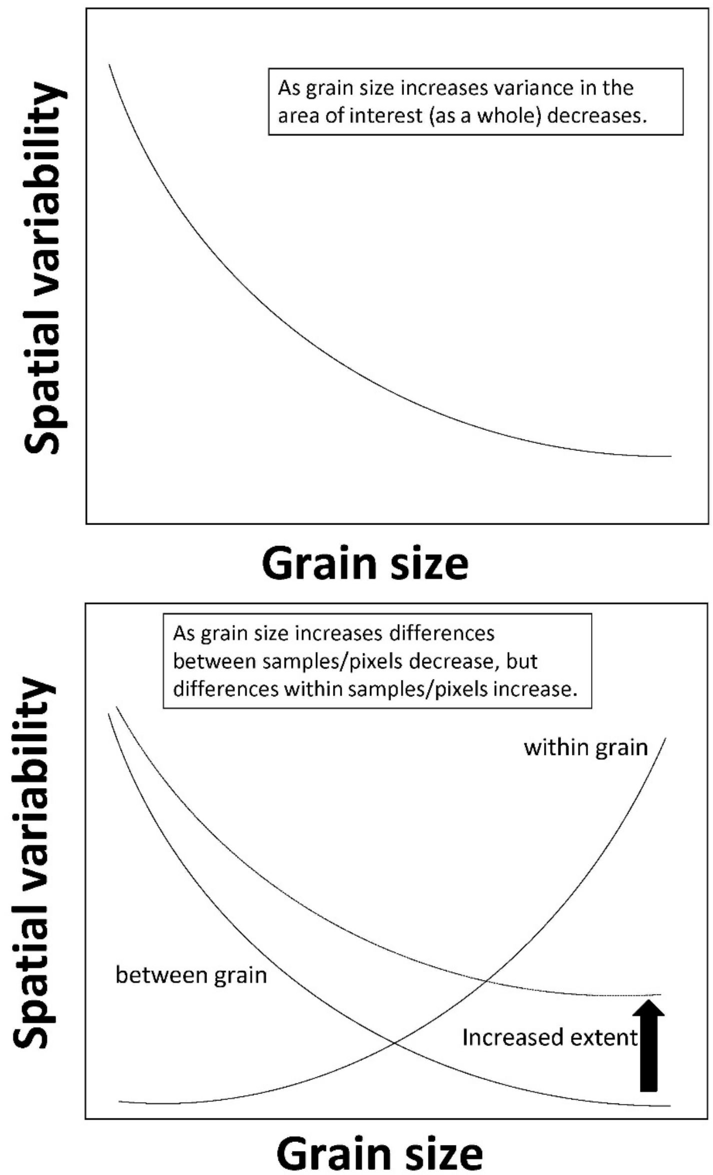


Figure 3. Relationships between variability and grain size. As grain size increases, the amount of variation between observations (e.g., plots) decreases (top panel). At the same time, variation within individual grains (e.g., plots) increases with increasing grain size (bottom panel). Figure adapted from Weins (1989).

Effects of Scale

Different patterns in nature emerge when the scale is changed. Below we provide examples from the scientific literature. In the examples it is important to remember that scale is associated with both time and space.

Real World Examples

In forests of the north-eastern United States, Least Flycatchers negatively influence the distribution of American Redstart (both are bird species) at the extent of 4-ha plots. However, at broad regional extents, these species are positively associated. This is expected to occur because at broad scales habitat suitability for both species overrides the influence of competition between these species at fine scales. Example is from Weins (1989).

In the Great Barrier reef, the distribution of fish species at the scale of coral patches is unpredictable due to chance events influencing the occurrence of individual species. However, at broader scales of reef systems, species composition is highly predictable. Example is from Weins (1989).

Plant physiologists studying plant transpiration at the scale of individual leaf surfaces have concluded that stomatal mechanisms regulate transpiration. While, meteorologists working at broad scales have concluded that climate is the principal control. Example is from Weins (1989).

Similarly, at fine scales litter decomposition rates are explained by the properties of the litter and decomposers, but at larger scales climate variables explain variation in decomposition rates. Example is from Weins (1989).

Fine scale studies of cattle grazing in the shortgrass prairie show that cattle select for specific elements of plant communities on the basis of short-term foraging decisions. However, at broader scales, cattle select vegetation types in proportion to their availability within landscapes (i.e., no evidence of preference). Example is from Weins (1989).

At finer scales, self-sustaining populations of lesser prairie chickens (shown by white line in figure 4) occurred in areas with more cropland cover compared to declining populations (shown by green line in figure 4). However, at broader scales self-sustaining populations occurred in areas with less cropland cover compared to declining populations (Fig. 4). Example is from Fuhlendorf et al. (2002).

“Soil scientists investigating changes in soil organic matter found that different patterns emerged when the temporal scale was changed. An observation window of years (i.e., temporal extent) showed seasonal changes in soil organic matter. While, an observation window of centuries showed long-term increases in soil organic matter tied to successional changes in the plant community. Example is from Sollins et al. (1983).”

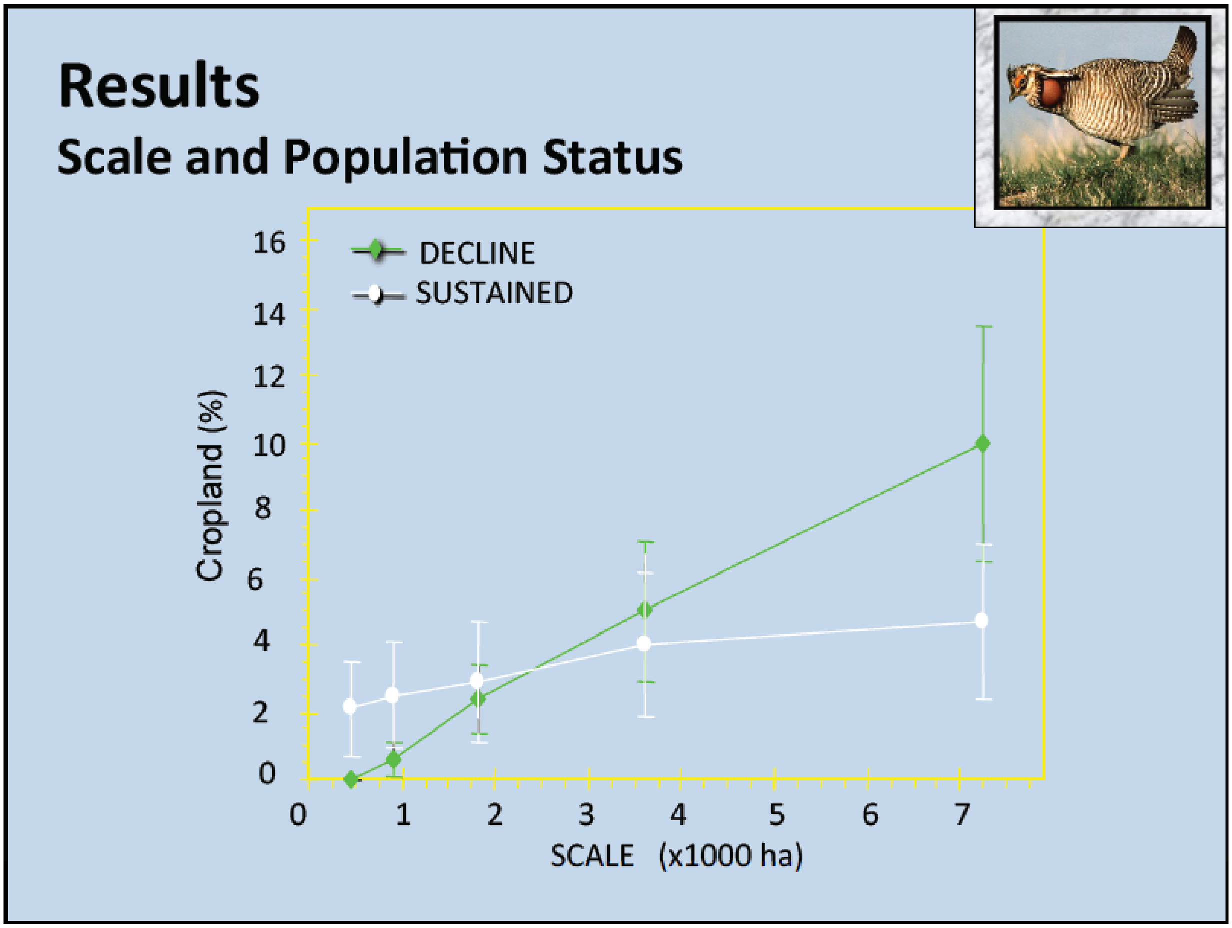


Figure 4. Cropland cover at various observational scales surrounding self-sustaining and declining populations of lesser prairie chickens. Points along lines show the amount of cropland cover associated with lesser prairie chicken populations at multiple scales. Figure is adapted from Fuhlendorf et al. (2002).

Question

Consider a map of global temperatures in 2020, which of the following best describes what would happen if the pixel size (i.e., grain size) was increased?

A. Variance among pixels would increase
B. Variance among pixels would decrease
C. Impossible to know
D. Global temperature would appear to be decreased
E. Global temperature would appear to be increased

Operationalizing Scale: Functional and Observational - Are There Different Types of Scale?

Functional scale, also referred to as the “scale of the phenomenon” (MA 2005), or the “absolute scale” (Turner and Gardner 2015), is the magnitude or rate of a process of interest (Cumming et al. 2006), referring to the extent or duration over which a phenomenon has an impact (MA 2005). For example, grazing by a herd of bison or plant invasions occur in specific dimensions of time and space. Functional scale reflects the “true” scale at which a system property (e.g., forage availability) affects a process of interest (e.g., grazing) (Li and Reynolds 1995; Fuhlendorf et al. 2017).

Observational scale, also referred to as arbitrary scale (Weins 1989), is a human construct used for measurement and consists of grain and extent (MA 2005). Observational scale may or may not accurately depict a functional scale and can influence how patterns are interpreted. Remember, functional scale reflects the scale(s) at which a system property affects a process (Li and Reynolds 1995), thus proper selection of scale affects our ability to understand and manage ecological processes. All observational scales are arbitrary--just because observational scales seems “right” provides no assurance that they perfectly represent the functional scale (Weins 1989). Selection of useful observational scales requires thinking about the functional relationships between a system property and the scale at which that property influences a process of interest. For example, what scales are relevant to a beetle versus a bison selecting a home range? Or a germinating acorn in a forest? Additionally, many natural phenomena are influenced by multiple scales and therefore require multiple observational scales to understand (e.g., real world examples provided earlier in this lesson).

Some considerations when selecting an observational scale

How big of an area or window of observation (i.e., extent) is needed to represent the process of interest? Considerations should include the amount of area or time needed to represent the full range of variability of the process of interest. For example, to understand seasonal weather patterns, an observation window of many years is needed.

What grain size is needed to make appropriate observations? Considerations include the size of what is being measured (e.g., grasses versus trees), how often a process of interest occurs, and the rate at which it occurs. For example, studying events that happen very quickly (i.e., earthquakes) may require that observations are taken over the course of seconds rather than hours or days.

What is an appropriate extent and grain combination? Some studies may require large extents with coarse grain, while, others may require large extents with fine grain. For example, seed dispersal may occur over a large area (i.e., extent), but germination may depend on very fine differences in soil, moisture, and light exposure that can only be appropriately represented with a small grain size.

What other scales are important? Processes at finer or broader scales may influence a studies results. For example, apparent population growth rates in wildlife populations could be driven by factors occurring at broader scales compared to the observational scale used in a study.

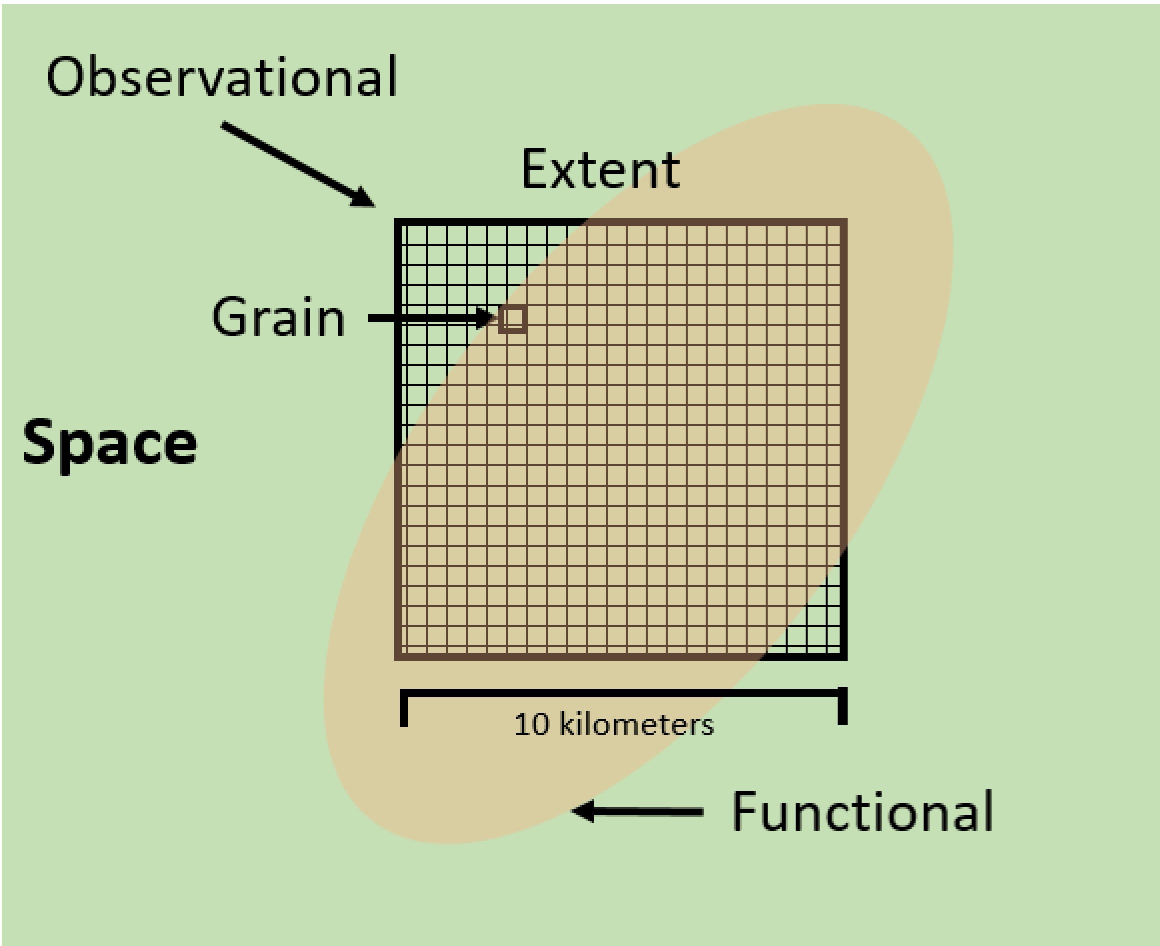


Figure 5. Conceptual example of observational and functional scale. Figure created by Dillon Fogarty

Question

Which of the following best describes observational scale?

A. The scale of measurement
B. Scale of phenomenon
C. Functional scale
D. Time
E. Space

Scale Mismatches - Can Scale Be Misused?

Scale mismatches arise when the observational scale does not align with goals and objectives related to the functional scale of a natural phenomenon (Cumming et al. 2006). In studies, scale mismatches can arise when inappropriate spatial and temporal scales are selected to make observations, or when variables are used that are not relevant to the data at the selected scale. Scale mismatches in studies often results in unexpected and misleading findings. In management applications, scale mismatches arise when a natural phenomenon is managed or regulated at inappropriate scales and results in the failure to meet a desired goal. Scale mismatches in management applications often occur when the rate of a phenomenon in time and space does not match the rate of management. For example, when controlling the spread of invasive species, a scale mismatch arises when management of invasive species is outpaced by expansion of invasive species (Roberts et al. 2018).

Multiscale and Cross-Scale Phenomena

Broad Scales Constrain Fine Scales

Many natural phenomena occur at multiple scales and different factors are better at explaining these phenomena at different scales (Turner and Gardner 2015). Cross-scale interactions occur when processes at one scale affect those at higher or lower scales (Allen et al. 2014). Hierarchical confinement is a specific case of cross-scale interactions and refers to when broad scale processes constrain a phenomena occurring at finer scales nested within the broader scale (Walker et al. 2006; Turner and Gardner 2015). In other words, factors that are relevant to broad scale (e.g., climate) constrain the influence of fine scale factors on an observed phenomena (Turner and Gardner 2015). For example, hierarchical confinement occurs when lake temperatures constrain what fish species occur in the lake, despite the presence of suitable vegetation and prey in the lake.

Fine Scale Patterns Become Broad Scale Patterns

Another case of cross-scale interactions is when fine scale phenomena become broad scale phenomena when they occur at the same time (i.e., synchronously) at the extent of a broad scale. This is referred to as “scaling up” or a “revolt” and helps explain why invasions, pest outbreaks, disease epidemics, economic depression, climate change, etc. occur (Holling 2001). Processes like births and deaths that occur asynchronously (or randomly) in time and space at a scale of interest result in relatively stable conditions and do not emerge as trends at broader scales. Thus, trends at small scales do not reflect large-scale trends unless there is synchrony at the extent of the larger scale.

For example, increasing invasive species presence on a single land parcel does not necessarily mean that the species is increasing at the regional scale because the species may be declining on other land parcels. However, when invasive species presence increases across many land parcels at the same time at the extent of the region, regional scale trends of increasing invasive species emerge. A key implication is that fine scale processes occurring over large extents can influence systems at broad scales. [example is from CRE]

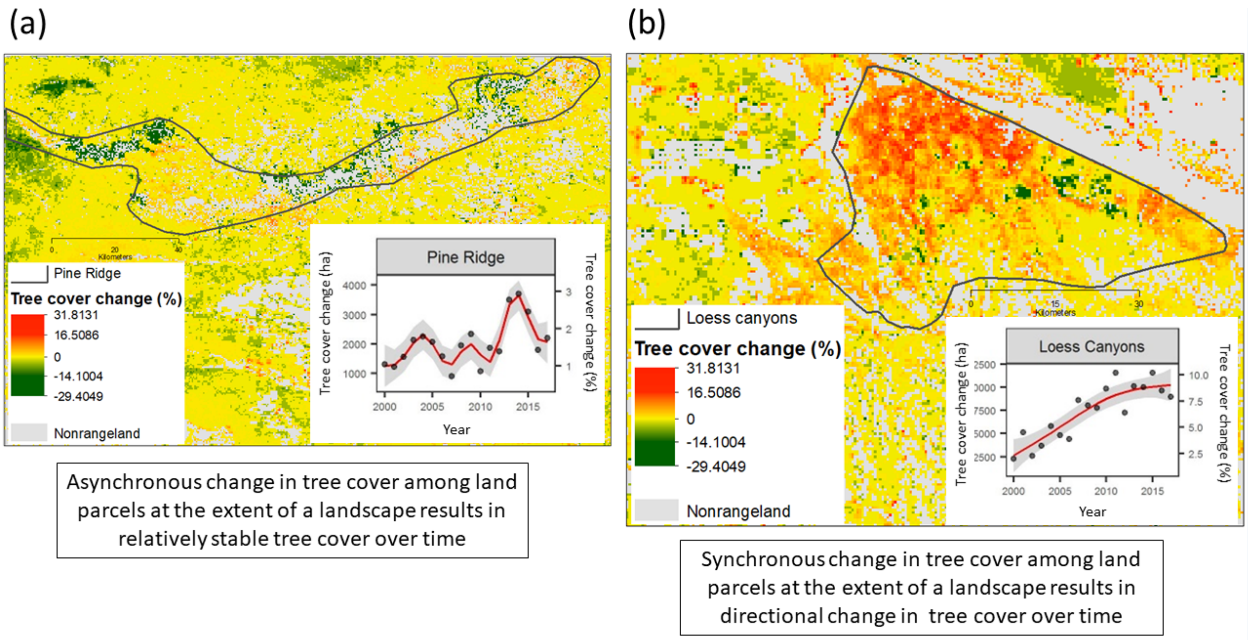


Figure 6. Example of tree cover changes in two landscapes over the course of 17 years. On the left panel (a), local changes in tree cover did not result in directional change at the landscape scale (tree cover fluctuates but is relatively stable over time). Local increases in tree cover (red) were offset over time by local decreases in tree cover (green) in other parts of the landscape. On the right panel (b), local increases in tree cover (red) resulted in an increase in tree cover at the landscape scale. In this landscape, local increases in tree cover occurred over a large proportion of the landscape and were too widespread to be offset by decreases in tree cover that occurred in other parts of the landscape (green). Figure created by Dillon Fogarty.

Question

Which of the following is an example of a broad-scale constraint?

A. Climate effects on regional crop production
B. A pest outbreak reduces forest cover
C. Local restorations lead to wildlife population growth

Utility of Scale - How Can Scale Be Used in Real-World Management?

Scale is a concept that applies to all aspects of management and is a critical component of achieving management goals. Failure to properly account for scale is a widespread issue in the management of natural resources that often leads to scale mismatches and failure to meet goals. To avoid scale mismatches in management it is important that managers consider multiple scales. Zooming in and out among scales will help identify what is needed, how much, and how fast management needs to occur in order to achieve a goal. Understanding when and where hierarchical confinement occurs is also important to avoiding unnecessary investments of time and money that are not capable of achieving a desired result. The following page provides a practical example of how scale can be used in a real-world application.

Scale Example - A Multi-Scale Approach to Lesser Prairie-Chickens

How do landscape patterns affect animals? Do animals respond differently to broad-scale patterns versus fine-scale pattern? How do animals respond to broad-scale land cover change compared to fine-scale changes? These were questions asked in a study of Lesser Prairie-Chickens in Oklahoma and Texas that can help us understand real-world implications of scale (Fuhlendorf et al. 2002).

In their study, the researchers looked at 10 separate populations of Lesser Prairie-Chickens in the panhandles of Oklahoma and Texas. They then classified each population as either “Declining” or “Sustained” based on decades of surveys.

Next, the researchers looked at the land around each population. At multiple scales, the researchers measured how much land consisted of cropland and how tree cover had changed over time. They used the same grain but different spatial extents including 450, 900, 1800, 3600, and 7200 hectares. This allowed them to look for relationships among scale, land cover, and Lesser Prairie-Chickens.

To picture how much land the researchers studied, it is important to know how big a hectare is. One hectare is approximately equivalent to two gridiron football fields. At the smallest scale (450 hectares) the researchers studied an area equivalent to 900 football fields surrounding each population. They scaled this up step-by-step until they reached the broadest scale (7200 hectares), which was the equivalent of 14,400 football fields, or 1.5 city blocks, surrounding each population.

The researchers found several important takeaways from their study (see Figure 1).

Researchers found that at finer scales (450 ha, 900 ha, and 1800 ha) the sustained populations had slightly higher percentages of cropland surrounding them. But at the broadest scales (3600 ha and 7200 ha) the declining populations had more cropland, while the sustained populations had similarly low cropland cover across all scales. This shows that influence of cropland cover on Lesser Prairie-Chickens is scale dependent. In other words, results from one scale do not match relationships at other scales.

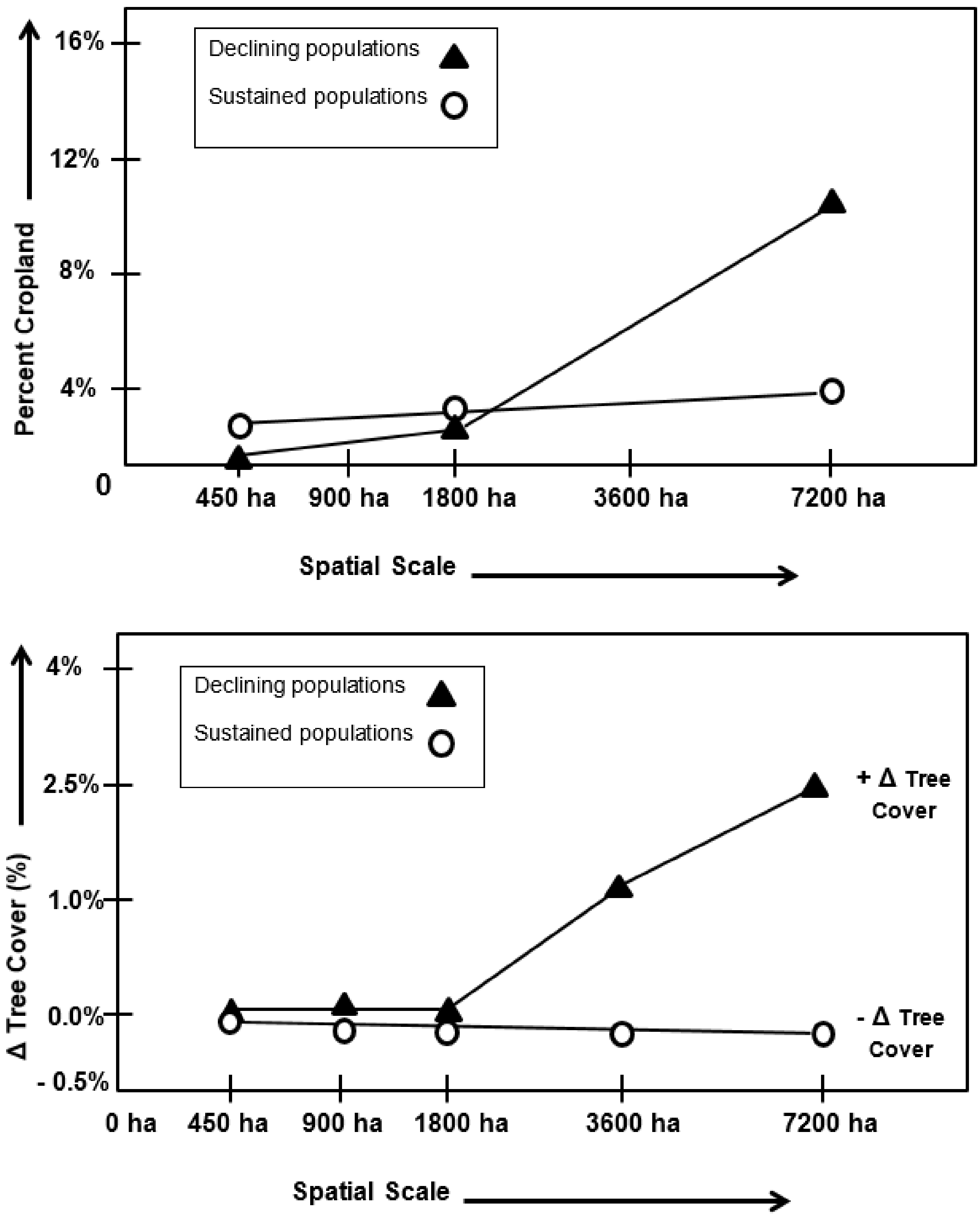


Figure 7. Adapted from Fuhlendorf et al. 2002

Source:

Fuhlendorf, S. D., Woodward, A. J. W., Leslie Jr., D. M., and J. S. Shackford. “Multi-scale effects of habitat loss and fragmentation on lesser prairie-chicken populations of the US Southern Great Plains.” Landscape Ecology 17 (2002): 617-628.

When studying the effect of changing tree cover on Lesser Prairie-Chickens at various scales, they found that at finer scales (450 ha, 900 ha, and 1800 ha) there was very little difference between declining and sustained populations. However, at the broadest scales (3600 ha and 7200 ha), tree cover changed very little for the sustained populations but increased around the declining populations. This indicates that Lesser Prairie-Chickens respond to increasing tree cover at broad scales. However, this does not mean that Lesser Prairie-Chickens are not sensitive to tree cover at fine scales. Lesser Prairie-Chickens avoid trees at fine scales, thus no populations occurred in areas with large increases in tree cover at fine scales

These findings are important to understand, especially for those who want to help the Lesser Prairie-Chicken, a species that has been in decline across much of its range. Firstly, the results from tree cover change are a warning to land managers who wish to manage for the Lesser Prairie-Chicken. Scale mismatches may occur when managers focus on removing trees at fine scales (i.e. <500 ha), but do not consider tree cover changes at broader scales (>3500 ha). To avoid declining prairie-chicken populations, tree cover must be reduced at broad scales.

In addition, the influence of cropland on Lesser Prairie-Chickens is scale dependent. At fine scales relatively low levels of cropland appears to have little influence on populations but at broad scales greater cropland cover is associated with declining populations. Thus, areas with high levels of cropland at broad scales are poorly suited for Lesser Prairie-Chicken reintroduction or local habitat improvement investments.

In summary, this example illustrates the importance scale in interpreting the influence of land use on wildlife populations. Different implications arise from different scales, thus it is increasingly important that we reconcile management goals with scale.

Summary - What Did We Learn?

Scale represents the physical dimensions of time and space for natural phenomenon and human observations. Observational scales are a human construct used to observe natural phenomena and are measured in terms of grain and extent. Functional scales refers to the area and timespan over which a phenomenon of interest has an impact. Many phenomena occur at multiple scales where there is not a single best scale, yet, some observational scales are better than others. Thus, scale is always a critical component of interpreting information because different conclusions can emerge from different scales. One way to overcome the issue of scale-dependent conclusions is by using multiple scales to understand or manage a natural phenomenon.

Key considerations

Different patterns emerge from different scales.

Patterns emerge from processes occurring at multiple scales and information from multiple scales is required to understand these natural phenomena.

Processes at broad scales can constrain the influence of processes at smaller scales. Recognizing this is essential in prioritizing management actions that are most likely to achieve a desired result.

Processes that occur at the same time across a broad extent result in directional changes. Therefore, fine-scale phenomena can become broad-scale phenomena when they occur synchronously at large extents. This is a fundamental concept for management because most management treatments are applied at scales that are finer than the scales associated with management goals.

References and Further Reading

References

Allen, C. R., Angeler, D. G., Garmestani, A. S., Gunderson, L. H., & Holling, C. S. (2014). Panarchy: theory and application. Ecosystems, 17(4), 578-589.

Chapman, R. N., Engle, D. M., Masters, R. E., & Leslie Jr, D. M. (2004). Tree invasion constrains the influence of herbaceous structure in grassland bird habitats. Ecoscience, 11(1), 55-63.

Cumming, G. S., Cumming, D. H., & Redman, C. L. (2006). Scale mismatches in social-ecological systems: causes, consequences, and solutions. Ecology and society, 11(1).

Fuhlendorf, S. D., Woodward, A. J., Leslie, D. M., & Shackford, J. S. (2002). Multi-scale effects of habitat loss and fragmentation on lesser prairie-chicken populations of the US Southern Great Plains. Landscape Ecology, 17(7), 617-628.

Fuhlendorf, S. D., Hovick, T. J., Elmore, R. D., Tanner, A. M., Engle, D. M., & Davis, C. A. (2017). A hierarchical perspective to woody plant encroachment for conservation of prairie-chickens. Rangeland ecology & management, 70(1), 9-14.

Fuhlendorf, S. D., Fynn, R. W., McGranahan, D. A., & Twidwell, D. (2017). Heterogeneity as the basis for rangeland management. In Rangeland systems (pp. 169-196). Springer, Cham.

Hay, G. J., Marceau, D. J., Dube, P., & Bouchard, A. (2001). A multiscale framework for landscape analysis: object-specific analysis and upscaling. Landscape Ecology, 16(6), 471-490.

Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. Ecosystems, 4(5), 390-405.

Levin, S. A. (1992). The problem of pattern and scale in ecology: the Robert H. MacArthur award lecture. Ecology, 73(6), 1943-1967.

Li, H., & Reynolds, J. F. (1995). On definition and quantification of heterogeneity. Oikos, 73(2), 280-284.

Millenium Ecosystem Assessment. (2005). Dealing with Scale. In Ecosystems and Human Well-being:A Framework for Assessment. Island press, Washington D.C.

Sollins, P., Spycher, G., & Topik, C. (1983). Processes of Soil Organic?Matter Accretion at a Mudfloe Chronosequence, Mt. Shasta, California. Ecology, 64(5), 1273-1282.

Turner, M. G., and R. H. Gardner. (2015). Introduction to landscape ecology and scale. In Landscape Ecology in Theory and Practice (p. 1-32). Springer, Cham.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. Ecology and Society, 11(1).

Wiens, J. A. (1989). Spatial scaling in ecology. Functional ecology, 3(4), 385-397.

Further Reading

Fuhlendorf, S. D., Woodward, A. J., Leslie, D. M., & Shackford, J. S. (2002). Multi-scale effects of habitat loss and fragmentation on lesser prairie-chicken populations of the US Southern Great Plains. Landscape Ecology, 17(7), 617-628.

Fuhlendorf, S. D., Hovick, T. J., Elmore, R. D., Tanner, A. M., Engle, D. M., & Davis, C. A. (2017). A hierarchical perspective to woody plant encroachment for conservation of prairie-chickens. Rangeland ecology & management, 70(1), 9-14.

Millenium Ecosystem Assessment. 2005. Dealing with Scale. In Ecosystems and Human Well-being:A Framework for Assessment. Island press, Washington D.C.

Turner, M. G., and R. H. Gardner. 2015. Introduction to landscape ecology and scale. In Landscape Ecology in Theory and Practice (p. 1-32). Springer, Cham.

Wiens, J. A. (1989). Spatial scaling in ecology. Functional ecology, 3(4), 385-397.

Scale Glossary

Asynchronous

A process or multiple processes that do not occur at the same time.

Broad scale

A spatial or temporal scale with an extent that is considered to be relatively large.

Cross-Scale Interactions

Processes at one scale that affect those at higher or lower scales

Extent

The entire window from which all observations are taken, referring to an area or time span.

Fine scale

A spatial or temporal scale with an extent that is considered to be relatively small.

Grain

The size or duration of the individual units of observation. Grain may refer to a plot size, pixel resolution, the size of grid cells, or the minimum unit of time from which observations are taken from.

Heterogeneity

Variability within a system that accounts for scale. It is the quality of something to be made up of many different parts, elements, kinds, or individuals with these different components occurring at different scales at varying densities.

Hierarchical Confinement

A specific case of cross-scale interactions in which broad scale processes constrain a phenomenon occurring at finer scales

Scale

The spatial or temporal dimension of an object or process, characterized by both grain and extent (Turner & Gardner, 2015)

Spatial scale

The entire area of interest (i.e., extent) and the smallest unit of area (i.e., grain) over which observations are taken. All measurements have a spatial scale.

Synchronous

A process or multiple processes that occur at the same time.

Temporal scale

The entire timespan of interest (i.e., extent) and the smallest unit of time over which observations are taken. All measurements have a temporal scale.