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GRTS and Graphs: Monitoring Natural Resources in Urban Landscapes

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16 GRTS and graphs

Monitoring natural resources in urban landscapes

Todd R. Lookingbill, John Paul Schmit, and Shawn L. Carter

Introduction

Environmental monitoring programs are an important tool for providing land managers with a scientific basis for management decisions. However, many ecological processes operate on spatial scales that transcend management boundaries (Schonewald-Cox 1988). For example, adjacent lands may influence protected-area resources via edge effects, source-sink dynamics, or invasion processes (Jones *et al.* 2009). Hydrologic alterations outside management units also may have profound effects on the integrity of resources being managed (Pringle 2000). The impacts of climate change are presenting challenges to resource management at local-to-global scales (Karl *et al.* 2009). This potential disparity between ecological and political boundaries presents an interesting dilemma for natural resource monitoring and is readily apparent in urban and agricultural environments, which tend to be dominated by external stressors (Collins *et al.* 2000). Despite their limited control over external land use, natural resource managers are concerned with processes such as development in the surrounding landscape, as these may lead to habitat loss and degradation that directly impair their resources. As a consequence, the management of the natural resources in and around parks and other areas requires a broad and dynamic understanding of the spatio-temporal patterns of environmental change. If monitoring is to be successful in providing data that inform management, information about regional and landscape context should play a critical role in designing monitoring strategies.

Urban parks provide a useful example of the influence of external stressors on managed resources. These parks tend to be small in area and tend not to encompass complete ecological units (e.g. watersheds or ecosystems; Forsyth and Musacchio 2005), conditions that could pose significant challenges to natural resource monitoring (Shafer 1995). Despite these challenges, or perhaps because of them, the conservation value of protected areas in urban environments has been increasingly acknowledged (Niemela 1999, Miller and Hobbs 2002, Lookingbill *et al.* 2007), and the significance of urban parks as biological refuges will likely increase as urbanization results in continued land conversion of adjacent habitats.

Design and Analysis of Long-term Ecological Monitoring Studies, ed. R.A. Gitzen, J.J. Millspaugh, A.B. Cooper, and D.S. Licht. Published by Cambridge University Press.

A more general challenge to long-term natural resource monitoring is to provide the different types of information needed to manage at short- and long-term temporal scales and multiple spatial scales (Levin 1992, Wiens *et al.* 2002). Monitoring to detect long-term trends is often accomplished by taking repeated measurements at permanent monitoring sites. However, data from these locations may provide little information on short-term urgent threats, which may not have been present when the monitoring program was initiated. Conversely, data collected to address urgent needs may not have the spatial or temporal coverage needed to determine broad-scale, long-term patterns. For example, data collected from remote sensing platforms are among the best options for monitoring landscape dynamics within parks and their surrounding ecosystems (Gross *et al.* 2009). Different imagery provides information at different temporal intervals and spatial grains and extents. Long-term records, such as those from moderate resolution Landsat imagery, can be leveraged to track broad-scale trends in development (Elmore and Guinn 2010) or phenology (McNeil *et al.* 2008). High-resolution imagery (e.g. Ikonos, Quickbird) may provide more valuable information for responding to more localized disturbance or other short-term monitoring needs (Lin *et al.* 2008). Approaches for integrating these diverse sources to provide a holistic assessment of natural resource condition are badly needed (see Gardner *et al.* 2008 for an example application of how this integration can be efficiently achieved).

In addition to scale considerations, the method of selecting monitoring locations is also an important determinant of the types of analyses that can be used on the data. For example, monitoring sites can be selected using either a probability-based or a model-based selection process (Edwards 1998; see Chapter 2). Randomized site selection based on probability sampling allows design-based inference that requires no assumptions about the population in order to produce valid estimates and a measure of the uncertainty of these estimates. Model-based selection occurs when locations are purposely (not randomly) chosen based on predictions that they have unique characteristics or have particular importance to the area being monitored. Importantly, model-based selection requires a rigorous theoretical or statistical model to take the place of, or supplement, randomization to guide the selection process and subsequent data analysis. Model-based selection has the advantage that it may meet survey objectives (e.g. achieving a specified precision) with less data collection (Urban 2000). However, the conclusions drawn from model-based selection are only valid if the underlying model itself is a valid representation of the system of interest.

In this chapter, we describe a hybrid approach to long-term monitoring that takes a regional perspective but does not ignore the specifics of local ecosystem dynamics (Box 16.1). The approach provides a probability-based sampling framework while allowing flexibility to include model-based samples that address more local, urgent management needs. This combined approach draws on the strengths of both design-based and model-based monitoring and addresses some of the limitations from which each suffers when applied individually. We illustrate the concepts with an example from our work monitoring forest dynamics within national parks of the National Capital Region in Maryland, Virginia, West Virginia, and Washington, DC, USA.

Box 16.1 Take-home messages for program managers

The status and trends of environmental resources are determined by local and regional influences that often transcend management boundaries. Therefore, long-term monitoring of landscapes may require information at multiple spatial scales and from multiple property owners to respond to varied and changing management objectives. Meeting such diverse needs requires a flexible, multi-layered approach. For example, the monitoring of landscape dynamics at multiple spatial scales can often benefit from the coordinated application of both direct field-based and remotely sensed observations. This chapter describes how a hybrid approach to monitoring can be used to consider specific landscape processes with reference to a larger, probability-based sample.

The first step of this hybrid approach selects permanent monitoring sites within a network of management units using probability sampling, as discussed throughout this volume. Data from these sites support unbiased estimation of regional status and trends for the overall population of interest, and detection of unanticipated patterns. The second step uses model output to locate additional monitoring sites in areas predicted to be of high importance for landscape-level processes. This chapter provides an illustrative example of the hybrid approach which incorporates use of a graph theory model applied to a regional land cover data set to identify forest patches of special management importance in maintaining habitat connectivity. Data from supplemental monitoring in these patches is integrated with monitoring data from network-wide monitoring to assess the condition of these high-priority patches.

The hybrid approach is especially useful when (i) information is needed at multiple resolutions and/or multiple extents (e.g. inside and outside the management unit boundaries); and/or (ii) information is needed to respond to multiple management challenges (e.g. some stressors are known, while others are not). Combining a model-based sample with probability sampling can give managers flexibility to address specific issues of high current importance while maintaining a surveillance program to flag unexpected environmental damage. Graph theory is especially useful for questions of spatial connectivity, but other model frameworks would also be appropriate based on the specific monitoring objectives. Location of the model-selected monitoring sites can change over time based on periodic reassessment of monitoring objectives, available information, and even land use change in and around the study area. In this sense, the dynamic, model-based and permanent-site, probability-based components of the monitoring are truly complementary. The designs are also complementary in that they facilitate partnerships between land managers with expertise and resources for long-term, repetitive measurement of their administrative units and researchers with complementary knowledge about the surrounding landscape context and interest in testing hypotheses about specific ecological variables.

A hybrid approach

Hybrid designs combining a fixed set of monitoring sites with additional, potentially "roving" sites whose locations are optimized to inform dynamic modeling of spatio-temporal processes and address shorter-term management priorities, have been advocated for the detection of change in natural resources and for understanding the underlying dynamics that produce change (Hooten *et al.* 2009a). We have observed that hybrid approaches can be useful when either of the following conditions are met (see also Brus and de Gruijter 1997): (i) information is needed at multiple resolutions and/or multiple extents (e.g. inside and outside the management unit boundaries); or (ii) information is needed to respond to multiple management challenges (e.g. some stressors are known, while others are not). We address each of these situations below.

Often, a significant drawback of a sampling strategy based on randomization alone is its inefficiency at capturing fine-scale spatial patterns over large spatial extents. Understanding these multi-scale patterns is important for protected areas that are interested in preserving spatially dependent processes, such as the movement of wildlife across the landscape. Data at regional scales may provide useful information on the constraints on these processes, but finer-scale data are required to understand mechanisms. One way of addressing this is through multi-stage sampling with design-based or model-assisted inference. For example, Nusser *et al.* (1998) provide an example of a two-stage sampling design in which land-cover measurements of primary units are used to improve estimates of variables measured at the secondary (sample-point) level and to detect changes that would not usually have been observable at the sample-point level. Alternatively, design- and model-based sampling can be combined. Models are useful tools for studying mechanisms, and model refinement (i.e. parameter optimization) is an additional benefit of model-based sampling. Thus, hybrid designs facilitate partnerships with a research community focused on testing hypothesis about specific ecological processes and variables (Jones *et al.* 2010).

Additionally, when the organism or process of interest is highly mobile or crosses an ecological/administrative boundary, different sampling strategies may be required at different locations on the landscape. Methods that efficiently identify the best sites for targeted sampling are especially important when those sites may lie outside of the direct administrative control of the monitoring agency. Adopting a monitoring approach that is sensitive to regional and landscape processes and stressors often requires coordinating efforts among multiple land owners. Hybrid approaches that use probability sampling for surveillance monitoring of regional trends, can use alternative methods to identify key neighbors for collaborative monitoring efforts.

A combination of sampling methods also can be used to respond to different monitoring challenges, such as the needs for assessing long-term changes in resource condition as well as addressing current management priorities and current hypotheses about the system (Chapters 3, 4, 22). Natural resource monitoring data can be used in either a retrospective or predictive manner (Yoccoz *et al.* 2001). The retrospective or post-hoc approach attempts to draw inferences from monitoring data after they have been collected, with no substantial effort to assess relationships a priori. A spatially balanced, probability sampling design lends itself to these types of evaluations, which can be useful for capturing unanticipated events such as the population decline of a particular species following the introduction of a novel pathogen. The predictive approach uses existing knowledge to guide data collection to address specific hypotheses. For example, model-based methods can apply information on habitat preferences and life history characteristics of a specific endangered species to identify habitat patches of special importance to populations of concern. Alternatively, model outcomes can be used to propose specific sites for potential management actions. These important patches may be missed entirely by the regional-level, random sampling. Predictive and retrospective uses of monitoring data both can provide managers with valuable information; whether it be through evaluating the impacts of past management actions or identifying the relative benefits of proposed actions. Whenever possible, however, predictive hypotheses should be developed because they allow for a more controlled examination of cause–effect relationships (Lookingbill *et al.* 2007).

Monitoring landscape dynamics

Our approach to forest vegetation sampling combines methods for generating a spatially balanced, probability sample of vegetation plots with model-based methods for identifying monitoring locations on the landscape that are particularly important to landscape processes and thus justify additional sampling effort. The randomized sampling provides an unbiased, coarse-scale assessment of regional trends. The model-based analysis, in contrast, targets forest patches that may have disproportionately large effects on ecosystem processes such as species dispersal. The model also identifies specific park neighbors whose properties potentially impact park resources and therefore helps to prioritize regional monitoring partnerships.

Probability designs are covered thoroughly in other chapters of this book (see Chapters 5 and 6), and we will not go into further detail here except to mention that monitoring of landscape dynamics at broad spatial scales can often benefit from the coordinated application of both direct, field-based and remotely sensed observations. We discuss above the importance of matching the spatial and temporal scale of imagery to the ecological pattern or process being assessed. An additional consideration in using remotely sensed data for monitoring is the choice of landscape metric. Literally hundreds of landscape pattern indices are available within the FRAGSTATS software package alone (McGarigal *et al.* 2002), and new metrics continue to be developed at a dizzying pace. The application of surface rather than patch-based metrics (McGarigal *et al.* 2009) and morphological spatial pattern analysis (Vogt *et al.* 2007) represent especially promising recent developments (Fig. 16.1). The Heinz Center (Heinz Center 2008) and US National Park Service (Gross *et al.* 2009), among others, have emphasized the value of landscape pattern indices in monitoring programs. A common pitfall is the selection of pattern indices for monitoring that are ecologically meaningful and independent. Cushman *et al.* (2008) provide guidance for metric selection based on seven fundamental properties of landscape configuration. Townsend *et al.* (2009) recommend a parsimonious

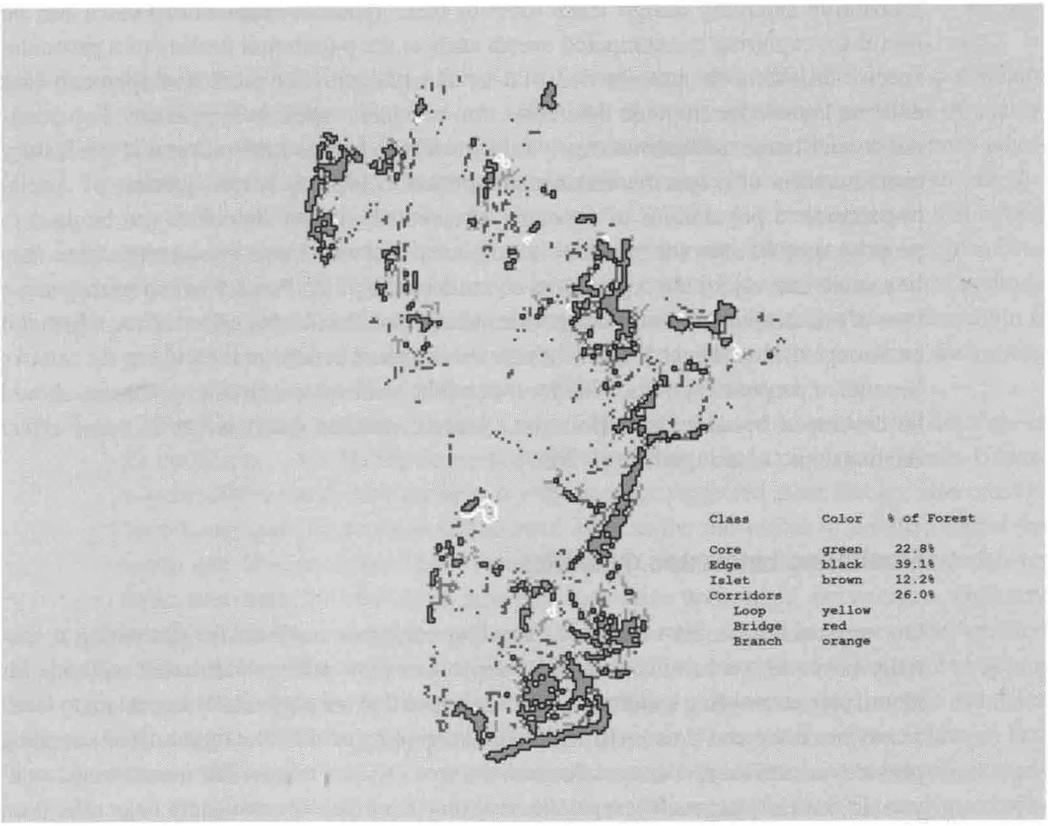

Figure 16.1 Representation of the connectivity of Antietam National Battlefield Park (Maryland, USA) landscape using morphological spatial pattern analysis. Landsat TM image analyzed using the GUIDOS (Graphical User Interface for the Description of image Objects and their Shapes) software version 1.2 (2008). See plate section for color version.

set of five metrics, including the graph theory-based metric described in our case study below, for monitoring landscapes confronted by fragmentation pressures.

A description of model-based approaches for hypothesis-driven monitoring requires additional attention, as these methods are traditionally less familiar to resource managers than probability-based designs (Gregoire 1998). With model-based frameworks, the model serves as a basis to make inference about a population parameter of interest. Urban (2000, 2002) provides some excellent examples of the application of habitat models, decision trees, and geostatistics to inform sample designs. Jobe and White (2009) provide another creative example using cost–distance modeling for human accessibility to assess vegetation monitoring plots accumulated over the last three decades in Great Smoky Mountains National Park.

Graph theory

Our case study describes the use of graph theory as a model for hypothesis-based, predictive modeling. Graph theory is an analytic technique for evaluating spatial properties

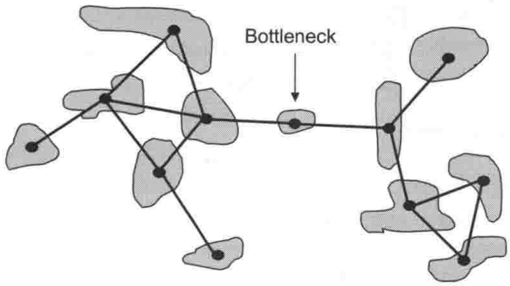

Figure 16.2 The connectivity of habitat patches in a landscape can be represented using graph theory. Pairs of patches are considered either connected or unconnected based on the distance between their edges. A graph can then be drawn that represents patches with points and connections between patches with lines. In this illustration, a bottleneck is shown that is highly important to linking two potential subcomponents of the graph.

of networks that has been applied for decades in fields such as transportation and communications (Harary 1969; Hayes 2000a, b). Recently, there have been an increasing number of applications of these and related connectivity methods such as circuit theory to assess the consequences of habitat modification and landscape change (e.g. Calabrese and Fagan 2004, Minor and Urban 2008, Rayfield *et al.* 2011). These approaches generally treat a landscape as a network of discrete habitat patches. The graph model considers pairs of these patches as either connected or unconnected based on some measure (Euclidean distance or other) of their spatial proximity (Fig. 16.2).

The graph-based model is appealing for large-scale monitoring because it provides a visually intuitive representation of landscape connectivity and provides a computationally efficient structure for analyzing data sets, e.g. by summarizing remotely sensed data collected from millions of pixels to a small subset of patch centroids for analysis and interpretation. A number of well-developed indices are available for quantifying landscape attributes based on properties of the landscape graph (see Pascual-Hortal and Saura 2006, Kindlmann and Burel 2008). One simple measure of the connectivity of a landscape is the proportion of total habitat area that is considered connected (A_{LC}; Ferrari *et al.* 2007). In addition to providing basic information about the overall landscape structure, the metric can be used to identify individual habitat patches of special importance by examining how selective patch removal changes the metric value (Urban and Keitt 2001). These critical bottlenecks for long-distance movement potential (Fig. 16.2) would be patches that if lost, damaged, or modified would greatly reduce the traversability of the landscape (e.g. result in significant decreases in A_{LC}).

A key challenge to the application of connectivity models to long-term monitoring is identifying the appropriate scale to parameterize the model. The construction of a landscape graph is organism-specific, and the same set of patches may yield different landscape graphs for species with shorter or longer dispersal capabilities. In instances where the dispersal characteristics (e.g. dispersal probability function, maximum dispersal distance) of an organism of concern are known, those attributes may be used to define patch connections (e.g. Goetz *et al.* 2009, Lookingbill *et al.* 2010). Otherwise, multiple dispersal distances can be systematically evaluated to determine the threshold

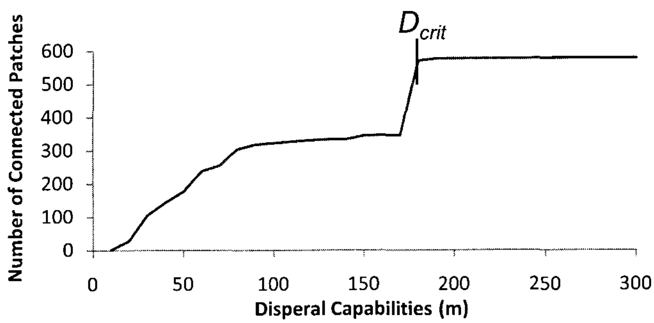

Figure 16.3 Connectivity (measured as number of connected patches) as a function of theoretical dispersal capabilities. A threshold of connectivity (D_{crit}) occurs at a dispersal capability of 180 m. Organisms capable of moving 180 m from one forest patch to another can move among nearly 100% of the patches in the landscape. This example is derived for the forests of Antietam National Battlefield Park.

distance at which the landscape may switch between being acceptably connected vs. disconnected (D_{crit}). Dispersal capabilities have been shown to be strongly nonlinear for most landscapes (Gardner *et al.* 1987), and D_{crit} values are often readily apparent from a curve of graph metrics (such as A_{LC} or the number of connected patches) versus dispersal distance (Fig. 16.3). One rule of thumb for assigning D_{crit} is the minimum distance a hypothetical organism would need to be able to disperse through non-habitat to be capable of moving among all habitat patches (i.e. for A_{LC} to equal 1.0). The value can be used to construct a graph by drawing lines between all patches separated by less than D_{crit}. The resulting graph represents the landscape as highly connected under current conditions, but highly sensitive to any loss or degradation of habitat. Graphs built using these D_{crit} threshold distances to identify patches of interest such as potential dispersal bottlenecks can be used for prioritizing site selection for monitoring purposes.

By identifying locally significant patches within a landscape context, the analysis provides a powerful tool for resource monitoring. Flexibility built into the sample design of long-term monitoring protocols allows the distribution of sample plots to be at least partially guided by specific natural resource concerns, such as preserving the overall landscape connectivity or the connectivity for a specific species. The contribution of a graph-theory analysis to the overall hybrid sampling strategy is thus to provide a complementary sample list frame for the assessment of targeted habitat changes through time.

The approach is tiered in that annual monitoring effort can be allocated first to the sampling of probability-based permanent plots. Remaining monitoring resources can then be directed towards the supplemental plots identified by the model analysis. Balancing total effort between these two components will depend on the overall objectives of the monitoring program and expected comparative value or importance of information produced by each component. For example, greater effort should be allocated to the model-based component when a single stressor is thought to be dominating the natural resource of concern or specific management actions are to be evaluated. When multiple or unknown stressors are thought to be dominating the system, in contrast, it would be appropriate to allocate greater sampling effort to the probability-based component of the sampling plan. In these instances, generating a sufficient model to test a hypothesis about one stressor is complicated by the variability introduced by the other stressors. The model-based component of the plan, though downplayed, is still important in attempting to disentangle the expected responses associated with the various stressors.

Additional considerations

Sample frames in relation to multi-scale monitoring

One of the first steps in any sample design is deciding on a target universe (target population) and related sample frame from which to sample to provide estimates for the target universe (Chapters 2, 5). In many cases these will correspond to simply the boundaries of the protected area or management unit being monitored. This will be commonly the case where the site is contiguous and has a more or less compact shape. In some cases, however, the issue is more complicated. Protected areas are frequently established as several discontinuous management units, such as a network of parks. The land between the units is not managed by the protected area, may be used for some other purpose (developed, agricultural, etc.), and may not be part of the target population. In this case, a sample could be selected from a single sample frame encompassing all management units (either including or excluding areas in between units), or independently from within each unit separately.

A similar situation occurs when a unit has an elongated shape, rather than a compact shape. This can occur when an area protects a linear natural feature, such as a river, a shoreline, or a barrier island. Conditions at one end of the site may differ drastically from conditions at the other end. When this occurs, it may be desirable to divide the area into sections with similar conditions, essentially leading to a separate sample frame for each section.

Sampling each management unit or section separately (i.e. with each of multiple smaller frames encompassing one management unit or section) may be preferred when the site or sites can be unambiguously divided up into smaller homogeneous units that are likely to be impacted by similar stressors and are the focus of management actions for the foreseeable future. This is essentially a stratified sampling approach if at least some of the same variables are measured in all units, with the goal in this case being to support independent estimates for each unit rather than to increase precision of estimates for the entire target population (Chapter 5). However, this independent sampling of each unit could decrease statistical power and complicate analysis when investigating issues at larger scales. Sampling multiple management units at once from one or more larger sample frames typically is preferred when it is difficult to divide the site into smaller units, or when stressors or management activities will cut across unit boundaries. For example, a monitoring program may be tasked with generating data for a network of a number of units in close proximity, rather than just one. In this case it may be desirable to identify conditions or trends that are common to all of the units rather than focus on issues unique to each one. Similarly, there may be a need to maintain maximum flexibility for future analyses combining subsets of data from each management unit for network-wide analyses. In these situations, a sample frame and sampling process that ignores the management unit "identity" is useful when generating a sample. On the other hand, it may be that few monitoring sites occur in any given area, and therefore there may be little power to examine status and trends on smaller scales. Regardless of what decisions are made about sampling frames, it is important to consider these issues ahead of time, and anticipate the need for analysis at a variety of scales, some of which may not yet be identified at the time the monitoring program is initiated.

Analytical considerations

As discussed elsewhere in this book (Chapter 2), specifying the approaches for analyzing the data is a critical early step in developing a quantitatively sound monitoring program. Selection of analysis methods typically follows closely from the determination of objectives. Model-based sampling designs provide specific hypotheses that can be evaluated, often with standard parametric statistics – e.g. comparing average metric values for different classes of locations on the landscape. Data analysis of probability designs, such as GRTS designs, are also specified elsewhere in the book (e.g. Chapters 6, 11, 14). More interesting, from the perspective of this chapter, is a discussion of the analytic framework for the hybrid approach.

There are two strategies for analyzing the data from the different monitoring components of the hybrid design. The first is to compare the data from the model-based approach to that of the random sampling. As an example, the fundamental benefit of a graph-theory analysis is that it will determine which habitat patches are likely to play a crucial role for some species, solely on the basis of the patch location in the landscape. The goal of the model-based portion of the monitoring could be to compare the habitat quality within these key patches to that of the protected area as a whole as determined from the probability-based sampling.

The second data-analysis strategy is to combine data from the two sampling frames to determine status and trends for the entire protected area. To do this, the data can be analyzed as an unequal probability stratified sample. For the analysis to be correct, it is important to keep in mind the location in the key patches could have been selected during either the first, probability sample or the second, model-based sample. Therefore the selection probability is the combined probability from each of these two components.

Forest monitoring of US National Capital Region parks

The US National Park Service's Inventory and Monitoring (NPS I&M) program was established to develop and implement a systematic and rigorous approach to monitoring natural resources in National Parks (Kaiser 2000, Fancy *et al.* 2009; see also Chapter 22).

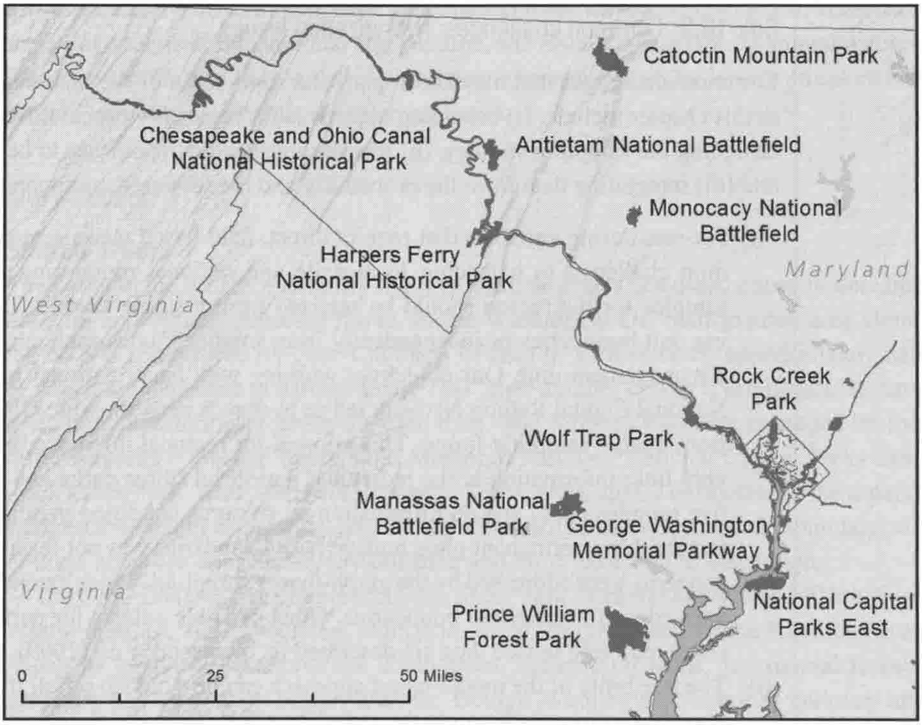

Figure 16.4 The US National Park Service National Capital Region I&M Network (NCRN) includes more than 75 000 acres distributed among 11 parks and is located in the urbanized landscape in and around Washington DC. See plate section for color version.

As part of the I&M program, parks of the eastern and midwestern US have collaborated to implement a consistent forest monitoring protocol based on the US Forest Service's Forest Inventory Analysis (FIA) and Forest Health Monitoring programs (Comiskey *et al.* 2009, Tierney *et al.* 2009). Key objectives of the program are to determine status and trends in (i) tree and shrub distribution and richness; (ii) tree and shrub basal area and density; (iii) volume of coarse woody debris (logs and large branches on the ground); (iv) presence and cover of exotic plant species; and (v) presence of certain forest pests and diseases.

The National Capital Region I&M Network (NCRN) has tested a strategy that combines the spatially balanced randomized sampling being conducted throughout the region with park-based modeling to define key locations for forest monitoring of landscape dynamics. We present an example of how a hybrid, two-step sampling design can be applied to forest monitoring of the 11 parks in the NCRN (Fig. 16.4). Our example also illustrates important decisions that must be addressed to implement the hybrid approach effectively (Box 16.2). Forests are the predominant natural vegetation cover for the parks in the NCRN, and most of the parks in the region have a specific mandate related to management of forests in their founding legislation. These include requirements to preserve natural forests, to preserve wildlife habitat, to protect watersheds, to provide recreation,

Box 16.2 Common challenges: hybridization issues

Common challenges that may accompany the application of the methods described in this chapter include: (i) balancing objectives for regional vs. local inference when designing the sampling strategy, (ii) identifying specific hypotheses to be examined, and (iii) integrating data from the probability and model-based components.

(i) For monitoring variables that require direct, field-based measurements, a common challenge in balancing local-scale and regional monitoring is whether samples for the region should be selected from a single sample frame ignoring unit boundaries or independently from smaller frames each encompassing a management unit. Our objectives working with small national parks in the National Capital Region Network led us to draw a network-wide GRTS sample from a large sampling frame. This allowed for regional inference but provided very little information at the individual park level (three parks had fewer than five samples each) and no information on resource condition in adjacent lands (establishing permanent plots outside park boundaries was not feasible). These concerns were addressed by the graph-theory sampling, which extended beyond park edges to watershed boundaries. Other possible extents for park sampling using remotely sensed data are described in Townsend *et al.* (2009).

(ii) The flexibility of the model-based approach can be a hidden pitfall if no leading hypothesis emerges to guide the sampling effort. Both the choice of model and parameterization of the model should be guided by the hypothesis defined at the outset of the sampling effort. The matching of appropriate model to hypothesis is a critical step in the process. The inferences drawn from the model-based sampling are highly dependent on the validity of the underlying model itself. An added benefit of the model-based sampling is that it will yield data that can be used to refine the model, and thus through continued iteration work toward design optimization (Hooten *et al.* 2009a).

(iii) Combining the data sets to provide integrated inferences at either the local scale or regional scales may be desirable, but should be undertaken with caution. For example, it would be inappropriate to simply lump the model-based sites with other sites as a single, statistical sample. Still, comparisons of data and estimates from each component may be of high value for examining and refining hypotheses of interest. Our case study provides an example of how the data from the model-based portion of the monitoring could be compared to data from the probability-based sampling to assess the habitat quality within key forest patches relative to that of the protected area as a whole.

and to protect scenic vistas. The most severe threats to park natural resources include high browsing pressure from white-tailed deer (*Odocoileus virginianus*), invasion by exotic plant species, loss of tree species such as eastern hemlock (*Tsuga canadensis*) and flowering dogwood (*Cornus florida*) due to pathogens, and regional changes in land use. Collectively, these threats have the potential to cause drastic changes in vegetation structure, species dominance and composition, and resources available to animal species. Effective monitoring should detect significant changes caused by known stressors and capture unanticipated trends in forest vegetation.

Site selection

Sample frame

The parks in the NCRN exemplify many of the challenges discussed above in deciding upon an appropriate sampling frame. In the Washington DC metropolitan area alone, the NPS is responsible for over 120 tracts of land of various sizes, approximately half of which are managed as natural areas. This large number makes it impractical to have a separate monitoring program for each tract. The forested tracts are managed by five different parks – George Washington Memorial Parkway, National Capital Parks East, Rock Creek Park, Wolf Trap Park, and part of the C&O Canal. The borders of these parks were established by legislation, and do not necessarily follow any natural boundary. All of these areas are impacted by urbanization and most have similar vegetation.

The C&O Canal is an example of a long, linear park. It stretches for over 290 km, from Washington, DC to Cumberland, Maryland, along the north bank of the Potomac River. Along its length, it borders dense urban areas, agricultural lands, and natural forests. The park has a common border with the George Washington Memorial Parkway and Rock Creek Park, cuts Harpers Ferry in half and passes less than 1 km from Antietam National Battlefield Park (NBP). In these areas, the lands managed by the C&O Canal often have more in common with the neighboring park than they do with the land in more distant parts of the canal.

For these and other similar reasons, it was decided that dividing the NCRN into park-based or other separate sample frames for forest monitoring would not be beneficial. Instead, the entire network of parks was included in a single sample frame and monitoring locations were chosen at random from this entire frame. When it is desirable to look at a specific park or other sub-area, the relevant data can be used for a more local analysis. However, a recognized drawback of our sample-frame decision is that the sample intensity in any particular area may be small.

Probability sampling

Once the appropriate sample frame was established, data for the first part of the sampling were collected following the NPS I&M forest monitoring protocol being uniformly implemented for eight I&M networks and three prototype parks in the eastern US (Comiskey *et al.* 2009). First, a list of potential sites was generated using a Geographic Information System (GIS) to establish a square grid of points, 250 m apart, over the entire region. All points that fell within park boundaries were treated as potential monitoring locations. Once the list of potential sites was determined, a Generalized Random Tessellation Stratified (GRTS; Stevens and Olsen 2004) design was used to randomly order the sites for monitoring (i.e. via the reverse hierarchical ordering approach described in Chapter 6). Sites were then visited in the random order generated by the

Table 16.1 The number of total grid points, sites visited, and sites selected for sampling per park in the US National Park Service National Capital Region Network using the GRTS design.

Park	Points in park	Points considered	Points monitored
Antietam National Battlefield Park	210	22	7
Catoctin Mountain Park	365	53	45
C&O Canal National Historical Park	1406	215	73
George Washington Memorial Parkway	332	68	33
Harpers Ferry National Historical Park	247	34	20
Manassas National Battlefield Park	284	45	15
Monocacy National Battlefield Park	106	18	3
National Capital Parks East	718	107	46
Prince William Forest Park	811	164	139
Rock Creek Park	195	30	18
Wolf Trap Park for the Performing Arts	9	1	1
National Capitol Region Network Total	4683	757	400

GRTS design process, and the first 400 sites on the list that were located in forest habitat and suitable for forest monitoring (e.g. safe for field crew, not overlapping with sensitive cultural resources, etc.) were selected (Table 16.1). These are being monitored with a 4-year serially alternating panel design (100 plots/year; see Chapter 7 for discussion of panel designs). Four hundred plots were chosen as a monitoring effort as this number is feasible given budgetary and staffing considerations. An initial power analysis indicated that 400 plots provides sufficient power to detect change in a wide variety of forest characteristics including tree density and basal area, density of coarse woody debris, and occupancy of exotic species (Schmit *et al.* 2009).

The flexibility of the GRTS approach was especially useful for working in NCRN parks, because it allowed sites to be excluded from monitoring based on the presence of vulnerable cultural/archeological resources or due to concerns with maintenance or visitor use. The GRTS design also allows the program to cope with unforeseen circumstances, such as changes in budget, or with potential monitoring sites which are inaccessible or unsuited for monitoring. These advantages make probability-based surveys such as GRTS a popular method for natural resource monitoring in urban landscapes such as then NCRN (e.g. Hope *et al.* 2003, Nowak 2008).

Combining probability and model-based sampling

For the entire region, the spatially balanced GRTS sampling provides a basis for statistical interpretation of broad-scale forest change. For any individual park, however, only a limited number of samples are collected (Table 16.1). The GRTS-selected sample sites are not necessarily located at locations within the landscape that are most sensitive to change or are of most interest to park managers; such information was not incorporated into the probability-sample design. However, the graph-based model analysis provides an efficient means for addressing these local management needs. The hybrid monitoring approach, therefore, allows for regional-level monitoring while also providing park-level flexibility to add samples that inform local management concerns. We illustrate this integration of park-based modeling information for Antietam NBP.

A consideration of spatial processes and landscape context in site selection is particularly important for the small, mixed land-use parks of the NCRN that can be heavily influenced by external stressors. Antietam NBP was established to preserve the site of the US Civil War battle of Antietam and is mandated to preserve the landscape as it was during the battle in 1862. Since the war, land use has changed considerably, requiring the park to undertake battlefield restoration activities to restore the historical vegetation (e.g. cutting regenerating forest to maintain open battlefields). The vegetation in the park is predominantly open fields, which surround a number of small woodlots (Fig. 16.5). Forest cover comprises 35% of the total area of the park, with significant forested areas occurring along Antietam Creek on the east side of the park, and the Potomac River, just to the west of the park. The land surrounding the park is a mixture of agricultural, forest, and urbanized areas.

As part of the region-wide forest monitoring in NPS units, 210 potential sampling sites were located within the park's 780-ha legislative boundary (Fig. 16.5a). Of these 210 potential sites, 22 points were sufficiently high on the GRTS ordered list of potential samples to be potentially included in the forest monitoring (Fig. 16.5b). Of these 22 points, 15 were eliminated, either because they fell on land which is not currently owned by the NPS or because they fell on NPS land which is maintained as an open field (Fig. 16.5c).

One of the objectives of forest monitoring in the park is to evaluate the condition of forest dispersal corridors for birds and small mammals. Additional sampling is required to understand the quality of corridors. In relatively small parks with high levels of fragmentation, like Antietam NBP, the most important corridors to promote park connectivity may not always be located within the park. Therefore, it is useful to also consider the quality of potential corridors that lie just outside the park.

Data for the model-based sampling were collected following the graph-theory methods outlined in Townsend *et al.* (2009). We first created a graph representation of the park using 10-m SPOT satellite imagery classified as forest/non-forest. The graph includes the 578 discrete forest patches contained within the park, along with 663 adjacent patches contained in small watersheds that feed into the park. By constructing graphs covering a range of potential dispersal capabilities, a critical dispersal threshold (D_{crit}) was identified (Fig. 16.3). This distance indicates the minimum distance an organism would need to be capable of traveling through non-forest to be able to move among all 578 patches in the park (i.e. dispersal capability of at least 180 m for the Antietam landscape). We used this D_{crit} value to construct a graph that represents park forests as fully connected (Fig. 16.5d). This approach assumes there is not a specific species of concern for the monitoring and applies the rule-of-thumb approach for creating the graph described above. If instead, a single species were the focus of the monitoring effort, then information on that species dispersal characteristics and other life history parameters could be used to build the graph (see Lookingbill *et al.* 2010 for an example of a single-species analysis). Separate graphs could also be created for multiple species with differing dispersal capabilities and the results overlaid to determine priority areas for monitoring.

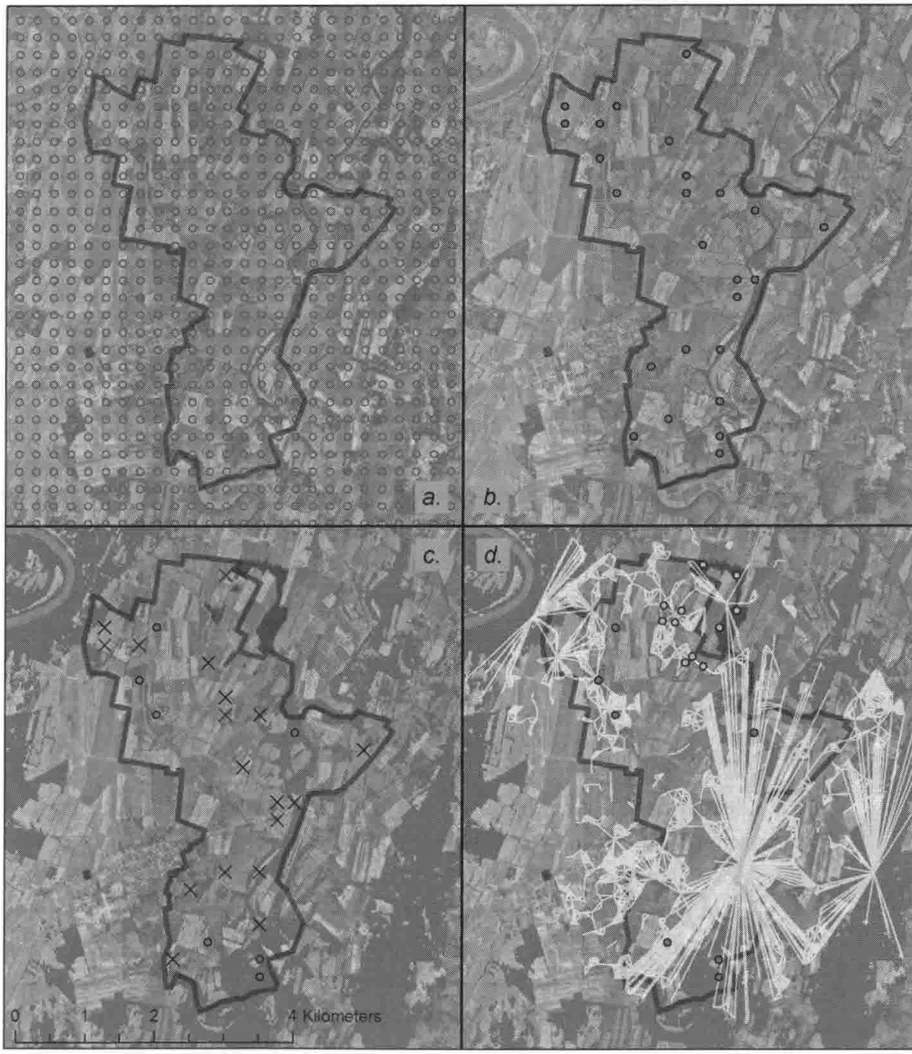

Figure 16.5 Example of the proposed approach to selecting monitoring sites in Antietam National Battlefield Park: (a) GIS was used to lay down a square grid of points, 250 m apart, over the entire NCRN. All points within park boundaries were treated as potential monitoring locations. (b) Of these potential locations, 757 were selected by the GRTS draw, 22 of which (red dots) fell within Antietam NBP. (c) These 22 sites were visited and the 7 that were in forest (red dots) were identified for monitoring. (d) Additional sample locations within potential bottleneck patches were identified by graph theory analysis. The graph representation of forest patches in and around Antietam NBP uses the D_{crit} value from Fig. 16.3 (i.e. 180 m) to define edges (yellow lines). Blue patches [shown in (c) and (d) for clarity] indicate priority locations for the 11 additional monitoring plots (green dots). See plate section for color version.

To identify priority areas in our Antietam example, we systematically removed each patch from our graph and then recalculated potential connectivity of the altered landscape. This iterative procedure identified specific patches whose loss would have the greatest effect on reducing the total area of connected habitat (A_{LC}) as shown in blue in Fig. 16.5d. When using our proposed method for developing a graph that represents the landscape as just barely connected (Fig. 16.3), there is generally an easily identifiable threshold change in A_{LC}. In these cases, removing a single patch can cause a change in connectivity of as much as 50%. For Antietam, these critical patches connect the Snavely Ford Woods along Antietam Creek in the eastern portion of the park to the riparian forest along the Potomac River northwest of the park. Those sites within the original sample grid frame (Fig. 16.5a) that fell within these forest patches but were not part of the original 400 sites selected were added to the proposed sampling effort. Also highlighted by the analysis was a relatively large patch of potential corridor forest just outside the park's current boundary. Because the park is continuously reassessing its holdings, this patch was added to the list of locations for monitoring. Sample points within the patch were located within the original GRTS framework, which was regional in scale and was not restricted to the current boundaries of NCRN parks.

Data collection

Forest vegetation plots were sampled at each site selected by the two-step design. The GRTS-based survey was conducted from 2006 to 2009 with the more focused, graph theory-based sampling conducted in 2008. For the GRTS-based component, data collected include identification of all woody plant species on the plot; measurement of trees (including saplings and seedlings), shrubs, and understory herbaceous plants; and quantification of coarse woody debris. These measurements were chosen as they provide information about the effects of deer browse, exotic invasive plants, and pathogens as well as about the quality of the habitat for wildlife. The graph theory-based component was concerned primarily with the quality of forest patches in terms of their invasive species composition and these plants were a focus of the data collection for that part of the sampling, as described below.

Testing management-relevant hypotheses with the hybrid design

The hypothesis to be tested by the model-based sampling was that the condition of important structural corridors in the parks differed from the overall quality of the parks' forests. Degraded corridors would be a cause for concern and potential management action, redirecting treatment to these critical resources. Alternatively, if superior quality corridors existed outside the park, it might be more efficient to focus conservation efforts on building strong partnerships with those neighboring landowners. We compared the invasive species communities found for the two different monitoring components as a means of testing our hypothesis. Eleven additional plots were sampled in patches identified by the graph-theory analysis (Minor *et al.* 2009). These were grouped in three clusters: two clusters comprised of a total of seven plots in critical patches within the park and one cluster of four plots within the potential corridor patch just outside the park's boundary. These data can be compared to the plots sampled in Antietam NBP as part of the GRTS design and the 400 plots sampled regionally.

As an example of our methodology, we compared the presence of invasive plant species on the seven forest plots from the GRTS sample with invasive species from the seven plots selected in Antietam NBP based on the graph-theory analysis. Our goal was to determine if there was a difference in the abundance of invasive plants between the two groups of plots. Within each plot, 12 quadrats (2 m long × 0.5 m wide) were surveyed for exotic invasive plants. Each plot was given an "invaded score", calculated by summing the number of invasive plants found on each quadrat of the plot. Thus, if a plot had two invasive plants, one found on eight quadrats and the other found on six quadrats, the invaded score for the plot would be 14. We determined the mean, variance, and confidence intervals of the invaded score for both the GRTS-based and the graph-based plots; analysis based on the GRTS design used the package "spsurvey" (Kincaid *et al.* 2009; see Chapters 6, 14) in R (R Development Core Team 2011). The plots from the GRTS-based survey had a significantly lower ($P < 0.05$) invaded score (17.1) than the seven critical corridor patches in the park (31.3). This is not surprising, as the plots selected based on the graph-theory model were, by design, located in smaller forest patches within the most fragmented part of the landscape. It was anticipated that these patches would be prone to invasion by edge-loving exotic plants, but the GRTS data provide a frame of reference for quantifying this degradation. If we take our exotic species metric as a reasonable measure of overall forest condition, we can conclude that these patches are unlikely to be serving a function as high quality forest corridors.

Interestingly, the four plots located in the patch outside the park boundary (Fig. 16.5d) had a mean invasive score (20.8) that did not differ significantly from the GRTS-based reference plots in the park. Given the greater forest cover outside the park (~42% in a 5-km buffer surrounding the park) than inside the park (~35% forest), the data fit with an expectation that larger, higher-quality forest corridors would exist outside park boundaries. It is worth noting that the lowest quality plot within this potential corridor (eight different exotic species with a total score of 26) was located closest to the park boundary. This observation leads to a secondary hypothesis to be tested by continued monitoring: invasive spread is occurring from the park into this potentially clean corridor. This concept was completely outside of our original conceptual model for the parks in this region, in which neighboring lands were viewed almost entirely as an external stressor and source of plant invasions. The next round of sampling could reallocate resources from the model-based portion of our sample design to focus on this new hypothesis.

Discussion

A review of the design of broad-scale monitoring programs found that most suffered from the lack of attention to the fundamental question: Why monitor? (Yoccoz *et al.* 2001). A clear and early statement of monitoring objectives is too often lacking (see also Chapters 2, 3, 18, 22). Without an explicit a priori objective statement, retrospective analyses of monitoring data permits only weak inference regarding the response of the system to management actions or proposed actions. Stronger inferences can be attained by comparing monitoring observations to existing model-based hypotheses. The graph-theory model proposed here provides a framework for this model-based sampling. The approach is particularly attractive for NCRN parks because it focuses monitoring around the issue of connectivity in fragmented landscapes, a topic of special concern for park management in these urbanizing settings. Future directions of this work include developing stronger linkages between the monitoring design and natural resource management activities within the parks (e.g. Lookingbill *et al.* 2008). The flexibility and hypothesis driven nature of the graph-theory approach provide a valuable tool for assessing effectiveness of management within an adaptive management framework.

The method of combining the design-based (based on the probabilistic GRTS design) and model-based (based on the graph-theory model) sampling addresses the inability of monitoring efforts to exhaustively survey large areas. In response to this challenge, a hybrid design produces: (i) a spatially balanced sample that is appropriate for regional trend detection and is not subject to biases produced by subjective selection of sites, and (ii) an efficient sample targeting sites that, based on the graph-theory model, are most critical to landscape-scale processes (in this case, species invasions). By providing information at the regional and landscape scales, data from a hybrid design can be valuable to management at multiple levels.

Future research and development

We have provided an example of how data from the two different sampling components can be compared. Further, the samples could be integrated regionally, for example, as an unequal probability stratified sample. One promising direction of future research would be to consider how the additional flexibility of the model design could be leveraged to provide a regional assessment that fluidly transcends spatial scale (e.g. through a correlogram or other similar spatial analysis).

The example application provided in this chapter also illustrates the selection of supplemental sites based on a hypothetical organism with movement capabilities equal to our rule-of-thumb D_{crit} distance that assumes full landscape connectance. Sites can also be identified as important in the context of managing for a particular wildlife species. For example, a number of small rodents and amphibians occupy the riparian forests of Antietam NBP, many of which have been shown to have dispersal abilities across non-habitat in the range of 180–500 m (Corry and Nassauer 2004). In cases where the focus is on a specific species, a reduced amount of data collection can take place at each of the plots, relating only to those aspects of the vegetation which are important to the species of interest. Additional refinements to the graph-theory model (e.g. multi-species, directional movement) or inclusion of altogether different model-based frameworks are other potential fruitful areas of research.

Summary

We have provided an overview of study design and analytic issues associated with long-term monitoring in mixed-use landscapes. The potential disparity between ecological and political boundaries in these landscapes poses a significant challenge for monitoring. An additional challenge is to provide information at relevant temporal and spatial scales to determine long-term trends and to address short-term urgent threats. We presented a hybrid method for confronting these challenges. The method combines spatially balanced, regional sampling with a model-based approach to address more local and immediate management needs. In the first step, locations for long-term monitoring are selected using a GRTS design. The randomized sampling provides an unbiased, coarse-scale assessment of regional trend. In the second step, a graph-theory model is applied to satellite imagery to identify additional monitoring locations to address more local concerns. The case study in the NPS National Capital Region illustrates how, in addition to providing information at different spatial scales, the sampling methods are complementary in their general approaches to monitoring. GRTS sampling provides a post hoc assessment of environmental changes that may or may not have been anticipated. The graph theory-based sampling provides an opportunity for a priori hypothesis testing of specific ecosystem processes – e.g. species dispersal and landscape connectivity. The graph-theory assessment additionally places park features into a broader landscape context by using maps of habitat within and around park units. The results are both hypothesis-based and provide new hypotheses for future monitoring via a flexible design.

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