

# Chapter 11

## Using Spatial Statistics and Landscape Metrics to Compare Disturbance Mosaics

Monica G. Turner and Martin Simard

### OBJECTIVES

The causes and consequences of disturbances are major research topics in landscape ecology (Foster et al. 1998; White and Jentsch 2001; Turner 2005, 2010). Disturbances are of particular interest because of their reciprocal interactions with landscape pattern—they both respond to and create spatial heterogeneity (Turner 1987). Understanding the disturbance-created landscape mosaic is important for conserving resources and biodiversity, anticipating potential consequences of global change on disturbance regimes (Turner 2010), and managing landscapes in ways that mimic attributes of natural disturbances or keep a landscape within its historic range of variability (Perera et al. 2004; Long 2009). The spatial patterns created by disturbances can also provide novel insights into the state and dynamics of a landscape (Fraterrigo and Rusak 2008). Thus, disturbance has been a primary focus of landscape ecology for a long time (e.g., Turner 1987).

Disturbance-created heterogeneity also provides an opportunity to compare and contrast different approaches for quantifying spatial variability. Disturbances differ in severity (effects on the biota) across the landscape, and this variation can be quantified using continuous measures (e.g., the amount or proportion of tree basal area killed by disturbance) or represented categorically (e.g., high vs. low severity). These different types of data require distinct methods of analysis. Spatial statistics characterize the spatial dependence in continuous data, whereas landscape metrics quantify spatial pattern in categorical data (Gustafson 1998). How ecological

---

M.G. Turner (✉)  
University of Wisconsin—Madison, Madison, WI, USA  
e-mail: [turnermg@wisc.edu](mailto:turnermg@wisc.edu)

M. Simard  
Université Laval, Quebec City, QC, Canada

interpretations differ based on these methods, and whether they provide complementary or redundant insights, is often not considered in landscape studies. Most studies use one or the other kind of data but not both. In this lab, students will compare spatial patterns created by three different kinds of disturbance using spatial statistics and landscape metrics and then contrast the interpretations that emerge from these complementary approaches. Upon completion of this lab, students will have accomplished the following objectives.

Part 1. Using spatial statistics to compare mosaics generated by different disturbances:

1. Quantify and compare landscape patterns generated by fire, insect outbreaks, and clear-cut harvesting in forested landscapes of Greater Yellowstone (Wyoming, USA) using spatial statistics applied to continuous measures of disturbance severity;
2. Learn to use and interpret output from GS+, a commercially available program for spatial statistics; and
3. Gain experience fitting different theoretical models to empirical semivariograms of disturbance severity and understand how model choice can influence interpretation.

Part 2. Analyzing fire patterns using landscape metrics and spatial statistics:

1. Describe and compare landscape patterns generated by fire in Greater Yellowstone using landscape metrics applied to categorical measures of fire severity using FRAGSTATS;
2. Interpret the landscape metrics and evaluate the effects of different classification schemes on the numerical results and ecological interpretations; and
3. Compare results obtained using spatial statistics (on continuous data) and landscape metrics (on categorical data) for quantifying fire patterns and determine whether these approaches provide complementary or redundant ecological insights.

This is an advanced exercise recommended for two successive class periods. This lab assumes basic understanding of semivariance and correlograms (completion of Chapter 5), as well as landscape metrics and the use of FRAGSTATS (Chapter 4). The lab also requires a geostatistics software program GS+ (© Gamma Design 2015), which can be found online at <https://www.gammadesign.com/>. The software is available as a free 10-day demo version. Lastly, while not essential, familiarity with vegetation indices derived from remote sensing data (as in Chapter 1) is helpful.

## INTRODUCTION

Disturbance has long been recognized as an important driver of landscape heterogeneity and integral to understanding landscape dynamics (Watt 1947). A **disturbance** is defined as a relatively discrete event that disrupts the structure of an ecosystem, community, or population and changes resource availability or the physical

environment (White and Pickett 1985). Recent treatments of disturbance advocate for separating out environmental drivers, initial system properties, and physical and biological mechanisms by which the system is affected so that different kinds of disturbance can be more easily compared (Peters et al. 2011). Disturbances are interesting in that they both create and respond to spatial heterogeneity in the landscape, and this is one reason disturbance has received so much attention in landscape ecology (Turner 1987, 2010). Landscape ecological studies of disturbance focus on several aspects of these relationships (Turner and Gardner 2015).

A variety of attributes are used to characterize a disturbance regime. Included among these are the spatial location of the disturbance, the size and shape of disturbed patches, and the variation in disturbance severity within the affected area. In this exercise, you will compare the spatial patterns created by three different disturbance types—fires, bark beetle (*Dendroctonus*) outbreaks, and clear-cuts—in the Greater Yellowstone Ecosystem (GYE).

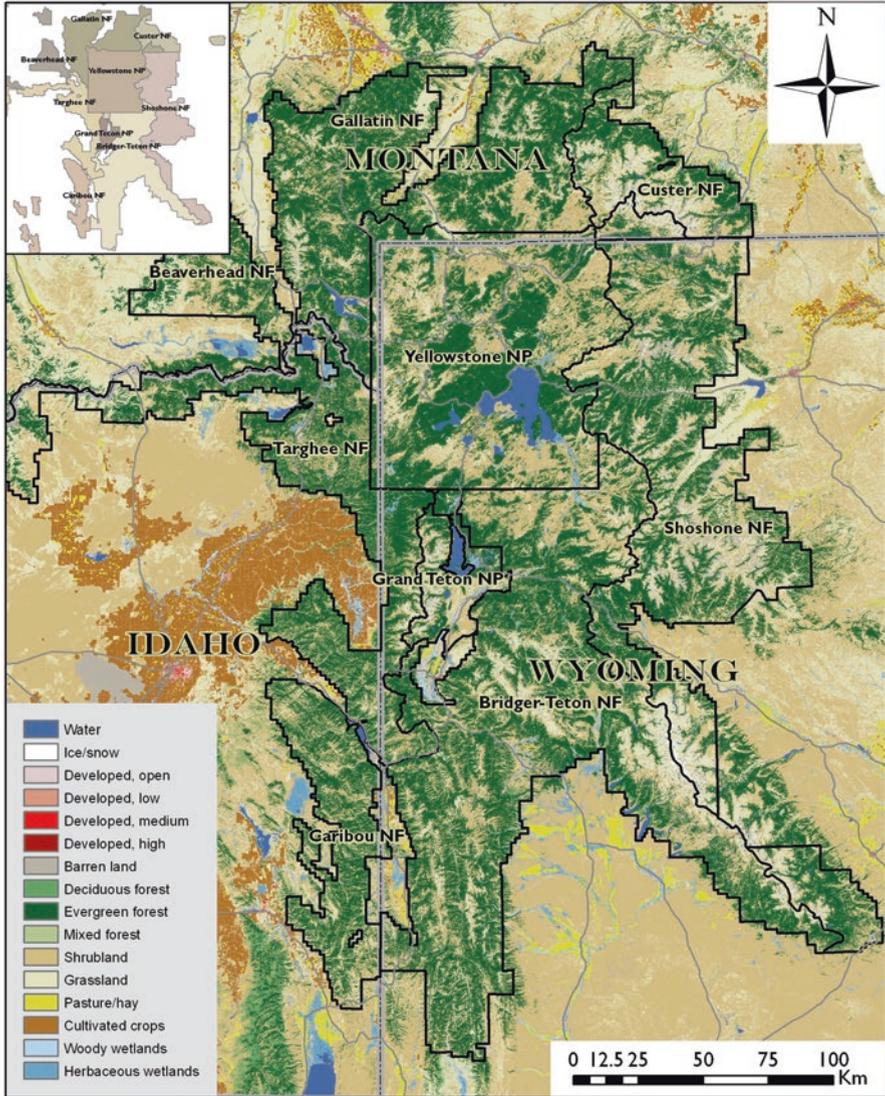
## Study Area and Disturbances

The 80,000 km<sup>2</sup> GYE is centered on Yellowstone National Park (YNP) and straddles portions of Wyoming, Montana, and Idaho (Figure 11.1). The GYE is unique in interesting respects—most notably the extensive geothermal features and large populations of native wildlife for which the region is famous—but in many ways it is also representative of coniferous forest ecosystems in the northern US Rocky Mountains.

YNP encompasses ca. 9000 km<sup>2</sup>, most of which lies on a high (elevation ca. 2100–2700 m) volcanic plateau with relatively gentle relief. Surrounding the plateau are higher, rugged mountains of various crystalline, sedimentary, and volcanic substrates, as well as broad river valleys and basins characterized by a semiarid climate. Approximately 80% of YNP is dominated by lodgepole pine (*Pinus contorta* var. *latifolia*) forest, although subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*) are locally abundant at high elevations. At lower elevations, Douglas-fir (*Pseudotsuga menziesii*) and aspen (*Populus tremuloides*) forests grade into sagebrush (*Artemisia* spp.) steppe and grasslands. The climate is characterized by cold, snowy winters and dry, mild summers.

Portions of the GYE have a history of intensive resource exploitation, including logging, grazing, market hunting, and mining (as in other parts of the Rocky Mountains), as well as an expanding wildland-urban interface on private lands. The GYE differs from much of the rest of the Rocky Mountain region, however, in that much of the pre-Columbian flora and fauna remain intact, in part because the GYE contains one of the largest tracts of wild, undeveloped land in the continental USA (Gude et al. 2006). This largely pristine condition makes Yellowstone uniquely suitable for research into natural landscape patterns and processes at multiple scales and comparisons with human-created patterns.

We will consider two components of the natural disturbance regime: fire and bark beetles. **Stand-replacing fire** is an important component of the natural disturbance



**Figure 11.1** Location of the Greater Yellowstone Ecosystem, USA, from which the landscape maps of spatial patterns of disturbance used in these exercises were obtained

regime in the GYE and in many conifer forests throughout western North America (Turner and Romme 1994; Schoennagel et al. 2004). Infrequent, high-severity fires kill most of the trees either via intense surface fire or fire spread through the crowns of the trees. Climate, particularly severe regional drought, sets the stage for occasional years of extensive conflagrations. Stand-replacing fires occur in the GYE at 100–300-year intervals (Romme 1982; Romme and Despain 1989; Millspaugh et al. 2000;

Schoennagel et al. 2003). In 1988, large fires affected more than 30% of the GYE and created a complex spatial mosaic of burned patches that varied in size, shape, and severity (Turner et al. 1994). Fire weather was extreme: it was the driest summer on record in YNP (Renkin and Despain 1992), as dry cold fronts brought high wind and lightning but no rain. The 1988 fire season is considered to have ushered in a new era of fire activity in the West (Running 2006), and stand-replacing fires have continued to occur during many subsequent summers.

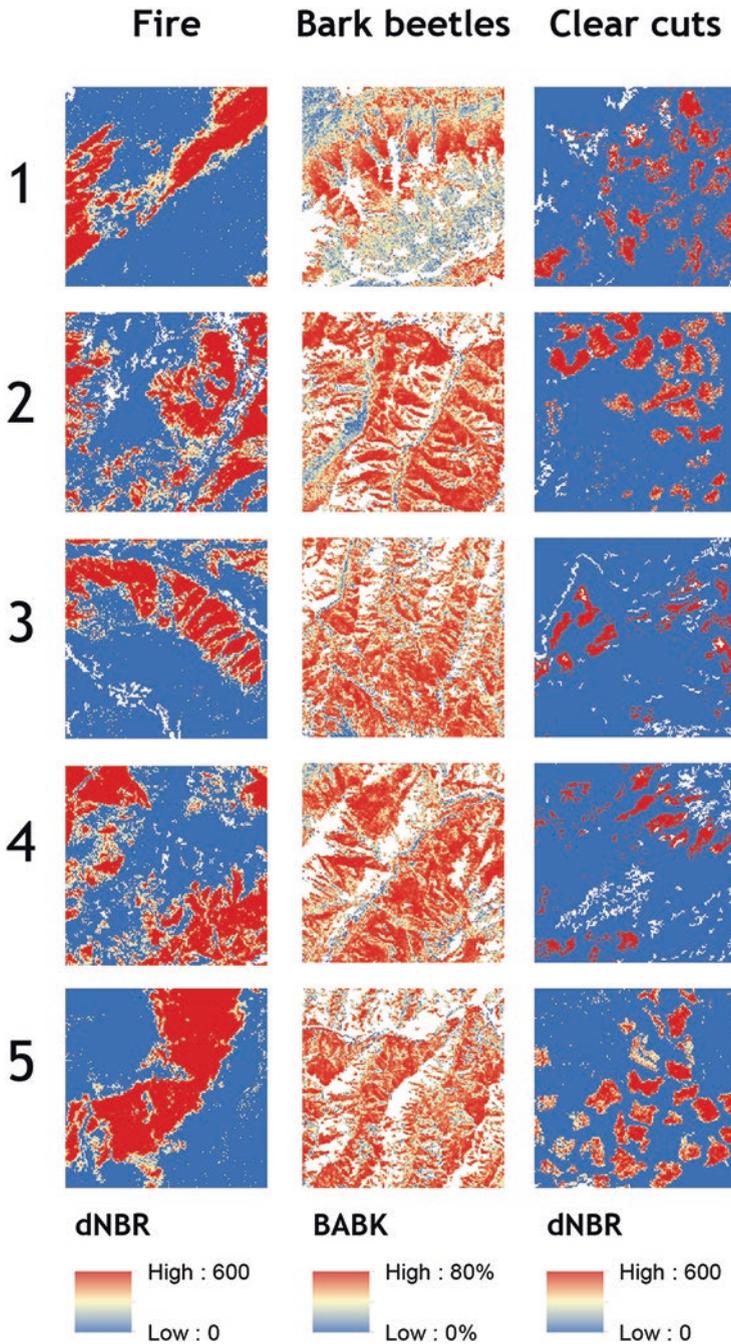
**Bark beetles** are also a key element of the natural disturbance regime in the GYE, and insect outbreaks have been recorded since 1922 (Furniss and Renkin 2003). Bark beetles are phloem-feeding specialists native to temperate and boreal coniferous forests (Raffa et al. 2008; Bentz et al. 2010). These insects are important because they kill healthy trees over extensive areas during episodic outbreaks. In contrast to fire, however, bark beetles do not kill all trees within a stand because they preferentially select larger trees. Furthermore, the forest floor and duff layer remain intact following bark beetle attack. Between 2003 and 2012, both mountain pine beetle (MPB) and Douglas-fir beetle (DFB) were active in lodgepole pine and Douglas-fir, respectively, in the GYE (Simard et al. 2012). Understanding the dynamics of both natural disturbances remains important throughout forests of western North America. The extent and severity of bark beetle epidemics have reached unprecedented levels (Raffa et al. 2008), and the frequency of large, severe fires continues to increase (Westerling et al. 2006, 2011). These trends are expected to continue because climate change—especially warmer temperatures, earlier snow-melt, and more severe summer droughts—is implicated for both disturbances.

We will also consider an anthropogenic disturbance: **clear-cut harvesting**. During the mid-twentieth century, many national forests in the GYE were subject to harvesting where merchantable trees were clear-cut in strips or patches distributed across the forest (Tinker et al. 2003). Forestry activities were particularly conspicuous along the western boundary of YNP where the differences in landscape patterns inside and outside of the national park provide an illustration of how human actions can change landscape patterns (see Figure 11.1).

## Part 1. Using Spatial Statistics to Compare Mosaics Generated by Different Disturbances

In this first part of the lab, you will compare the spatial structure of the three different disturbance types (fires, bark beetle outbreaks, and clear-cut harvest) in the GYE. Five landscapes (5 × 5 km) of each disturbance type were sampled from disturbance maps generated from remote sensing data (Landsat, 30-m pixels,  $n = 15$  different maps). These disturbance maps were created by analyzing differences between images taken before and after the disturbance event (Figure 11.2).

The fires and clear-cuts both date from the late 1980s, and the severity of these disturbances is represented here by a disturbance index based on the **Normalized**



**Figure 11.2** Landscape maps of spatial patterns created by three different types of disturbance in Greater Yellowstone corresponding to the data files used in Part 1. See text for description of map categories and interpretation. Areas of more severe disturbance are in redder colors

**Burn Ratio (NBR).** The NBR uses a band ratio (similar to the NDVI, described in Chapter 1) to measure disturbance severity within each grid cell based on the reduction in live biomass after the disturbance (Key and Benson 2006). The NBR uses two bands of Landsat that are most affected by fire and logging but in opposite ways. The near-infrared band is sensitive to decreases in forest biomass, and a short-wave infrared band captures increases in extent of bare soil. To create the index, these two bands are combined mathematically to calculate the NBR for each pre- and post-disturbance image. The post-disturbance NBR map is subtracted from the pre-disturbance NBR map to generate a difference map that contains values of **dNBR (delta Normalized Burn Ratio)**, which represents the change between the pre- and post-disturbance image. Here, we use the dNBR value as an index of disturbance severity. Unburned and unlogged areas show little change in NBR between the two image dates, and thus dNBR values are very low. Areas burned or clear-cut show large changes in NBR between the two image dates, and as a result, dNBR values are high. Greater values of dNBR correspond to higher disturbance severities (see Figure 11.2).

The bark beetle outbreak map was created using a similar approach with pre- and post-disturbance images but with a different disturbance index, the **Moisture Stress Index (MSI)**. The MSI is well suited to detect subtle changes in forest biomass, like those created by insect outbreaks that selectively kill some trees and do not directly affect the forest understory (Jin and Sader 2005). The **dMSI (delta Moisture Stress Index)** values were linked to field-based measurement of beetle-caused tree mortality to map the outbreak severity as measured by **cumulative basal area beetle-killed (% BABK)** between 1999 and 2007 (see Figure 11.2). This timeframe includes an outbreak first recorded in 2003 that lasted for several years. As with dNBR, greater values of dMSI indicate higher severity of the bark beetle outbreak (i.e., more beetle-induced tree mortality).

Although the remote sensing indices differ, dNBR and dMSI both quantify disturbance severity and return continuous values for each pixel. In all maps, non-forest pixels were removed from analysis, and undisturbed forest pixels were assigned an index value of zero.

## EXERCISE 1: Describing Disturbance Patterns Qualitatively

Begin this lab by inspecting Figure 11.2 and considering those patterns while answering the next question. Your instructor may suggest that you complete this exercise prior to arriving in class.

*Q1* Qualitatively describe the spatial patterns of the three disturbance types (Figure 11.2) in your own words. How would you characterize the pattern produced by each disturbance? How are they visually similar and different?

## EXERCISE 2: Quantifying Disturbance Patterns Using Spatial Statistics

Next, describe the spatial patterns of each disturbance type using variograms and correlograms computed using GS+ software.

1. Thoroughly read the **handout Instructions for GS+** and familiarize yourself with the general steps and options in the software before proceeding further (Your instructor may suggest you read this prior to coming to class, to save valuable class time).
2. Generate an isotropic variogram and a correlogram (see GS+ handout) for each sample landscape using GS+. You will need to open each file separately in GS+. For each variogram, use an **exponential model** so that comparisons can be made using the same theoretical model. Remember to set the **Lag Class Distance** to 30 so that it matches the resolution of the data, which is 30 m. Be sure to record summary statistics (e.g., mean, minimum, maximum) for the response variable ( $Z$ ) when you inspect the results, as well as the information described below.
3. In Table 11.1, record the parameter estimates listed below from each variogram. Save these results in an Excel worksheet so that you can produce the required graphs and use these results later in Part 2.
  - **Nugget** ( $C_0$ ), the intercept of the model variogram representing variance at scales less than the minimum lag distance or variance arising from measurement error that cannot be resolved
  - **Sill** ( $C_0 + C$ ), or maximum semivariance
  - **Range** ( $A$ ), which represents the limit of spatial dependence or the distance over which measurements are autocorrelated
  - **Proportion of structural variance** [ $C / (C_0 + C)$ ], which estimates the magnitude of spatial dependence in the data
  - **Fit** ( $R^2$ ) of the model to the data

*NOTE:* When reporting numerical information, be consistent and appropriate in your use of significant digits. Do not report unrealistic precision, and be consistent in your summaries so the values can be easily compared.

4. Using the same landscape data file, compute the correlogram. In Table 11.1, record the parameter estimates below from each correlogram. Save the results in an Excel worksheet.
  - **Magnitude of the largest correlation** (usually  $r$  for the first lag distance)
  - **Lag distance** at which the correlogram declines to approximately  $r=0.2$
  - **Lag distance** at which the correlogram declines to approximately  $r=0$
5. Repeat the above steps for all landscapes ( $n=15$ ).
6. Using the parameter estimates in Table 11.1, calculate the mean of each parameter for each disturbance type (so  $n=5$  for each mean). Create a bar graph (with error bars of plus and minus one standard error for the 5 replicates) of the mean estimated **range** value (on the  $Y$ -axis) by disturbance type (classes on the  $X$ -axis). Create another bar graph for the mean values of the **proportion of structural**



**variance**, and the **lag distance** at which the correlogram declines below  $r=0.2$  (thus, you will produce three graphs).

- To compare results obtained from the variograms and correlograms, use the observations from Table 11.1 to create a scatterplot of the lag distance at which the correlogram declines to about  $r=0.2$  (on the  $Y$ -axis) vs. the range estimate from the variogram (on the  $X$ -axis). For this plot, use all observations, irrespective of disturbance type ( $n=15$ ). Add a linear trend line and show the coefficient of regression ( $R^2$ ) and the equation.

**Q2** Describe the spatial patterns of each disturbance type using the variograms and correlograms computed in GS+ and explain the relationship between the statistics and the qualitative description from **Q1**. Use the results (Table 11.1) and graphs you produced, and reference these appropriately to support your interpretations and address these aspects:

- Make sure to discuss the overall magnitude of semivariance in the data, as well as the proportion of that variance that reflects spatial dependence (i.e., autocorrelation), the fit of the model, and the estimated distances (range) over which the response variables are autocorrelated.
- Use estimates of  $r$  from the correlograms when thinking about the strength of the autocorrelation.
- Inspect the scatterplot. Do the semivariograms and correlograms for the same map(s) lead to consistent interpretations of the spatial patterns?

**Q3** Interpret the relationship between the spatial statistics and the ecological processes (fire, insect outbreak, and clear-cutting) associated with each disturbance type.

- Is there any consistent “signature” of these disturbance patterns that relates to the different mechanisms that generate them?
- Within a particular disturbance type, do the results suggest different conditions that may have influenced the disturbances? Use the parameter estimates in Table 11.1 and your graphs to answer this question.

### **EXERCISE 3: Understanding Differences Among Theoretical Models of Semivariance**

Select **one** of the three disturbance types (your choice) to explore how quantitative results and interpretations can vary among different theoretical models (exponential, spherical, linear, and Gaussian) fit to empirical semivariance values.

- For the five landscapes within the disturbance type that you selected, fit three additional theoretical models (spherical, linear, Gaussian) to the empirical semivariogram.
- In Table 11.2, record the parameter estimates for each additional model (i.e., nugget, sill, range, proportion of structural variance, and fit) and in an Excel worksheet. Examine the range estimates and proportion of structural variance and compare their mean values among theoretical models.

**Table 11.2** Results obtained for different theoretical models fit to empirical semivariograms of the same disturbance type.

**Disturbance type = \_\_\_\_\_**

Replicate map	Model	Fit ( $R^2$ )	Nugget ( $C_o$ )	Sill ( $C_o + C$ )	Prop. structural variance	Range ( $A$ ), in $m$
1	Exponential					
	Spherical					
	Gaussian					
	Linear					
2	Exponential					
	Spherical					
	Gaussian					
	Linear					
3	Exponential					
	Spherical					
	Gaussian					
	Linear					
4	Exponential					
	Spherical					
	Gaussian					
	Linear					
5	Exponential					
	Spherical					
	Gaussian					
	Linear					

Note that the results for the exponential model can be copied here from Table 11.1

**Q4** How do your descriptions of spatial pattern and interpretations change with different theoretical models fit to the semivariance? Which of the theoretical models provides the best fit for the data, and is this consistent across each of the five landscapes? How will the choice of model influence the scientific conclusions that can be drawn from this analysis, and why is that important?

**OPTIONAL EXERCISE 4: Kriging Disturbance-Severity Patterns**

A valuable use of semivariance analysis is to interpolate expected values and generate a continuous map of the variable of interest. Select one of the disturbance types and use the results from the semivariogram analysis to kriging a map of disturbance pattern. Depending on the disturbance you select, the kriged map will be a continuous landscape of dNBR or dMSI values that share the same statistical properties as the data used in computing the semivariance. How does the kriged map compare with the original map from which spatial dependence was quantified?

## Part 2. Analyzing Fire Patterns Using Landscape Metrics and Spatial Statistics

Disturbance is often mapped in discrete classes (such as categories that represent both high and low severity and undisturbed areas). These classes are often derived from continuous measures, such as those used in Part 1, by setting a threshold value to convert the continuous variable to a category. The choice of threshold and how many categories to represent in a map of disturbance severity can influence the quantitative measures of spatial pattern, including patch size, patch shape, connectivity of disturbed area, distance to edge, etc.

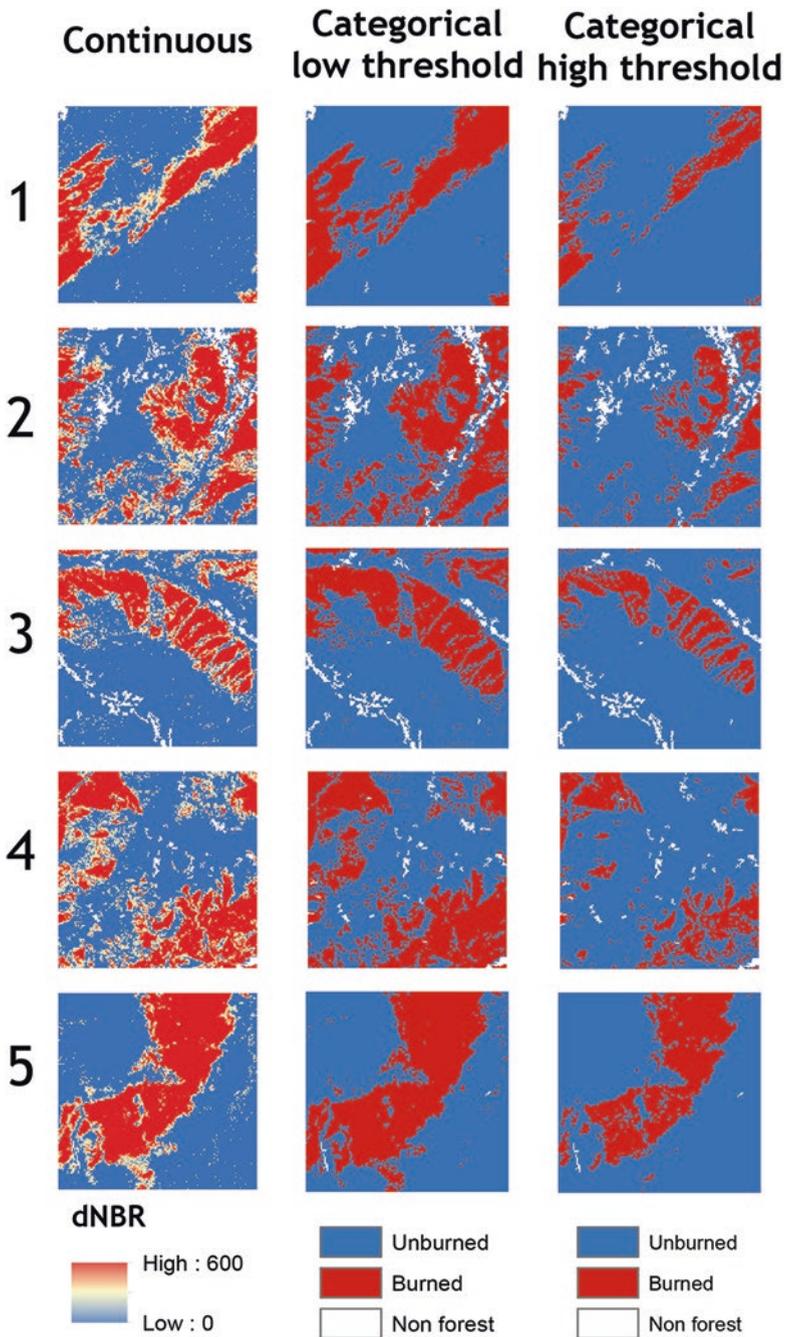
In the exercises in Part 2, you will compute landscape metrics for fire patterns (from the same five landscapes of fire-created patterns in Part 1) using categorical data analyzed in FRAGSTATS. You will compare two categorization schemes, each with a different minimum dNBR threshold for defining burned areas (Figure 11.3), to explore the effects of classification scheme on numerical output. Binary maps of fire pattern (which use only two categories, burned vs. unburned) that were derived from the continuous maps of dNBR are provided for you. The dNBR maps were reclassified to categories using two alternate classification schemes. Maps of all burned areas used a low threshold ( $dNBR > 170$ ) and include a range of burn severities, i.e., all areas affected by fire. Maps of high-severity burned areas used a high threshold ( $dNBR > 600$ ) and include only the upper end of burn severities where fires would all be stand replacing.

### EXERCISE 5: Selecting Landscape Metrics

For each of the ten landscapes (2 thresholds  $\times$  5 reps = 10 landscapes), you will use FRAGSTATS to characterize the spatial patterns of the burned landscapes. Choosing which metrics to quantify in any analysis is an important step, as each metric provides information about some aspect of pattern, and many metrics are redundant. You will include the five metrics listed below in your selection **plus** five others of your own choosing. You must have a rationale for selection of each and should choose indices that you think will have different (complementary) information about the spatial patterns.

- **Landscape-level metrics:** edge density (ED) and contagion (CONTAG)
- **Class-level metrics:** proportion of landscape occupied (PLAND), number of patches (NP), and mean patch size (AREA\_MN)

**Q5** Provide the rationale for each metric you selected for analysis. Which among these do you expect to be related to the variogram parameters, and how might they be related? Which metrics do you expect to provide new/different information about the spatial pattern? Explain your reasoning.



**Figure 11.3** Landscape maps of spatial patterns created by fire in Greater Yellowstone. Continuous maps are the same as in Figure 11.2. The “low-threshold” maps identify all cells that were affected by fire (i.e., range of fire severities). The “high-threshold” maps identify only patches of high-severity fire and exclude areas of low-severity fire

## EXERCISE 6: Quantifying Fire Patterns Using FRAGSTATS

Students are urged to consult the documentation for FRAGSTATS, which is excellent and can be downloaded from <http://www.umass.edu/landeco/research/fragstats/fragstats.html>.

It is assumed that students know how to run FRAGSTATS on their computer system (as you learned in Chapter 4). Use an **8-neighbor rule** for patch identification, and set the cell size to **30 m**. More details on the appropriate settings (rows, columns, cell size, etc.) are given in the **Instructions for FRAGSTATS**, which accompanies this chapter. Your output data (landscape metrics as well as class-level metrics for burned and unburned forest) should be saved in Excel for subsequent use. In these datasets, class 0=unburned and class 1=burned.

Once you have generated the output files from FRAGSTATS for all ten landscapes, compare the metric results for each of the classification schemes (mean with error bars,  $n=5$ ) using either graphs or a table. For class-level metrics, only include results for burned habitat. However, you will need metrics for burned and unburned habitat for some of the questions below.

**Q6** Briefly describe the spatial pattern of the landscapes that used the low dNBR threshold vs. the maps of high-severity fire only (i.e., the high dNBR threshold) (Figure 11.3). How did the assignment of the low and high threshold affect the quantitative estimates of burn patterns? What is your ecological interpretation of these patterns, and does your interpretation change with the classification scheme?

## EXERCISE 7: Using Spatial Statistics and Landscape Metrics to Compare Disturbance Mosaics

Next, you will compare and contrast the results from Part 1 (spatial statistics with continuous data) with the results generated above in Part 2 (analyzing categorical data). To do so, follow these steps:

1. Plot the landscape metrics (*Y*-axis) vs. the **range** estimates (*X*-axis) obtained from the semivariogram analyses in Part 1. When plotting class-level metrics, include both the burned and unburned categories on your plots by assigning a different symbol.
2. Plot the landscape metrics vs. the **proportion of structural variance** obtained from the semivariogram analyses in Part 1. When plotting class-level metrics, include both the burned and unburned categories on your plots by assigning a different symbol.
3. Although the sample size is small, compute correlation coefficients for each relationship and report a correlation table.

**Q7** Given the pairwise comparisons generated between output from spatial statistics vs. landscape pattern indices, as well as how you interpreted disturbance

patterns using these quantitative approaches separately, which of your expectations (from Q5) were supported, and which were not supported? How are these analysis methods similar and different, and do they provide complementary or redundant information? Does your ecological interpretation change qualitatively with the methods used?

**Q8** What spatial analysis approaches would you recommend for future studies of disturbance patterns and why? Are certain disturbance agents potentially best suited to continuous vs. categorical representation, and if so, why?

## REFERENCES AND RECOMMENDED READINGS<sup>1</sup>

- Bentz BJ, Regniere J, Fettig CJ et al (2010) Climate change and bark beetles of the Western United States and Canada: direct and indirect effects. *BioScience* 60(8):602–613
- Despain DG (1990) *Yellowstone vegetation. Consequences of environment and history in a natural setting*. Roberts Rinehart, Boulder, p 239
- \*Fortin MJ, Dale MRT (2005) *Spatial analysis: a guide for ecologists*. Cambridge University Press, New York, NY, USA, p 369. *An extremely helpful reference book for applications of spatial statistics.*
- \*Foster DR, Knight DH, Franklin JF (1998) Landscape patterns and legacies resulting from large, infrequent forest disturbances. *Ecosystems* 1(6):497–510. *Classic paper describing how different natural disturbances create landscape patterns.*
- \*Fraterrigo JM, Rusak JA (2008) Disturbance-driven changes in the variability of ecological patterns and processes. *Ecol Lett* 11:756–770. *A terrific conceptual and practical overview of how to consider and quantify variance and why that is useful.*
- Furniss MM, Renkin R (2003) Forest entomology in Yellowstone National Park, 1923–1957: a time of discovery and learning to let live. *Am Entomol* 49:198–209
- Gude PH, Hansen AJ, Rasker R et al (2006) Rates and drivers of rural residential development in the Greater Yellowstone. *Landsc Urban Plan* 77:131–151
- \*Gustafson EJ (1998) Quantifying landscape spatial pattern: what is the state of the art? *Ecosystems* 1:143–156. *Another classic, this paper nicely contrasts continuous and categorical landscape data and analyses.*
- Jin SM, Sader SA (2005) Comparison of time series tasseled cap wetness and the normalized difference moisture index in detecting forest disturbances. *Remote Sens Environ* 94:364–372
- Key CH, Benson NC (2006) Landscape assessment: sampling and analysis methods. In: Lutes DC, Keane RE, Caratti JF et al (eds) *FIREMON: fire effects monitoring and inventory system*. General technical report RMRS-GTR-164-CD, USDA Forest Service. Rocky Mountain Research Station, Ogden, pp LA1–LA51
- Long JN (2009) Emulating natural disturbance regimes as a basis for forest management: a North American view. *For Ecol Manage* 257(9):1868–1873
- Millsbaugh SH, Whitlock C, Bartlein PJ (2000) Variations in fire frequency and climate over the past 17 000 yr in central Yellowstone National Park. *Geology* 28(3):211–214
- Perera AH, Buse LJ, Weber MG (eds) (2004) *Emulating natural forest landscape disturbances: concepts and applications*. Columbia University Press, New York
- Peters DPC, Lugo AE, Chapin FS et al (2011) Cross-system comparisons elucidate disturbance complexities and generalities. *Ecosphere* 2:81

<sup>1</sup>NOTE: An asterisk preceding the entry indicates that it is a suggested reading.

- Raffa KF, Aukema BH, Bentz BJ et al (2008) Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *BioScience* 58(6): 501–517
- Renkin RA, Despain DG (1992) Fuel moisture, forest type, and lightning-caused fire in Yellowstone National Park. *Can J For Res* 22(1):37–45
- Romme WH (1982) Fire and landscape diversity in subalpine forests of Yellowstone National Park. *Ecol Monogr* 52(2):199–221
- Romme WH, Despain DG (1989) Historical perspective on the Yellowstone fires of 1988. *BioScience* 39:695–699
- Running SW (2006) Is global warming causing more, larger wildfires? *Science* 313:927–928
- Schoennagel T, Turner MG, Romme WH (2003) The influence of fire interval and serotiny on postfire lodgepole pine density in Yellowstone National Park. *Ecology* 84(11):2967–2978
- Schoennagel T, Veblen TT, Romme WH (2004) The interaction of fire, fuels, and climate across rocky mountain forests. *BioScience* 54:661–676
- \*Simard M, Powell EN, Raffa KF (2012) What explains landscape patterns of tree mortality caused by bark beetle outbreaks in Greater Yellowstone? *Glob Ecol Biogeogr* 21:555–567. *An empirical study of bark beetle outbreak severity, this paper gives background on the outbreak patterns in the landscape used here.*
- \*Tinker DB, Romme WH, Despain DG (2003) Historic range of variability in landscape structure in subalpine forests of the Greater Yellowstone Area, USA. *Landsc Ecol* 18:427–439. *Another Yellowstone paper, this study contrasts logging patterns and fire-generated patterns.*
- Turner MG (ed) (1987) *Landscape heterogeneity and disturbance*. Springer, New York, p 239
- Turner MG (2005) Landscape ecology: what is the state of the science? *Annu Rev Ecol Evol Syst* 36:319–344
- Turner MG (2010) Disturbance and landscape dynamics in a changing world. *Ecology* 91(10): 2833–2849
- Turner MG, Romme WH (1994) Landscape dynamics in crown fire ecosystems. *Landsc Ecol* 9(1):59–77
- Turner MG, Gardner RH (2015) *Landscape ecology in theory and practice*, 2nd ed. Springer, New York
- \*Turner MG, Hargrove WH, Gardner RH et al (1994) Effects of fire on landscape heterogeneity in Yellowstone National Park, Wyoming. *J Veg Sci* 5:731–742. *One of the very first papers to quantify postfire landscape heterogeneity, this paper presents landscape metrics for areas affected by the 1988 Yellowstone fires.*
- Watt AS (1947) Pattern and process in the plant community. *J Ecol* 35:1–22
- Westerling AL, Hidalgo HG, Cayan DR et al (2006) Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313:940–943
- Westerling AL, Turner MG, Smithwick EAH et al (2011) Continued warming could transform Greater Yellowstone fire regimes by mid-21<sup>st</sup> century. *Proc Natl Acad Sci* 108:13165–13170
- White PS, Jentsch A (2001) The research for generalities in studies of disturbance and ecosystem dynamics. *Prog Bot* 62:399–450
- White PS, Pickett STA (1985) Natural disturbance and patch dynamics: an introduction. In: Pickett STA, White PS (eds) *The ecology of natural disturbance and patch dynamics*. Academic Press, Orlando, pp 3–13