

Comparing power among three sampling methods for monitoring forest vegetation

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Abstract: We compared three methods of sampling forest vegetation for their ability to reliably estimate changes in species richness, plant abundance, and overstory basal area and composition. Methods include the US Forest Service's Forest Inventory and Analysis (FIA) method and two other methods being considered for use in monitoring National Parks in the Northern Great Lakes ecoregion. All methods were successful at detecting changes in composite variables but lacked sufficient enough power to detect a 20% change in the abundance of most individual species. All three methods had high power for detecting changes in overstory tree communities but differed greatly in their ability to track shifts in understory composition and diversity. Although complete walk-through surveys of all species present provided adequate power for tracking changes in diversity, sampling only 12 ground layer quadrats limited the power of the FIA method. Methods that sample the understory more intensively provide a better balance of sampling effort and provide higher power to detect changes in forest understory communities. Aggregating data across sites of similar habitat also provides more powerful estimates of change.

Résumé : Nous avons comparé la capacité de trois méthodes d'échantillonnage de la végétation forestière à estimer avec fiabilité les changements de richesse en espèces, d'abondance des espèces, de surface terrière et de composition de la canopée. Ces méthodes incluent la méthode d'inventaire forestier et d'analyse du Service forestier des É.-U., ainsi que deux autres méthodes qui échantillonnent le sous-bois de façon plus exhaustive. Nous examinons ces méthodes en vue de leur utilisation dans le cadre d'un programme de suivi de la végétation dans un parc national de l'écorégion du nord des Grands Lacs, aux É.-U. Toutes ces méthodes peuvent détecter les changements dans les variables composites mais ne sont pas capables de détecter un changement de 20 % ou moins dans l'abondance de la plupart des espèces. Les trois méthodes peuvent facilement détecter les changements dans les communautés d'arbres de la canopée mais leur capacité à suivre les variations de la diversité et de la composition du sous-bois est très différente. Ainsi, les méthodes qui échantillonnent le sous-bois de façon plus intensive sont beaucoup plus performantes que celle du Service forestier pour détecter un changement de richesse et de composition du sous-bois. Même si des relevés complets qui échantillonnent toutes les espèces présentes sont adéquats pour suivre l'évolution de la diversité, un échantillonnage de seulement 12 quadrats au sol limite la performance de la méthode du Service forestier. Les méthodes qui échantillonnent le sous-bois de façon plus exhaustive procurent un meilleur équilibre de l'effort d'échantillonnage ainsi qu'une plus grande capacité à détecter les changements dans les communautés forestières de sous-bois. Le regroupement des données provenant de stations qui constituent des habitats similaires permet également d'obtenir de meilleures estimations du changement.

[Traduit par la Rédaction]

Introduction

Monitoring is vital both for assessing ecological change and for devising effective responses to it. We also use ecological monitoring to assess how current conditions compare with natural ranges of historic variability. Although the general value of monitoring programs is widely acknowledged and their numbers have increased [e.g., Ecological Monitoring and Assessment Network (EMAN) in Canada (Vaughan et al. 2001) and United States Long Term Ecological Re-

search (US LTER) Network (Hobbie et al. 2003)], many such programs appear to collect insufficient (or inadequate) data to make reliable inferences regarding long-term ecological change (Legg and Nagy 2006), reducing their utility for informing management decision making (Bisbal 2001). For example, most studies of recruitment limitation in forests tend to focus on one or a few stands and extend from one to only a few years (Clark et al. 1999).

Because monitoring programs that have low power to detect ecological changes may create a false sense of security despite serious changes, their power and objectives should be determined at their outset (Peterman 1990; Legg and Nagy 2006). Failures to detect actual changes are termed type II errors. "Power" refers to the probability of detecting a true change given some particular sample and is a function of the sample size, variability, effect size, and type I error rate (α ; Sokal and Rohlf 1995). We generally achieve increased statistical power by reducing the error of our estimates with more sampling or by using more powerful statistical tests (e.g., parametric and randomization tests). Retrospective power analyses can be used to evaluate the adequacy and

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reliability of sampling (e.g., the Shenandoah National Park vegetation inventory program; Mahan et al. 2007). However, power tests are more informative if applied during the design phase (Cohen 1988; Foster 2001; Dixon and Pechmann 2005). Although some argue that retrospective power analyses should never be conducted because power and resulting P values depend on observed effect sizes (Goodman and Berlin 1994; Gerard et al. 1998; Hoenig and Heisey 2001), prospective power analyses require a priori estimates of anticipated effect sizes and expected errors for parameters of interest (Morrison 2007). Lacking such a priori estimates, resource managers often proceed to develop monitoring programs without making important initial assessments to ensure that the data they collect will allow managers to reliably track key variables.

Forests consist of multiple layers of vegetation, many functional guilds, and a diverse set of species that can respond sensitively to environmental conditions (Noss 1990). Regularly sampling these layers thus provides an informative set of indicators for tracking ecological change in a community that provides the structure and productive base for most organisms. The ground layer is of particular importance because of its diversity (e.g., 2684 herb and shrub species versus 148 tree species in the Wisconsin flora; available from wisplants.uwsp.edu/VascularPlants.html) and because turnover there can be rapid owing to the presence of short-lived species. Hence, this arises as a key issue for evaluating the suitability of alternative sampling methods.

The primary objectives of the National Park Service's vegetation monitoring program in the Great Lakes ecoregion are to determine (i) whether plant communities are shifting in composition, (ii) how the structure of plant communities is changing, and (iii) what the rate and direction of change are for particular focal species. Scientists also seek to link these observed changes to other variables and to potential driving factors. The Park Service in this region particularly seeks to assess changes associated with: succession, soils, terrestrial pests and pathogens, and keystone herbivores like white-tailed deer (Route and Elias 2005). Spatially extensive, long-term monitoring programs are also likely to cast light on climate change induced responses including shifts in plant phenology, geographic range, and local abundance (Bradley et al. 1999; Davis et al. 2000; Houghton et al. 2001). Monitoring programs also gain power if they can be linked with historical surveys (e.g., Rooney et al. 2004) or more geographically widespread networks.

Here, we compared three methods for sampling forest vegetation in the context of the nine National Parks in the upper Great Lakes Region (Fig. 1). First, we evaluated methods of the US Forest Service's Forest Inventory and Analysis (FIA) program. The FIA program was developed in the 1930s to estimate standing stocks of timber volume across the US National Forests and was extended in 1999 to monitor US forestlands of any ownership (Frayer and Furnival 1999). Second, we applied and evaluated the method first used by the Plant Ecology Laboratory of the University of Wisconsin–Madison (PEL) in the 1940s and 1950s. The PEL method is associated with a detailed historical baseline data set (Curtis 1959) that has been used to document changes in forest communities (e.g., Rooney et al. 2004; Rogers 2006). Finally, we developed a new "Hybrid"

method designed to efficiently sample forest vegetation (Johnson et al. 2006). Because both the FIA and PEL methods emphasize sampling the overstory, we sought to place greater emphasis on adequate understory sampling with the Hybrid method.

We evaluated the estimates of species richness returned by all three methods and compared their statistical power for detecting change in vegetation metrics associated with the overstory, midcanopy, and ground layer. Because several forest habitat types exist among the Great Lakes Inventory and Monitoring Network (GLKN) parks, we compared methodologies across representative habitats in both the Apostle Islands (APIS) and Pictured Rocks (PIRO) National Lakeshores. As we demonstrate, stratifying analyses by these habitat types can improve estimates of variables and consequent power for detecting ecological change. Such stratification raises important issues of how to identify these habitat types and track transitions among them. We return to these issues in the Discussion.

Policy goals

The US National Park Service (NPS) established its inventory and monitoring program to evaluate park resources and facilitate early detection of ecosystem changes. The nine parks of the GLKN considered vegetation change to be a priority indicator of ecosystem health and thus sought to design protocols to assess local and regional plant community composition every 5–10 years, and thus change over time. Their specific goal in this program is to have 80% power to detect a 20% change in various vegetation metrics while maintaining a 10% false-change error rate (type I error, α). Such changes might occur in either a short or long period of time. This criterion closely resembles those used in other resource monitoring programs (e.g., Park Service Fire Monitoring Program; USDI National Park Service 2003).

Methods

Study locations

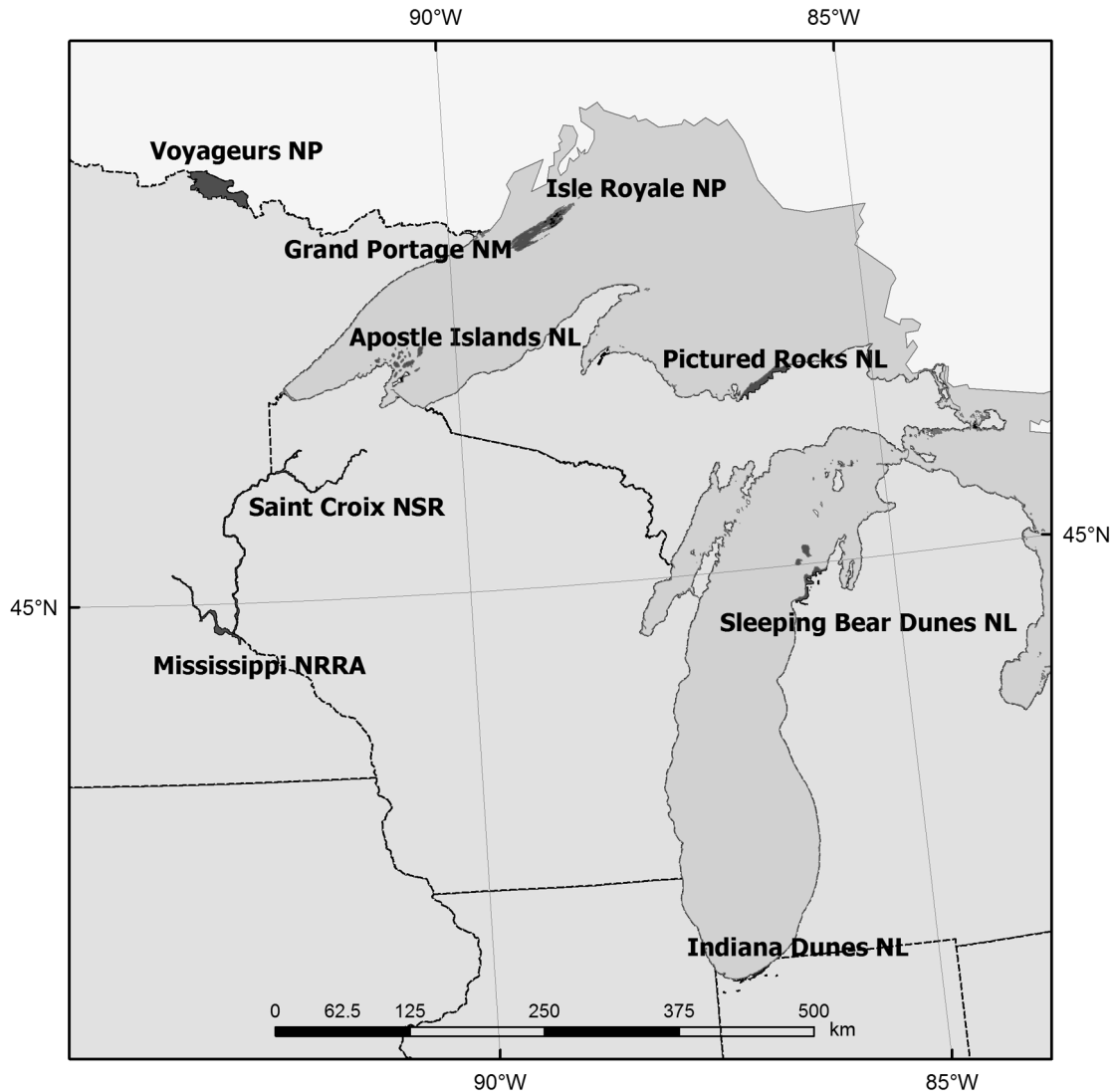
We compared paired methods at each study site within APIS and PIRO National Lakeshores, which both lie adjacent to Lake Superior (Fig. 1). The APIS are an archipelago of 21 islands at the tip of the Bayfield County peninsula in northwestern Wisconsin. PIRO extends along the northern shoreline of Michigan's Upper Peninsula. Its forests contain elements of eastern deciduous forests together with many wet forests (i.e., cedar swamps and wetland conifer forests). Both parks also maintain a mix of northern hardwood, conifer, and some southern boreal forest. PIRO is divided into two distinct ownership and management zones—a federally owned shoreline and a nonfederal buffer zone subject to sustained yield timber harvesting and other consumptive uses. The buffer zone contains more early-successional stands (i.e., younger trees and a dense understory) than the federally owned shoreline.

Site selection

Apostle Islands National Lakeshore

We resampled 20 sites that had been initially surveyed

Fig. 1. Map of the Great Lakes Inventory and Monitoring Network, United States. NL, National Lakeshore; NM, National Monument; NP, National Park; NSR, National Scenic Riverway; and NRRRA, National River and Recreation Area.



using PEL methods in 1958, which allowed us to simultaneously collect data for a separate study of long-term plant community changes. Twenty is the minimum number of sites likely to be sampled at each park by the GLKN. We selected sites to allow adequate replication within a few dominant habitat types, which tended to concentrate sites among the larger islands. We relocated sites using original maps and descriptions from Beals and Cottam (1960).

Pictured Rocks National Lakeshore

We resampled 20 of the permanent FIA-style plots installed by PIRO resource managers 4–5 years earlier. We allocated sampling effort across habitats at PIRO in rough proportion to the logarithm of each habitat's area, purposely excluding scarce habitats and recently logged sites. We used topographic maps and GPS units to relocate the permanently marked FIA plots.

Survey methods

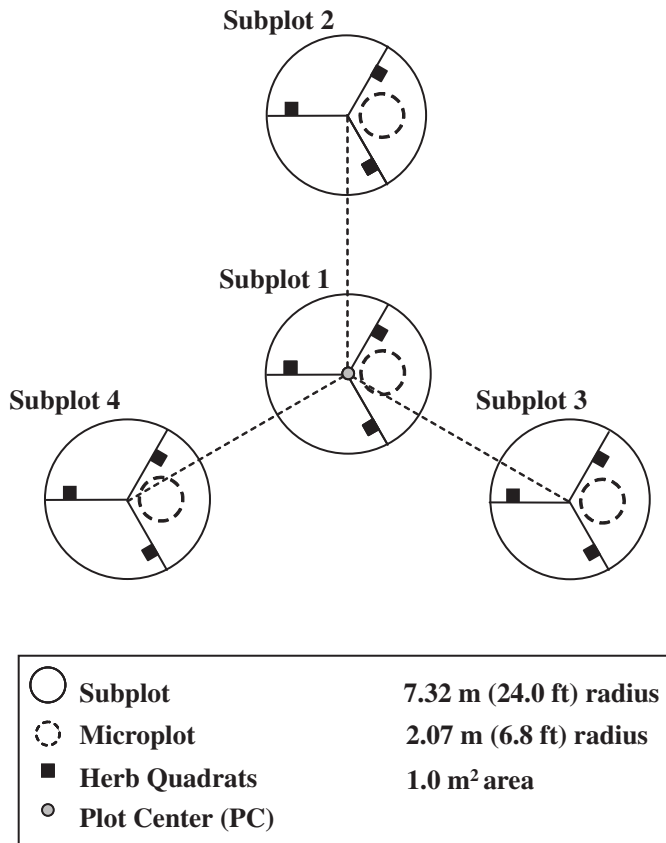
We defined all woody plants >10.16 cm diameter at breast height (DBH) as trees, those 2.54–10.16 cm DBH as

saplings, and those <2.54 cm DBH as tree seedlings or shrubs. These criteria (based on PEL methods) depart slightly from FIA definitions for trees (>12.70 cm DBH) and saplings (2.54–12.70 cm DBH). We identified individual shrubs as a cluster of one or more stems arising from the same root system within 2.5 cm below the soil surface. We did not enumerate woody vines or *Rubus* spp. as it was difficult to count individuals. Within the 1 m² ground layer quadrats at each site, we recorded the presence of all vascular plant species, including tree seedlings, shrubs, and herbs (referred hereafter as “ground layer” plants) rooted within the quadrat.

Forest inventory and analysis

The original FIA protocol aimed at sampling overstory trees has been repeatedly revised to include additional metrics. A standard national configuration is now being implemented under the Enhanced FIA program. As of 2000, four permanent fixed-area circular plots are positioned in a triangular array across ~0.61 ha (1.5 ac) of forest for FIA (McRoberts et al. 2005; Fig. 2). The Enhanced FIA program

Fig. 2. Diagram of the Forest Inventory and Analysis (FIA) phase 2 and 3 plot design. Subplots were used for sampling trees at Apostle Islands (APIS) and Pictured Rocks (PIRO), but were also used for sampling saplings and for conducting ground layer walkthroughs at PIRO. The outer subplots are located 36.6 m away and at 0° (subplot 2), 120° (subplot 3), and 240° (subplot 4) from the plot center of subplot 1. Microplots were used to sample saplings at APIS and shrubs at both APIS and PIRO. Quadrats were used to sample the presence of herbaceous and woody ground layer plants. These quadrats were located 4.57 m away at 30°, 150°, and 270° from the center of each subplot, along coarse woody debris transects; however, we do not present coarse woody debris data here.



integrates components of previous phase 2 (P2) FIA and Forest Health Monitoring (FHM) programs in a phase 3 (P3) protocol that samples, among other indicators, ground layer variables associated with forest ecosystem health. The P3 protocol is applied to one-sixteenth of all forested FIA sites or approximately one plot per 39 000 hectares (96 000 ac) throughout the United States (McRoberts et al. 2005). The FIA program also is undergoing intensification in many of the Great Lakes states.

The four FIA subplots have a radius of 7.32 m (Fig. 2). Subplots 2, 3, and 4 are located 36.66 m away horizontally at azimuths of 0°, 120°, and 240°, respectively, from the center of subplot 1. Within subplots, we identified all trees and measured their DBH. Each subplot contained a microplot with a radius of 2.07 m located 3.66 m due east from the subplot center. In these we recorded the species and DBH of all saplings and the number of all shrub species.

Because sampling at APIS demonstrated that few saplings were detected with this method, we adjusted the protocol at PIRO to sample the full subplot for saplings (the area sampled for trees).

As per the FIA protocol, we sampled all ground layer vascular plants within twelve 1 m² quadrats at each site. These quadrats were placed 4.57 m from each subplot center along transects running out at azimuths of 30°, 150°, and 270°. We also implemented the FIA protocols for a thorough timed walkthrough survey at PIRO to record all the ground layer species present in all subplots (673 m²).

Plant Ecology Laboratory methods

We applied the PEL methods originally used by Beals and Cottam (1960) to sample sites at APIS. The PEL approach sampled a ~1 ha area via 40 points typically spaced 10 paces apart along four parallel transects 10–20 paces apart, depending on size and shape of the area (Fig. 3). They always placed transects to maintain a buffer of at least 25 m from the forest edge. At each of these 40 points, PEL used the “point-centered-quarter” method to sample four trees noting their diameters and distances from the point. By assuming that trees are distributed randomly, they could estimate tree density, basal area (BA), and other variables of interest. This method, however, introduces systematic biases when trees are actually clumped or overdispersed (Cottam and Curtis 1956), which we discuss further in the Discussion. The original PEL method noted all ground layer species present within a 1 m² quadrat at every other point ($n = 20$). However, beginning in the early 2000s, the PEL methods have been enhanced by doubling or quadrupling quadrat numbers. Hence, we sampled the ground layer within 1 m² quadrats at 40 points (Fig. 3). We also sampled saplings and shrubs in 4 m² quadrats centered on each of 40 points (an addition to the PEL method; Johnson et al. 2006). For resampling the original stand area, transects were laid out relative to a random start point.

Hybrid method

We developed the Hybrid method to efficiently sample an area similar to that covered by the FIA method and applied this method at PIRO. The layout consists of three parallel permanently marked 6 m × 50 m transects that are quick to set up and efficient to survey without backtracking (reducing trampling). Transects were spaced 50 m apart to extend the sampled area to roughly the same extent as the FIA method (0.88 versus 0.92 ha for the FIA method and 1.74 ha for the PEL method; Table 1). We identified the species and measured the DBH of all trees and saplings within each 6 m × 50 m strip transect. The end points on each transect formed the center of two 2.82 m (9.25 ft) radius circular plots (Fig. 4) used to sample the number of individuals for each shrub species. We sampled ground layer plants in 1 m² quadrats placed 5 m apart along each transect ($n = 30$ total quadrats). This spacing was sufficient to ensure that quadrats represent independent subsamples of the site for most understory species (based on analyses of spatial autocorrelation—analyses not shown). We also conducted thorough 15 min walkthroughs along the 6 m × 50 m transects (Fig. 4), noting all ground layer species not yet recorded within the sampled quadrats.

Fig. 3. Diagram of the Plant Ecology Laboratory (PEL) plot design. Trees were sampled using the point-quarter method at the same point as the position of herb quadrats.

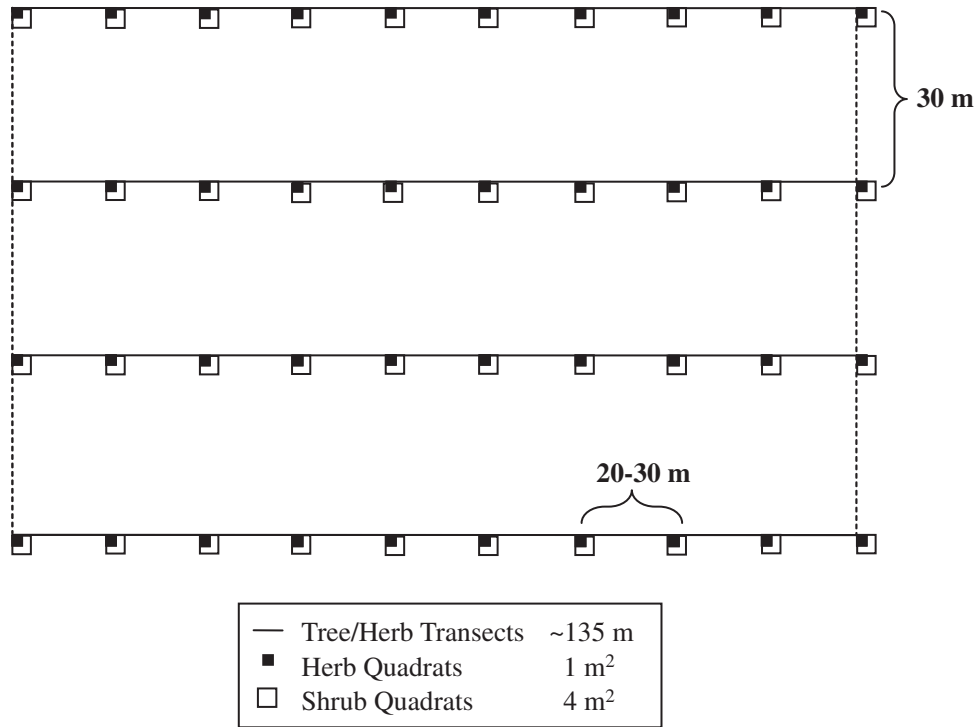


Table 1. Sample area characteristics for each sample method used at Apostle Islands (APIS) and Pictured Rocks (PIRO) National Lakeshores, summer 2005.

		Location			
		APIS		PIRO	
		Sampling method		Sampling method	
Vegetation type	Parameter	PEL	FIA	FIA	Hybrid
	Aerial extent with 10 m buffer (ha)*	1.740	0.920	0.920	0.880
	Number of forested stands sampled	20.00	20.00	20.00	20.00
Herbs:					
Quadrats	Sample area per stand (m ²)	40.00	12.00	12.00	30.00
	Minimum distance between any two quadrats (m)	15.00	7.920	7.920	5.000
	Mean (±SE) distance between any two quadrats (m)	71.16 (±1.160)	41.44 (±1.980)	41.44 (±1.980)	53.88 (±1.500)
Walkthroughs	Sample area per stand (m ²)	—	—	673.0	900.00
Trees	Sample area per stand (m ²) [†]	3282 (±1388)	673.0	673.0	900.0
Shrubs	Sample area per stand (m ²)	160.0	53.85	53.85	149.8
Saplings	Sample area per stand (m ²)	160.0	53.85	673.0	900.0

Note: PEL, Plant Ecology Laboratory of the University of Wisconsin–Madison method; FIA, US Forest Service Forest Inventory and Analysis method; and Hybrid, new method designed to efficiently sample forest vegetation.

*Aerial extent for FIA is based on a 53.98 m radius around plot center with a 10 m buffer.

[†]The sample area for PEL trees = 160 trees/(density per m²); the mean distance to all 160 trees per stand was used to estimate tree density per m² using the following formula: density per m² = 1 m²/(mean distance in metres)².

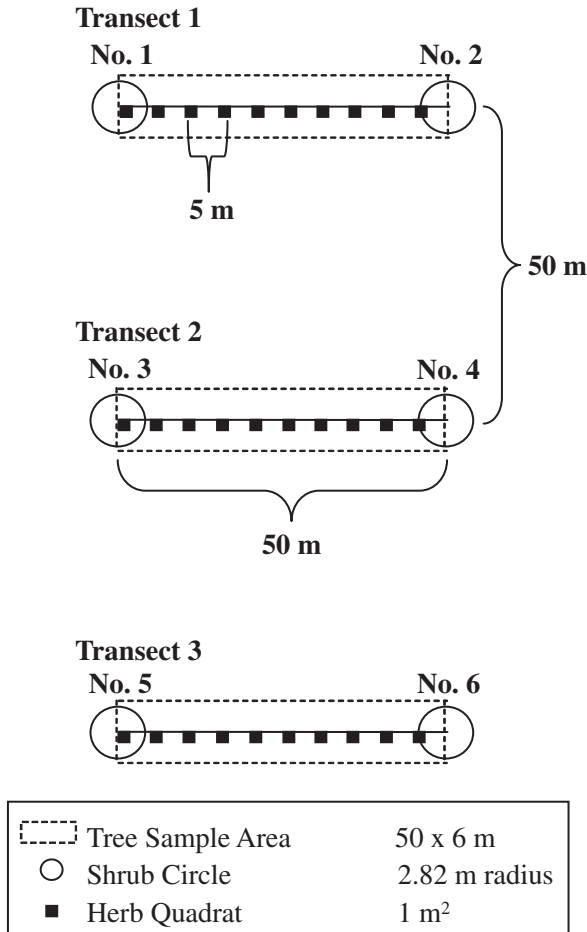
Statistical analyses

We used nonmetric multidimensional scaling ordination to poststratify sites at APIS and PIRO into discrete habitat groups (PC-ORD Version 4.25; McCune and Grace 2002). Our distance matrix was based on Bray–Curtis measures of dissimilarity among sites using frequency data for the ground layer species. Clear groupings of sites emerged from these ordinations with the patterns of differentiation most highly correlated with overstory composition (BA of dominant tree species) among environmental variables.

We applied two-way analyses of variance (ANOVA) to evaluate how estimated levels of species richness in each vegetation layer varied in response to sampling method, habitat type, and their interaction (i.e., does how species richness depend on habitat vary by sampling method). Where needed, the data were log transformed to meet the homogenous variances assumption of ANOVA.

We next generated species–area curves for ground layer vegetation by habitat to compare how additional sampling increased estimates of total species richness as a function of

Fig. 4. Diagram of the Hybrid plot design used for comparison with the Forest Inventory and Analysis (FIA) method at Picture Rocks (PIRO) National Lakeshore. All trees (>2.5 cm DBH) were sampled within the tree sample area, including saplings. Quadrats were used to sample the presence of herbaceous and woody ground layer plants. These quadrats were located along coarse woody debris transects; however, we do not present coarse woody debris data here.



the total area sampled by each method. We applied EstimateS to the frequencies of species in each layer across all plots in a stand to generate sample-based rarefaction curves and 95% confidence intervals (Colwell 2005). To evaluate how precisely each method estimated total tree BA (m^2/ha), we calculated its mean and standard error within each habitat type at both APIS and PIRO as a function of the number of individual trees sampled and expressed this as a percentage of the mean.

Power analyses

The Great Lakes Network seeks to implement sampling methods to allow them to detect a 20% change ($\alpha = 0.1$ and power $\geq 80\%$) in various vegetation metrics between successive sampling periods. Just when such a 20% change will become detectable clearly depends on the rates at which these metrics change and the interval of remeasurement. The NPS expects to resample sites every 5 years, implying that very rapid changes might be detected even after a single interval, while slower changes would become manifest more slowly after several rounds of sampling.

We evaluated the relative statistical power of each sampling method for detecting this 20% change (δ) by modeling systematic ecological change and evaluating how sensitive each sampling scheme is for detecting this change. In particular, we modeled 20% increases and decreases in various metrics between an initial year A relative to a final, hypothetical year B when the new mean metric would have the value:

$$[1] \quad \bar{x}_B = \bar{x}_A + \delta \bar{x}_A$$

To mimic reality, we allowed the δ_i for each site i , to vary stochastically around a mean change of 20%, with a standard deviation, σ (see the following), giving values of δ_i from the normal distribution ($0.2, \sigma^2$). We further accounted for within-site variability by allowing the values of change among subplot and transect units to vary according to a normal distribution around the δ_i for a site with a variance equal to what we actually observed among subunits at that site in 2005.

To obtain reasonable estimates for σ , we compared our 2005 data with those collected at the same sites in 2001 at PIRO, as well as similar 5 year change data collected in northern Wisconsin forests (D.M. Waller, unpublished data). For each reference site j , we solved eq. 1 for the percent change (δ_j) in the mean value of a given metric between the two sample years and determined the standard deviation (σ_{obs}) across all δ_j . We ran the model with the observed standard deviations (σ_{obs} , rounded to the nearest 0.1 or 0.05).

We used nonparametric Wilcoxon tests to assess whether the differences in means detected between years A and B were significant, repeating each simulation 1000 times. We estimated the power or probability that the simulated change would be observed using each sampling method, as the frequency that the modeled change was detected as “significant” based on a false-change (type I) error rate of $\alpha = 0.1$. We performed all analyses with R version 2.3.1 (R Development Core Team 2006). We performed these simulations for a representative set of composite variables including BA, density, and species richness and overall frequency as well as the frequency of a few common guilds and species.

Results

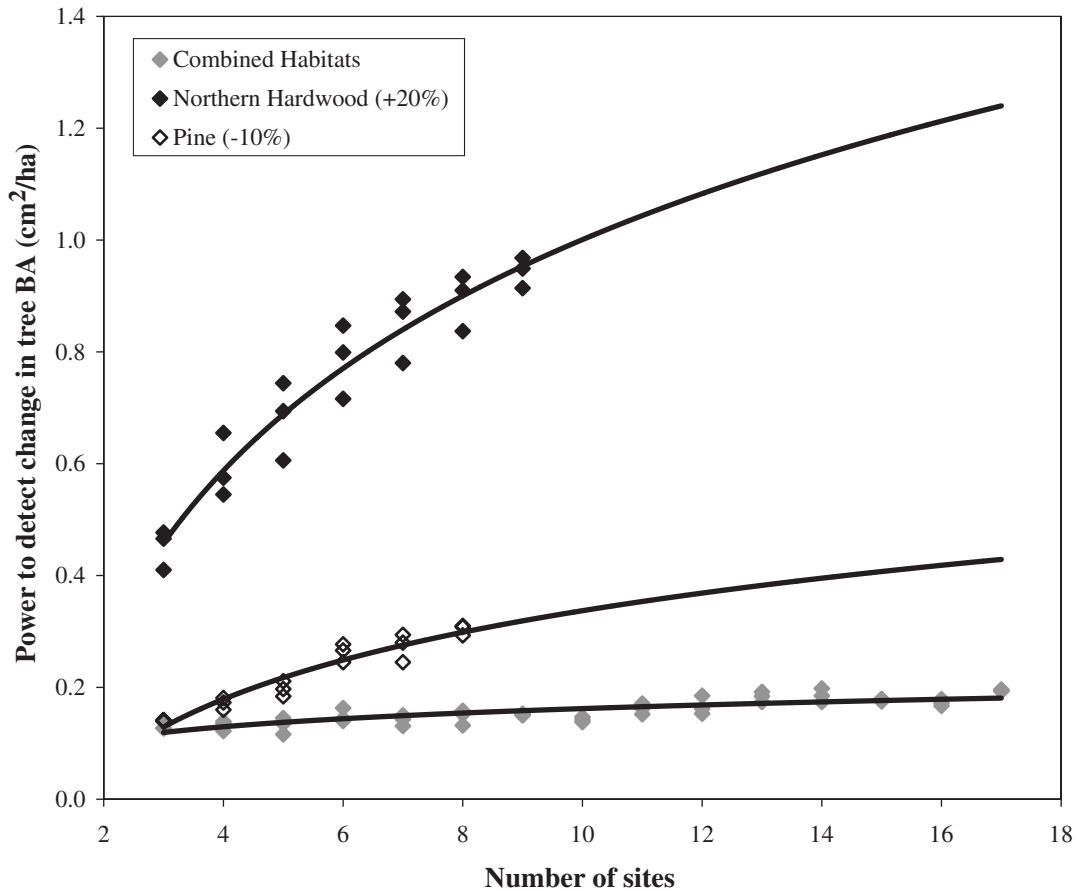
Habitat groupings

The ordination analyses allowed us to classify sites at APIS as upland mixed hardwood, conifer–hardwood mix, or hardwood–conifer mix and at PIRO as northern hardwood, pine, cedar swamp, or wetland conifer. These classifications were used for stratifying sites in analyzing patterns of species richness. For example, the Hybrid method could detect a 20% increase in tree BA in Northern Hardwood sites at PIRO, but was unable to detect a simultaneous 10% decrease in BA at Pine sites (Fig. 5). When we pooled both habitats for analysis we lost power, despite an increase in overall sample size, for detecting the change that we observed previously with data aggregated by habitat (Fig. 5).

Patterns of species richness

Distinct habitat types differed considerably in species richness within the same forest layer. However, our estimates of how species richness varied with sampling method

Fig. 5. Power to detect a change in tree basal area (BA, cm²/ha), when sites across habitat types were analyzed separately and jointly (grey diamonds) with data obtained with the Hybrid method at Pictured Rocks National Lakeshore (PIRO). This depicts a modeled scenario where two habitat types experienced different changes in tree BA—Northern Hardwood sites increased by 20% and Pine sites decreased by 10%. The modeled changes were applied to empirical data collected at these sites in the summer of 2005. Logarithmic regression lines have been fitted to the values obtained from running the model with the observed σ (0.05) and $\sigma = 0.10$ and 0.15.



did not depend on habitat (i.e., there were no significant interactions in the two-way ANOVAs). This allows us to compare power between the methods in the following without explicitly mentioning the habitat(s) involved.

Trees

Not surprisingly, given its greater sampling, the PEL method detected far more individuals and a mean of 30% more species of trees per site (8.6 versus 6.1) than the FIA method at APIS controlling for habitat type ($F_{1,34} = 12.7$ and $P < 0.01$). The PEL method also consistently gave higher estimates of BA than the FIA method (Fig. S1),² perhaps reflecting a systematic bias (see Discussion).

Despite differences in plot shape, arrangement, and area surveyed, the Hybrid and FIA methods returned similar estimates and comparable levels of precision for most metrics concerning trees at PIRO. Estimated mean richness of tree species, for example, did not differ between the Hybrid and FIA methods ($P = 0.48$) and the two methods gave similar estimates of BA. The larger area surveyed using the Hybrid

method (900 versus 673 m²) allowed it to detect 20%–35% more individual trees, reducing the standard error (Fig. S2).²

Because the PEL method sampled saplings across an area 66% larger than the FIA method at APIS (Table 1), the PEL method also detected more species (3.8 versus 2.1; $F_{1,34} = 3.41$ and $P < 0.001$). Estimates of density, however, did not differ between methods ($P = 0.35$). Perhaps because the Hybrid method sampled only 25% more area for saplings than did the modified FIA method, neither richness nor density differed between these methods at PIRO ($P = 0.48$).

Shrubs

At APIS, the PEL method sampled 66% more area for shrubs (Table 1) than did the FIA method, producing estimates of species richness for shrubs that averaged 40% higher (8.6 versus 5.2; $F_{1,34} = 11.1$ and $P < 0.01$). In contrast, although the Hybrid method sampled a 64% larger area for shrubs than FIA at PIRO, it detected only a mean of 20% more shrub species (6.6 versus 5.2 ($F_{1,32} = 2.76$ and $P = 0.11$)).

²Supplementary data for this article are available on the journal Web site (cjfr.nrc.ca) or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Building M-55, 1200 Montreal Road, Ottawa, ON K1A 0R6, Canada. DUD 5246. For more information on obtaining material refer to cisti-icist.nrc-cnrc.gc.ca/irm/unpub_e.shtml.

Ground layer

The larger number of quadrats allowed the PEL method at APIS and the Hybrid method at PIRO to capture more of the species present in the ground layer than the FIA method (APIS: 21 versus 13 species, $F_{1,34} = 8.04$, and $P < 0.01$; PIRO: 19 versus 14 species, $F_{1,32} = 4.30$, and $P < 0.05$). These differences largely reflect species accumulation in larger area samples as illustrated by the parallel rarefaction curves for the Hybrid and FIA methods at PIRO (Fig. S3)² and the PEL and FIA methods at APIS. As expected, mean richness within 1 m² ground layer quadrats was equivalent between the FIA and Hybrid methods at PIRO ($F_{1,32} = 0.87$ and $P = 0.36$) and between the FIA and PEL methods at APIS ($F_{1,34} = 9.17 \times 10^{-5}$ and $P = 0.99$). Mean total species richness estimated via the walkthrough surveys did not differ between the FIA and Hybrid methods in the commoner habitats (27.0 versus 25.8; $F_{1,22} = 0.06$ and $P = 0.80$), although the Hybrid walkthrough detected 24% more species than the FIA at the wetland–conifer site.

Statistical power to detect change

Trees

The FIA and PEL methods both had high power to detect a 20% change in tree density and BA at APIS (Table 2). However, the PEL method required fewer stands than the FIA method to detect this level of change (three to four fewer for density and greater than five fewer for BA). The FIA method also had high power for detecting 20% changes in tree density and BA at PIRO. However, the Hybrid method required two fewer stands than FIA to attain 80% power to detect this change in BA (Table 3). All methods had notably low power to detect a 20% change in the density of individual tree species like *Betula papyrifera* Marsh. at APIS (Table 2) and *Fagus grandifolia* Ehrh., *B. papyrifera*, or *Tsuga canadensis* (L.) Carrière at PIRO (Table 3), despite the fact that these species dominated the sites sampled.

At APIS, the FIA method had low power to detect a 20% change in sapling density and BA. The PEL method had 44% more power for detecting changes in sapling density and 21% more power for capturing changes in BA (Table 2). At PIRO, the Hybrid method did not reach 80% power, however, it still outperformed the modified FIA method by attaining 69%–70% power for detecting a 20% change in sapling density and BA (exceeding the FIA method by 12.6% and 42.9%, respectively; Table 3).

Shrubs

All methods produced high power for detecting a 20% change in the species richness of shrubs at APIS and at PIRO (Tables 2 and 3). However, the FIA method required eight more sites than the PEL method and three more sites than the Hybrid method to attain $\geq 80\%$ power. Both the PEL and FIA methods had high power for detecting a 20% change in the number of shrubs at APIS. Nevertheless, only five sites sufficed to reach 80% power using the PEL method versus 16 sites using the FIA method (Table 2). At PIRO, neither the Hybrid nor the FIA method attained more than 50% power for detecting a 20% change in the number of shrubs (Table 3). The PEL method had 99% power for tracking change in the frequency of woody plants observed

in the ground layer quadrats at APIS versus 74% power with the FIA method (Table 2). However, at PIRO, both the FIA and Hybrid methods had only moderate power for detecting change in woody seedlings and shrubs sampled within 1 m² quadrats (Table 3).

Although the PEL and FIA methods had high power to detect changes in the number of shrubs at APIS, neither method was intensive enough to detect 20% changes in the abundance of individual species of shrub or tree seedlings such as *Taxus canadensis* Marsh. or *Acer spicatum* Lamb. (Table 2). The forty 1 m² ground layer quadrats of the PEL method allowed us to detect 20% changes in the frequency of *Taxus* with 99.8% power using 17 of the 20 sampled sites. The FIA method achieved 71% power for detecting a 20% change in *Taxus* across 15 sites (29% lower than the PEL method; Table 2).

Ground layer

The PEL and Hybrid methods consistently outperformed the FIA method in being able to detect changes in ground layer vegetation. The FIA method never acquired 80% power for any variable assessed using the ground layer quadrats (Tables 2 and 3). In contrast, PEL required only 13 sites to reach 80% power to detect a 20% change in forb richness at APIS (versus 48% power attained with 19 sites using FIA). Similarly, the Hybrid method achieved a power of $\geq 80\%$ to detect a 20% change in species richness of forbs with 17 sites at PIRO, whereas FIA never reached even 20% power for this metric. At APIS, the total frequency of forbs assessed using the PEL method proved to be a sensitive indicator of change with only seven sites needed to reach 80% power. At PIRO, the Hybrid method reached 66% power to detect a 20% change in total forb frequency, whereas FIA never exceeded 15% power using the same number of sites (Table 3). For detecting changes in the frequency of ferns, the Hybrid method had approximately twice the power of the FIA (Table 3). This difference was even greater at APIS where the additional area sampled with the PEL method provided 86% more power than FIA for detecting changes in the frequency of ferns (Table 2). No method reached even 20% power for detecting a 20% decline in the frequency of the most abundant herb species [*Clintonia borealis* (Ait.) Raf. at APIS (Table 2) and *Maianthemum canadense* Desf. at PIRO (Table 3)].

Both the FIA and Hybrid methods reached $>90\%$ power to detect a 20% change in total species richness of ground layer species at PIRO using walkthrough data (Table 3). However, the Hybrid walkthrough surveys provided 50% more power for detecting changes in the richness of forbs relative to the FIA method (Table 2). With the Hybrid method, both walkthrough surveys and quadrat sampling gave similar high power ($>80\%$) for detecting a 20% change in forb richness (Table 3) using 15 sites.

Discussion

Prospective power analyses based on empirical field data and anticipated patterns of change provide valuable insights for comparing alternative field-survey methods. The results from these simulations have assisted the GLKN in making decisions regarding the trade-off in sampling sites more in-

Table 2. Power (percentage of P values < 0.1 ; power values $\geq 80\%$ are in boldface type) of the US Forest Service Forest Inventory and Analysis (FIA) and the Plant Ecology laboratory of the University of Wisconsin–Madison (PEL) sampling methods for detecting changes in vegetation at Apostle Islands National Lakeshore, Wisconsin.

Level of analysis	Vegetation parameter	FIA		PEL		σ^\dagger	Power (%) to detect 20% change			Min. no. of sites sampled to attain 80% power [‡]	
		Area sampled per site (m ²)	No. of sites*	Area sampled per site (m ²)	No. of sites*		FIA	PEL	Additional power of PEL at 20% change	FIA	PEL
Ground layer quadrats	Forb frequency	12.0	19	40.0	20	0.15	45.6	99.9	+54.3	ns	7
	Forb richness	12.0	19	40.0	20	0.20	47.9	94.5	+46.6	ns	13
	Fern frequency	12.0	16	40.0	17	0.20	10.4	96.0	+85.6	ns	11
	Fern ally frequency	12.0	17	40.0	19	0.20	7.4	57.4	+50.0	ns	ns
	<i>Clintonia borealis</i> frequency	12.0	11	40.0	11	0.25	16.9	18.9	+2.00	ns	ns
	Woody understory frequency	12.0	20	40.0	20	0.20	74.3	99.4	+25.1	ns	10
	<i>Taxus canadensis</i> frequency	12.0	15	40.0	16	0.35	71.3	99.8	+28.5	ns	6
Shrub quadrats – microplots	Shrub richness	160.0	20	53.9	20	0.25	93.9	99.9	+6.00	14	6
	No. of shrub stems	160.0	20	53.9	20	0.25	88.8	100	+11.2	16	5
	No. of <i>Taxus canadensis</i> stems	53.9	15	160.0	15	0.25	21.8	55.7	+33.9	ns	ns
	No. of <i>Acer spicatum</i> stems	53.9	20	160.0	20	0.25	15.3	59.0	+43.7	ns	ns
Sapling quadrats – microplots	Sapling density (no./m ²)	53.9	17	160.0	20	0.3	10.5	54.9	+44.4	ns	ns
	Sapling BA (no./m ²)	53.9	17	160.0	20	0.3	1.50	22.9	+21.4	ns	ns
Tree subplots	Tree density (no./m ²)	673.0	20	~ 3282	20	0.10	99.6	100	+0.40	8	4–5
	Tree BA	673.0	20	~ 3282	20	0.10	98.5	100	+1.50	10	<5
	<i>Betula papyrifera</i> density (no./m ²)	673.0	12	NA [§]	—	0.10	33.8	NA	NA	ns	NA

*The sample sizes do not always equal 20, the maximum number of sites, because that variable of interest was not present at all sites.

[†]Sigmas for each metric based on those observed with 5 year changes at Pictured Rocks and in northern Wisconsin.

[‡]Sample sizes were not always sufficient (ns) for some variables to attain 80% power.

[§]The point-centered quarter method used by the PEL method did not allow for calculations of density for individual species.

Table 3. Power (percentage of P values < 0.10 ; power values $\geq 80\%$ are in boldface type) of the US Forest Service Forest Inventory and Analysis (FIA) sampling method and a new sampling method designed to efficiently sample forest vegetation (Hybrid) for detecting a 20% change in vegetation sampled at Picture Rocks National Lakeshore, Wisconsin.

Level of analysis	Vegetation parameter	FIA		Hybrid		σ^\dagger	Power (%) to detect 20% change			Min. no. of sites to attain 80% power [‡]	
		Area sampled per site (m ²)	No. of sites*	Area sampled per site (m ²)	No. of sites*		FIA	Hybrid	Additional power of hybrid at 20% change	FIA	Hybrid
Ground layer quadrats	Forb frequency	12	19	30	19	0.30	13.3	66.2	+52.9	ns	ns
	Forb richness	12	19	30	20	0.20	18.3	89.9	+71.6	ns	17
	Fern frequency	12	19	30	20	0.25	41.0	87.2	+53.3	ns	16
	Woody vegetation frequency	12	16	30	16	0.35	62.8	59.1	-3.7	ns	ns
	<i>Maianthemum canadense</i> frequency	12	10	30	15	0.30	12.6	18.6	+13.7	ns	ns
Subplot walkthroughs	Understory species richness	673	15	900	15	0.20	92.3	97.9	+45.7	11	8
	Forb richness	673	15	900	15	0.20	68.5	85.2	+54.0	ns	13
Shrub quadrats	Shrub richness	53.6	17	149.8	17	0.25	80.5	95.5	+15.0	17	10
	No. of shrub stems	53.6	17	149.8	17	0.25	50.4	48.6	-1.8	ns	ns
Tree subplots	Sapling density (m ²)	673	11	900	11	0.30	57.4	70.0	+12.6	ns	ns
	Sapling BA/ha	673	11	900	11	0.30	25.6	68.5	+42.9	ns	ns
	Tree BA/ha	673	19	900	19	0.10	99.8	100	+0.2	9	7
	Tree density	673	19	900	19	0.10	99.8	100	+0.2	7	7
	<i>Fagus grandifolia</i> density (no./m ²)	673	8	900	8	0.20	3.6	2.1	-1.5	ns	ns
	<i>Betula papyrifera</i> density (no./m ²)	673	9	900	11	0.10	22.6	18.0	-4.6	ns	ns
	<i>Tsuga canadensis</i> density (no./m ²)	673	5	900	7	0.10	9.7	11.0	+1.3	ns	ns

Note: BA, basal area.

*Sample sizes do not always equal 20, the maximum number of sites, because that variable was not represented at all sites. The two exceptions to this occurred with shrub sampling, for which $N_{\max} = 17$, and with tree sampling, for which $N_{\max} = 19$, owing to logistics.

[†]Sigmas for each metric based on those observed with 5 year changes at Pictured Rocks and in northern Wisconsin.

[‡]Sample sizes were not always sufficient (ns) for some variables to attain 80% power.

tensively versus sampling more sites (*sensu* Zielinski and Stauffer 1996; Field et al. 2005).

The PEL method is thorough but has several disadvantages. First, the plotless approach makes it impossible to re-sample exactly the same location. This may confound local sampling variance with true biological changes occurring through time, thus reducing the power for detecting change. Second, the PEL method sampled four times as many trees per site as the FIA method, but this took roughly four times longer. The additional power gained from the greater sample size with the PEL method does not justify the additional time invested, which, on average, yielded only two additional tree species per site. Third, the point-centered quarter method of PEL assumes that trees are located randomly. This method leads to underestimates of density and BA when trees are aggregated (Cottam and Curtis 1956) and overestimates these variables when tree distributions are uniform (Bryant et al. 2005). If crew members judge larger trees to be nearer the central point, estimates of basal area are biased further. We observed PEL estimates that were higher than those generated by the FIA plot-based method, suggesting that the larger trees sampled in these forests may be distributed more uniformly than random. This discrepancy leads us to recommend fixed-area plots for long-term monitoring programs. Steinke and Hennenberg's (2006) work confirms that area-based methods perform more consistently than plotless methods.

We initially expected the P3 version of the FIA protocol to meet the objectives of the GLKN program in tracking overstory composition, tree size structure, the composition and structure of shrubs, and the composition and abundance of herbaceous species. The FIA method did meet some of these expectations by achieving good statistical power for tracking shifts in tree density, composition, and BA and reasonable power for detecting change in the shrub layer. This success reflects the original purpose and design of the FIA method to accurately estimate tree cover, forest type, and timber volume. Given that it also is quicker to implement than the PEL and Hybrid methods (Johnson et al. 2006) and extends to vast areas of public and now private forestland in the United States, it is worth considering for adoption in other long-term monitoring programs.

Despite these strengths, the FIA method lacks sufficient power to reliably track important trends in overall forest plant community structure and diversity. This lack in power relative to the other methods is often dramatic and extends to many metrics. One would need to sample at least eight more sites to reach the same power as the Hybrid method for assessing changes in shrub richness (or 11 more sites relative to the PEL method). This lack of power is particularly pronounced with regard to metrics inferred from the ground layer quadrats. The more extensive set of herb quadrats sampled in the Hybrid and PEL methods provided far greater power for detecting changes in these metrics, including the frequency of forbs, ferns, and woody-understory vegetation. Because this stratum represents the most diverse and rapidly changing component of forest vegetation, it has the most value for providing sensitive and early indicators of change. Although the walkthrough surveys allow fairly reliable estimates of understory richness, it was disturbing not to find any statistically significant correlation between species richness inferred from the FIA's 12 m² quadrats

and the actual plant diversity estimated from the walk-through area (673 m²; Johnson et al. 2006).

Walkthrough surveys considerably extend our ability to detect rarer species. However, replicate quadrats are still needed to track shifts in abundance as estimates of visual cover (included in FIA P3 protocols) are subject to considerable error and a lack of repeatability among observers (e.g., Hope-Simpson 1940; Greig-Smith 1983; Legg and Nagy 2006). Because of these limitations, the GLKN decided a priori to instead track changes in abundance using frequency data (presence among replicate quads) to provide more consistent and comparable estimates (Critchley and Poulton 1998; Ringvall et al. 2005).

The inferior power of the FIA method, particularly for understory vegetation, of course reflects the fact that it samples less area for trees, shrubs, and saplings and far less area for ground layer plants. While this undersampling limits the power of the FIA method for detecting changes in most vegetation metrics, it has the countervailing advantage of taking less time to complete a survey than the other methods, potentially allowing field crews to sample more sites in the same time. This, in turn, could increase overall statistical power. Unfortunately, the time saved per site using the FIA method is generally small relative to the time required to locate and travel to and from the sites (Johnson et al. 2006). This time saved might be a reasonable trade-off if the difference in power were slight, but many additional sites would be required with the FIA method to attain similar power as observed with more intensive sampling methods for detecting changes in many of the components of forest communities that are the focus of the GLKN monitoring program. Given that much of the cost associated with monitoring programs is attributed to travel and plot setup time, sampling each site somewhat more intensively would appear to add power more efficiently than sampling additional sites (Scott 1998), although this balance depends on the question(s) being pursued.

For historical reasons, the FIA method places disproportionate emphasis on the overstory relative to the more diverse understory community. While it is possible to further modify the FIA method, for example, by adding additional herb quadrats, any such ad hoc modifications would reduce standardization and thus comparability across habitats and regions. It has already been modified to include a walkthrough survey of all species present in the subplots, which substantially improved its ability to detect changes in overall species richness. However, such walkthrough surveys do not allow us to estimate other aspects of change including the relative abundances of species and overall community composition and structure.

Our FIA sampling method departed from the published FIA protocol in certain respects. First, we did not actually measure the distance to each tree from the plot center. While such consistency is desirable and allows teams to track the growth of particular trees, the very low error statistics (SD = 0.1) when resampling trees at sites at PIRO 5 years after the initial surveys suggest that there is no need to map trees to reach NPS objectives, particularly if this reduces the time available to sample understory vegetation. At APIS, saplings were not abundant enough to allow either the FIA or PEL method to attain high statistical power for detecting 20% changes. This general dearth of saplings led us

to increase the FIA sample area for saplings at PIRO from the microplot to the entire-subplot level. This generated substantially more data on saplings at PIRO, where the mean density of saplings turned out to be almost 14-fold greater than at APIS. Despite this, neither the intensified FIA method nor the more intensive Hybrid method reached high power for detecting significant changes in sapling density or BA. This represents a distinct weakness in all methods being compared in that detecting changes in tree recruitment and shrub abundance could provide important early indicators of ungulate impacts and exotic species invasion.

None of the three monitoring methods proved capable of reliably detecting changes in individual ground layer species. While such changes might be detectable with many more ground layer quadrats, the number of such quadrats required is impractical for routine monitoring. Although the PEL ground layer–quadrat data allowed us to detect 20% changes in the frequency of *Taxus canadensis* at APIS, this was the only instance in which any method achieved high power for tracking changes in an individual species. This probably reflects the fact that *Taxus* is abundant on many of the Apostle Islands, improving the statistical basis for inferring changes in its abundance. Few other species in the region are comparably abundant. The power tests reveal that we can rarely detect modest changes even in *M. canadense*, the most abundant herb in the region (Rooney et al. 2004). Most species exist at lower densities filling our data sets with zeros or low numbers as commonly occurs with ecological community data (McCune and Grace 2002). Thus, it will often be more effective and efficient to monitor composite community variables based on data from multiple species (Manley et al. 2004).

Metrics that sensitively reflect change at one park may be poor indicators of change at another. For example, it proved possible to detect changes in forb frequency at APIS, but we had considerably less power to detect change in forb frequency at PIRO. Likewise, the FIA protocol for sampling shrubs proved adequate to detect 20% changes in shrub stem number at APIS, but detecting such changes at PIRO proved difficult.

Plant-community data allow ecologists to compute a broad set of composite indicators. These include conventional measures of forest structure like stand density, BA, and various successional indices as well as measures of community composition including species richness in each layer, patterns of relative abundance, measures of overall community similarity or distance among sites, exotic abundance, and floristic quality (e.g., see Rooney et al. 2004). Although tracking changes in overall species richness may be important in some cases, this simple metric is often less informative than patterns of relative abundance or measures of community composition that usually respond more sensitively to shifts in environmental conditions or management. In their investigation of factors influencing understory vegetation in northern Wisconsin forests, Brososke et al. (2001) found that differences among patches in species composition were considerably larger than differences in species richness. Dividing species into functional groups or guilds could provide an additional set of composite indicator variables. We only pursued this in a very general sense by grouping all of the forbs, ferns, and shrubs, but we might have achieved high power by applying other grouping strategies. Insect-pollinated plants, for example, are

emerging as a guild experiencing systematic declines in both Europe (Biesmeijer et al. 2006) and northern Wisconsin (Wiegmann and Waller 2006). Such composite variables that share common responses to environmental conditions integrate much of the variation found within and among quadrats and species, providing statistically more reliable metrics for tracking ecological change (Ferrier and Guisan 2006).

In the same way that composite community indicators gain power by combining responses across multiple species, combining data across multiple sites will often expose regional trends before they become evident at individual sites. This provides a strong incentive to combine data from multiple sites whenever this is feasible and appropriate. However, as we demonstrated (Fig. 5), aggregating data across different forest habitat types can diminish this power to detect change if the metric of interest (e.g., BA) responds differently in different habitat types (Foster 2001). Thus, it is important to stratify the data by habitat type when combining data across sites to reduce the residual variance and increase statistical power. Otherwise, it is possible to lose statistical power when habitats subject to different magnitudes and directions of change are lumped in a single analysis.

In the context of NPS and US Forest Service monitoring, we recommend combining data for sites of similar habitat across parks or forests in the same region when conducting regionwide analyses. Doing so can enhance statistical power for detecting ecological change. For example, Shaw et al. (2005) aggregated FIA data collected in pinyon–juniper woodlands from the county to the state and regional level, providing high power to detect even low levels of change despite high county-level variation in tree mortality. However, resource managers and scientists should also consider the transitions that sometimes occur between habitat classifications (e.g., owing to disturbance and succession). Such transitions might be handled either by stratifying on the basis of soil or bedrock geology, which are unlikely to shift (Mahan et al. 2007), or by developing a landscape-level probability model to take such transitions into account (Pickett and White 1985).

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