Combining High-Resolution Aerial Photography with Gradient-Directed Transects to Guide Field Sampling and Forest Mapping in Mountainous Terrain

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ABSTRACT. Forest inventory and management relies on accurate maps of vegetation structure and composition. Creating such maps typically proceeds in two main stages: delineating stand boundaries on midscale aerial photography (≈1:15,000) followed by collection of reference data in field plots. Technical and logistical limitations arise with respect to the resolution of photography, the allocation of field plots, and the sequence of the stages. Here we present a novel approach for forest mapping that (1) places the mapping process as the last rather than the first stage; (2) concentrates sampling in areas with strong environmental gradients; and (3) uses large-scale, high-resolution aerial photography (≈1:2,000) to supplement field data and midscale airphotos. Our design builds on observations that plant communities in mountainous areas often exhibit strong correlations with environmental variables and that digital or hardcopy maps of these variables are becoming more widely available. In the first stage, 1:2,000 aerial photography is obtained via helicopter-mounted small-format cameras along flight lines that are located subjectively to follow significant environmental gradients. In the second stage, field plots are placed within airphoto transects to provide reference data of forest conditions. An integrated analysis of plot data and high-resolution photography provides the empirical basis for the development and calibration of an interpretation key. In the third stage, this key is applied to the delineation and classification of forested area on stereoscopic 1:15,000 aerial photography across the landscape of interest. We demonstrate this approach using a watershed in southwestern British Columbia and compare four probability-sampling designs with the gradient-directed approach proposed here using computer simulations. The results indicate that sampling along topographic gradients leads to a loss of accuracy with respect to estimation of distributional parameters. However, gradient-directed sampling is as likely as probability sampling to capture the full range of variability in forest conditions, with greatly improved logistics and cost-effectiveness. We conclude that our sampling design is a practical alternative for mapping projects in topographically complex landscapes. For. Sci. 49(3):429–443.

Key Words: Small-format aerial photography, sampling design, gradsects, forest structure, dry montane forests.

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MAPS OF CURRENT STAND CONDITIONS, along with their associated databases of structural and ecological attributes, are among the most important tools for effective management of forested landscapes. Creating and updating these maps are time-consuming and difficult tasks, particularly in areas where forests are fine-grained mosaics of structurally complex stands. Limited time and financial resources require compromises between standards of accuracy, statistical rigor, and allocation of field plots. Consequently, adequate sampling designs for landscape-scale mapping projects remain a topic of much debate (Bourgeron et al. 1994, Neldner et al. 1995, Stohlgren et al. 1997).

Many structural attributes of forests, such as tree height, canopy cover, and vertical complexity can be reliably estimated by stereoscopic analysis of aerial photography (Howard 1991, p. 296–306). Midscale photography, in particular, is well suited for stratifying forests into individual stands and estimating or measuring their specific characteristics. At a scale of 1:15,000, the standard 25 × 25 cm print covers approximately 3.5 × 3.5 km of ground, equivalent to 1,225 ha. Stereoscopic midscale airphotos acquired with large-format metric cameras are available in many countries and form a common basis for forest mapping and inventory in North America (Aldrich 1979, Gillis and Sundstrom 1999).

Despite considerable advances in automated processing of digital airborne or satellite-based imagery, major challenges remain to successfully replicate the full spectrum of diagnostic elements and human expertise available for manual analysis of airphotos, such as shape, pattern, texture, and context (Coops and Culvenor 2000, Franklin et al. 2000, Hyyppä et al. 2000, Shugart et al. 2000, Lefsky et al. 2001). In the foreseeable future, visual interpretation of aerial photographs will therefore continue to play an important role in forest inventory and management (Wulder 1998). During this time, new approaches to airphoto acquisition and analysis can improve current procedures with respect to accuracy, efficiency, and direct as well as indirect costs (Pitt et al. 1997).

We present a novel three-stage approach to landscape-scale mapping of variability in forest structure. It maintains at its core the use of midscale aerial photography as the primary data source for distinguishing and interpreting forest stands. However, it differs from traditional procedures by (1) placing the mapping process as the last rather than the first stage; (2) concentrating field sampling in areas with strong environmental gradients; and (3) providing a supplementary source of data in the form of high-resolution aerial photography. The atypical combination of the components, particularly the inclusion of high-resolution aerial photography, is meant to provide a case for creative applications of existing technology and to challenge common perceptions of limitations of small-format camera systems for landscape-level sampling. In the following three sections, we describe the components of our sampling design, give an example of its application in the dry montane forests of southern British Columbia, and, via a simulation model of the sampling process, provide empirical data on its accuracy and efficiency relative to traditional sampling designs.

Components of the Sampling Design

The traditional procedure for airphoto-based forest mapping and inventory consists of two main stages: (1) delineation of polygons with similar vegetation characteristics on midscale aerial stereo photography; and (2) sampling in the field to provide quantitative measures of vegetative and other characteristics of each photo stratum (Gillis and Sundstrom 1999). Despite its long and successful application, visual interpretation of aerial photography has a number of inherent problems. One of them is the subjective nature of delineating polygons and estimating their characteristics, with accuracy and consistency depending on the experience and thoroughness of the photo interpreter as well as on the optical and spectral resolution of the source photography. No two photo interpreted maps will have the exact same polygon boundaries and stand parameters, not even when completed by the same person—a problem often emphasized by the proponents of computer-based procedures (Fournier et al. 1995). In many instances, discrepancies between two photo-interpreted maps are attributable to the absence of sharp boundaries between adjacent forest stands. They thus reflect real ambiguity in the forest itself and present a general problem whenever forests are divided into discrete polygons (Heuvelink and Huisman 1996, Lowell 1996). Discrepancies due to human error, on the other hand, generally decrease with skills and training particular to the characteristics of the project area (Gross and Adler 1996).

Unfortunately, the sequence of work in the common two-stage design interferes with the development of site-specific knowledge for the photo interpreter: map polygons are delineated *before* data are collected on the ground. All decisions about criteria for delineating and interpreting forest stands have to be made with only limited knowledge—usually based on past inventory data or some level of field reconnaissance—about current forest conditions in the study area. Moreover, the analysis of field data in the second stage might lead to good reasons for changing any or all of the criteria employed in the first stage but current procedures typically do not allow for revisions of the original stratification (e.g., Gillis and Sundstrom 1999).

Additional problems arise in the subsequent stage of correlating airphoto interpretation with field sampling. For example, it is often challenging to locate in the field a 2 ha site (the common minimum mapping unit) previously delineated on a 1:15,000-scale airphoto, particularly so in dense forests or roadless areas. Yet accurately relating photo sites to field sites—and *vice versa*—is a critical component of forest inventory.

In the ideal case, a mapping project would have at its disposal complete coverage of remotely sensed imagery at high spatial resolution as well as a representative sample of georeferenced field plots *prior* to delineating any polygons. While the ideal case may not be achievable, several changes to existing procedures may shorten the gap between the desired and the possible. Here we propose a sampling design that integrates two procedures originally developed for opposite ends of sampling scales: high-resolution aerial photography and plot sampling along gradient-directed transects.

Large-Scale, High-Resolution Aerial Photography

Aerial photography at very large scales (1:250 to 1:2,500) has been used for more than four decades in various tasks related to forest management (Aldrich et al. 1959, Lyons 1966, Nielsen et al. 1979, Spencer 1984). Government agencies and private companies operate a number of different systems utilizing 35 mm or 70 mm small-format cameras (Warner et al. 1996). In Canada, one of the commonly used configurations consists of two customized Hasselblad Mk70 cameras, mounted in a long metal boom attached to a Bell 206B Jet Ranger helicopter parallel to the direction of flight (Hall and Aldred 1992). Both cameras are triggered simultaneously, at predetermined intervals, to obtain overlapping images of the ground. The photo scale of each image depends on the flying height of the helicopter at the time of image exposure and the focal length of the camera lenses. The high ground resolution of a few centimeters (Pitt et al. 1997) allows detailed analyses of vegetation and site conditions. Typical applications of this technology include regeneration assessment, fuels inventory, habitat typing, and estimation of tree mortality (Muraro 1970, Croft et al. 1982, Befort 1986, Hall and Aldred 1992).

In addition to the benefit of a level of detail that cannot be achieved with conventional large-format cameras, small-format photography has several other advantages:

- ➤ During field sampling in the photo area, the location of measured objects—trees, coarse woody debris, shrubs, etc.—can be marked on the photographs and tied to reference points established with global positioning system (GPS) receivers.
- ➤ High-resolution photographs give a detailed “birds-eye” perspective of the plot area. This provides an important cognitive link between the three-dimensional characteristics of a stand experienced during field sampling and its vertical representation in the stereo model during the subsequent mapping process with midscale photography.
- ➤ Equipment and aircraft rental are relatively inexpensive, and the end-user can directly influence the timing, location, and extent of the flight lines as well as the type of film and the scale of the photography (Warner et al. 1996, Chapter 11).

On the other hand, a number of disadvantages need to be considered as well:

- ➤ The small area of ground covered by each photograph makes it difficult to target a specific site and often requires preflight marking of sampling locations with balloons or colored fabric.
- ➤ For the same reason, large-scale photography is not appropriate for complete coverage of large areas.
- ➤ The combination of small-format camera, aircraft movement, and low flying height above ground leads to variable and sometimes significant levels of image distortion due to camera tilt and radial displacement (Warner et al. 1996, pp. 64-71).

Our proposed application of small-format photography aims to overcome its technical disadvantages with three adjustments. First, photo acquisition is designed to result in a series of overlapping images along transects. Even over steep terrain, helicopter-mounted camera boom systems are capable of acquiring continuous strips of stereo images at a relatively constant scale; this eliminates the need for preflight marking of plots and at the same time provides a photo map for easy navigation between field plots. Second, small-format photography is used as a supplementary rather than exhaustive source of information; flight lines typically cover less than 5% of the study area. Third, our use of high-resolution airphotos is largely restricted to visual interpretation and field navigation and thus does not have to meet more stringent standards of image geometry required for photogrammetry.

Sampling Along Gradient-Directed Transects

Large study areas with variable topography incorporate many sources of heterogeneity in forest conditions (Lertzman and Fall 1998) and thus generally require a large number of sampling sites in order to accurately map and quantify the biological and structural diversity within and among vegetation communities (Stohlgren et al. 1997). However, financial and logistical constraints usually dictate some trade-off between the number of field plots, their spatial location and extent, and the intensity of sampling within each plot. In many cases, a mapping project is primarily interested in accurate characterization of the range of variability in the ecological and structural components of the forests and the distributional patterns of cover types (Lund and Thomas 1989, Shiver and Borders 1996, p. 1–3). This emphasis is different from plot-based forest inventories, which are concerned with unbiased estimation of specific variables based on a sample of field plots rather than complete maps. The latter require probability sampling strategies and these have since become the main criteria for evaluating the credibility of any kind of forest sampling (Johnson 2000, p. 1–3, Stehman 2001). A considerable disadvantage of basic probability sampling is, however, that it allocates sampling effort proportional to the frequency of occurrence of vegetation types in the study landscapes, i.e., common elements and average conditions. Unless sampling efforts are very extensive or based on *a priori* stratification, probability sampling therefore may fail to recover the full range of the variable(s) of interest (Gillison and Brewer 1985). In addition, lack of control over sampling locations may greatly increase the unproductive parts of fieldwork, such as traveling to and locating plot sites. Despite such reasons that argue against the use of probability sampling, very little research has focused on alternative approaches (Bourgeron et al. 1994).

The relief of a landscape modifies the temporal and spatial distribution of direct and indirect resources for plant communities, such as water, solar radiation, nutrients, and natural disturbances. Thus, changes in plant communities are often found to be associated with changes in topography (Whittaker

1960, Harmon et al. 1983, Ohmann and Spies 1998). With the general availability of digital elevation models (DEM) and geographic information systems (GIS) the distribution of various topographic attributes can be mapped and utilized for guiding the sampling effort (Moore et al. 1991, Franklin 1995). While many researchers implicitly consider topographic gradients for stratifying their sampling effort, perhaps the first to do so explicitly were Gillison and Brewer (1985). They developed a formal design that places field plots along belt transects that follow the strongest gradients of a number of environmental and topographic variables. Delineation of these gradient-directed transects, or gradsects, is based on previous knowledge or hypotheses about vegetation–environment interactions within the study area. In the original application of this procedure, the authors chose annual precipitation, topography, bedrock characteristics, and secondary drainage systems, in descending order of importance. Alternative combinations and rankings of gradients are discussed in Austin and Heyligers (1989), Bourgeron et al. (1994), and Neldner et al. (1995).

Despite the subjective determination of locations and dimensions of gradsects by the researcher, Gillison and Brewer provide some empirical evidence that gradsects can be superior to random or stratified random sampling designs in estimating frequency and distribution of vegetation types. At the same time, gradsect sampling achieved significant cost reductions in fieldwork and produced a classification key for vegetation mapping very similar to a key based on an intensive survey of the entire study area (Gillison and Brewer 1985).

Application Example

The sampling design described here was developed for a research project that aims to test hypotheses about the interaction of topographic and climatic site conditions with structural characteristics of dry montane forests. Two methodological objectives of this project that are relevant here are: (1) defining stand structure types for dry montane forests based on ecological processes of stand development (for operational purposes, the set of criteria and classes needs to be applicable to field surveys as well as airphoto interpretation); and (2) complete and consistent mapping of four study areas in southern British Columbia based on government-issue midscale aerial photography, utilizing the classification key developed for the first objective. The following description of how these objectives were approached focuses on the largest of the study areas, Arrowstone Creek Provincial Park.

Arrowstone Creek Study Area

The Arrowstone Creek study area is a 6700 ha protected watershed located about 80 km west of Kamloops, British Columbia, at 121º15'W and 50º53'N. Arrowstone Creek drains south towards the Thompson River, and elevations within the study area range from 670 m to 1700 m above sea level (Figure 1). A fine-grained mosaic of dry montane forests, which has experienced only limited human intervention, covers ≈90% of the study area. Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) is the most common tree species, while lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), hybrid white spruce (*Picea engelmannii* × *glauca*), and trembling aspen (*Populus tremuloides*) occur as secondary or early successional species (Lloyd et al. 1990).

Stage One: Locating Gradsects and Acquiring High-Resolution Aerial Photography

In our three-stage sampling design, gradient-directed transects provide the flight lines for acquisition of high-resolution aerial photography as well as the subsample of the study area to receive field plots. Based on visual assessments of the digital elevation model and midscale aerial photography provided by the British Columbia government, we selected the locations of six gradsects. Each gradsect crosses one of the major subdrainages and extends between opposite height-of-lands over a length of 2 to 3 km (Figure 1). We considered elevation, aspect, slope, and the configuration of subdrainages to be relevant environmental gradients in this study area. In addition, we used existing maps of the approximate distribution of the three main forest types in the watershed (dominated by ponderosa pine, Douglas-fir, and lodgepole pine, respectively), to adjust the placement of gradsects toward proportional representation of forest types.

Figure 1. Arrowstone Creek study area (6,763 ha), Kamloops Region, south central British Columbia. Digital elevation model with grayscale overlay of estimated mean daily direct solar radiation. Lighter areas correspond to higher radiation values. White dots indicate the locations of 90 field plots along six gradient-directed transects.

As Gillison and Brewer (1985) pointed out, gradients deemed important do not necessarily have to be captured by a single continuous gradsect. In our study area we captured the entire gradient of elevation by placing gradsects at approximately regular intervals perpendicular to the main stems of Arrowstone Creek, starting near the lowest part of the watershed in the South and extending to the headwaters in the North and West (Figure 1).

Using a 70 mm twin camera system operated by the B.C. Ministry of Forests in Kamloops, we acquired 178 overlapping stereo pairs along the 6 gradsects. Prior to the flight, we had marked gradsect locations and compass headings on 1:15,000 airphoto hardcopies. This proved to be sufficient for the helicopter pilot to find and follow the flight lines, eliminating the need for preflight marking of transect endpoints in the field. At an average flying height of 200 m above ground and a focal length of the camera lenses of 100 mm, each high-resolution image covers ≈100 × 100 m. Together, the gradsect photo strips cover less than 3% of the Arrowstone Creek study area (Figure 1).

Stage Two: Collecting Field Data along Gradsects

The second stage of the sampling design involves locating and sampling of field plots along the gradsects. All decisions on the number, dimensions, and placement of field plots, as well as the variables to be measured, need to be particular to the task at hand. In our study, we defined a stand as "a spatially continuous group of trees with similar vertical and horizontal pattern," and located one 0.1 ha fixed-area plot in the center of each stand intercepted by the gradsects. Stands that extended over more than 400 m of gradsect length received two or more plots 200 m apart. Navigation to the plots was accomplished by using 20 × 20 cm color enlargements of the 70 mm transparencies. Even in densely forested areas the patterns of easily recognized features—canopy gaps, downed logs, or standing dead trees—allowed for reliable identification of one's position in the photo area. Plot center locations were determined with a GPS receiver and postdifferentially corrected to about ± 5 m horizontal accuracy.

At each of 90 sample plots, we collected data on stand structure (age, height, dbh, crown class, etc.), evidence of past and present natural disturbances (fire scars, defoliation, etc.), species composition, and topo-edaphic site conditions (aspect, slope, soil moisture, etc.). All field data were transferred into a database and linked to the plot locations in the GIS.

Stage Three: Mapping on Midscale Airphoto Stereo Pairs

The third and final stage involves the visual interpretation of midscale airphoto stereo pairs for delineating and classifying all forested areas in the study landscape. Prerequisites for this task are decisions about the attributes to be estimated or measured for each mapped polygon as well as the development of an interpretative key for stand delineation and classification. Having completed the first two stages of this sampling design, the interpreter can now utilize the database of field plots and all of the high-resolution aerial photography. Setting up and calibrating an interpretative key generally requires a defensible compromise between the desired level of detail and the achievable accuracy of airphoto interpretation. Therefore, site-specific and current data about the study area are of great value.

The concept of distinguishing stand structure types based on a combination of physiognomic differences and processes of stand development was first proposed as a general framework by Oliver (1981) and recently expanded and applied in the dry montane forests of the United States Inland Northwest (O'Hara et al. 1996, Hessburg et al. 1999). Given our research emphasis on differences in stand structure, and after careful examination of field data and high-resolution airphotos, we selected three physiognomic attributes to form the basic structure for the interpretative key: (1) crown cover of dominant or veteran trees; (2) the proportions of up to four vertical strata, or crown cover classes; and (3) overall crown closure. To distinguish between different combinations of vertical strata, threshold values were derived empirically from the plot database. Thresholds for crown closure and the presence of dominant trees were adopted from British Columbia standards for vegetation inventory (Gillis and Sundstrom 1999). The resulting classification key contains 15 classes of stand structure: 3 early seral classes, 4 midseral classes, and 8 late seral classes (Table 1).

Stand mapping and typing on 1:15,000 stereo imagery proceeded in four steps. First, all forested areas (i.e., crown closure >10%) were delineated into stands according to the above definition. Second, for each polygon we visually estimated a number of stand and site attributes, including the three threshold criteria mentioned above. Third, all completed airphoto maps were ortho-rectified to a common geographical projection, incorporated into the GIS, and linked to the database of stand attributes. Fourth, the interpretation key was programmed as a database macro, and each polygon was assigned a stand structure class according to the thresholds of the key. Separating class assignments from the initial mapping stage is an important component of this process as it keeps airphoto interpretation more transparent and allows for *a posteriori* adjustments to the number or definitions of classes (Hessburg et al. 1999).

While the map of stand structure types is based on conventional 1:15,000 aerial photography, the 70 mm imagery is important in all aspects of our sampling design. During fieldwork, photo prints are the main tool for locating plots and navigating along transects. In the critical phase of deciding on the number and characteristics of classes, high-resolution airphotos are an efficient link for scaling between bottom–up, high-resolution field data and top–down, less detailed 1:15,000 imagery (Hinckley et al. 1998). Last but not least, the orthogonal viewpoint and high level of detail of 70 mm imagery allow reliable measurements of crown cover by stratum or species (Croft et al. 1982), providing a cost-efficient tool for an empirical assessment of map accuracy (*sensu* Congalton and Green 1997).

The resulting map of stand structure types in the Arrowstone Creek study area contains 15 forest classes plus 1 class with all areas <10% crown cover. The average stand area is 4.02 ha, with a lower limit of 0.5 ha and an upper limit of 75 ha.

Table 1. Stand structure classes of dry montane forests, as defined for this study. Classes are differentiated by overall canopy closure (%) and the presence of four crown strata as a proportion of total canopy closure. Values of C1 to C4* are average proportions computed from 1,582 photointerpreted forest polygons in the Arrowstone Creek study area.

		Canopy closure				
Code	Class name	Total (%)	C1	C2	C3	C4
SSS	Stand Initiation, Single Stratum	10–100	0.01	0.03	0.10	0.86
SEO	Early Seral, Stem Exclusion, Open Canopy	10–39	0.02	0.12	0.75	0.11
SEC	Early Seral, Stem Exclusion, Closed Canopy	40–100	0.02	0.09	0.84	0.05
MRO	Midseral, Regeneration Ingrowth, Open Canopy	10–39	0.04	0.26	0.21	0.49
MRC	Midseral, Regeneration Ingrowth, Closed Canopy	40–100	0.03	0.18	0.16	0.63
MMO	Midseral, Multistrata, Open Canopy	10–39	0.04	0.24	0.51	0.21
MMC	Midseral, Multistrata, Closed Canopy	40–100	0.03	0.30	0.52	0.15
ORS	Late Seral, Regeneration Ingrowth, Sparse Canopy	10–24	0.10	0.21	0.41	0.28
ORO	Late Seral, Regeneration Ingrowth, Open Canopy	25–39	0.10	0.18	0.41	0.31
ORC	Late Seral, Regeneration Ingrowth, Closed Canopy	40–100	0.11	0.17	0.48	0.24
OMS	Late Seral, Multistrata, Sparse Canopy	10–24	0.14	0.29	0.41	0.16
OMO	Late Seral, Multistrata, Open Canopy	25–39	0.16	0.27	0.39	0.18
OMC	Late Seral, Multistrata, Closed Canopy	40–100	0.15	0.29	0.42	0.14
OSO	Late Seral, Single Stratum, Open Canopy	10–39	0.23	0.42	0.20	0.15
OSC	Late Seral, Single Stratum, Closed Canopy	40–100	0.19	0.48	0.23	0.10

* C1: Dominant and veteran trees; C2: Codominant trees; C3: Subdominant and small (<15 m tall) codominant trees; C4: Suppressed trees and saplings (≈2 to 7 m tall).

Class proportions vary considerably, ranging from 0.8% for the least common to 26.7% for the most common class. Six classes cover less than 2.5% of the study area and are examples of rare forest types that often require special consideration in forest management but are the most difficult to detect, delineate, and sample (Stohlgren et al. 1997).

Simulation Exercise: Comparing Sampling Designs

The basic purpose of a sampling design is to provide reliable information in a time- and cost-effective manner (Shiver and Borders 1996, p. 1–3). Accuracy and efficiency can be tested either directly or by means of a comparison with other designs (e.g., Johnson 2000). In the original paper on gradsect sampling, Gillison and Brewer (1985) report on a formal comparison of gradsects with randomly located transects and a random subset of a larger set of gradsects, respectively. The results favored the gradsect design, as it achieved the same level of accuracy (with respect to detecting vegetation types) at less cost than probability designs. However, Gillison and Brewer's application of gradsects differs in both intent and application from our use of gradsects within a three-stage design. To provide an independent evaluation of gradsects in the context of our three-stage design, we conducted a retrospective simulation exercise in which we compare gradsect sampling to four probability designs.

The Arrowstone Creek map of stand structure classes, in its final form as described in the previous section, was used as the control landscape. Its associated digital elevation model provided individual layers of elevation (m a.s.l.), slope (°), and aspect (°) values. All data sets were coregistered to a common geographical projection and stored in a 25 × 25 m raster grid. For the purpose of this simulation, all data layers were assumed complete and accurate representations of the study area. In addition, we assumed that the digital elevation model was the only data source available prior to sampling in the field.

A limitation of this simulation is that it was not implemented as a stand-alone, automated Monte Carlo-type study (e.g. Lertzman et al. 1998) but rather as a manual procedure using actual data and basic GIS and database tools. Therefore, we had to limit the number of model runs to five per sampling design and, consequently, our results provide relative rather than absolute differences; the number of replications is too small for meaningful tests about statistical significance of differences.

Choice and Implementation of Sampling Designs

Out of the large number of sampling designs available for forest inventory and mapping (Eberhardt and Thomas 1991, Johnson 2000), we selected two designs with clustering of plots and two designs without clustering (Figure 2). Though any design with disjointed or irregularly located field plots is impractical to implement with supplementary high-resolution aerial photography, we included a simple random design because it is generally considered a benchmark for forest inventory (Stehman 2001). Stratified random sampling, our second design, may involve similar logistical challenges with respect to fieldwork (depending on the criterion for stratification) but is more commonly used than simple random sampling. Here we include a sampling design stratified by a topographic parameter—six classes of slope direction, or aspect—given our assumption of having DEM-derived data available only. The other two designs, line-plot sampling and random-transect sampling, are variants of multistage cluster sampling (Shiver and Borders 1996, Chapter 8) and, because of their clustering of plot locations, can readily incorporate high-resolution photography (Figure 2b).

General procedures for implementing the simulation exercise were:

- ➤ Each design was set up to sample 90 field plots, the number of plots in our actual sampling campaign in the Arrowstone Creek study area.

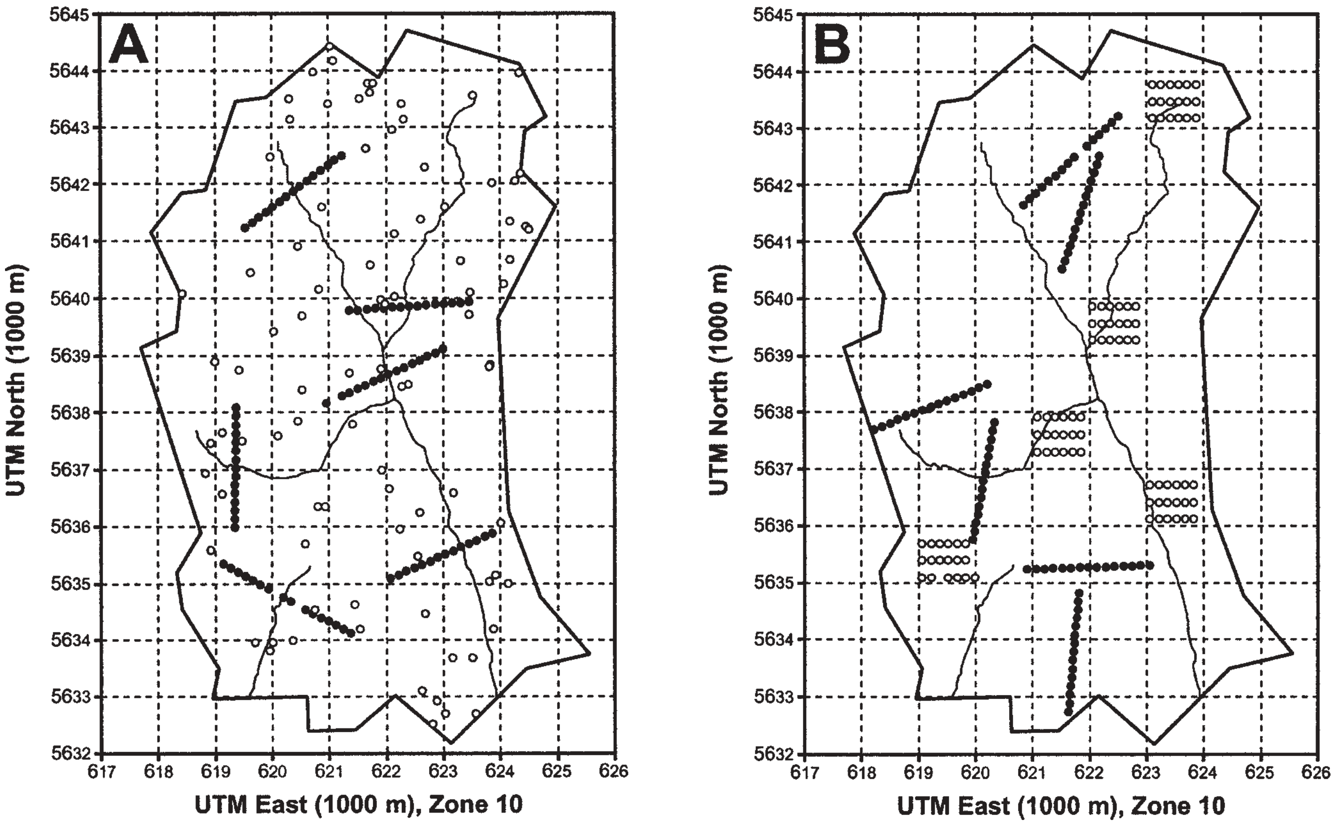


Figure 2. Examples of four simulated sampling designs in the Arrowstone Creek study area. Each design consists of 90 plots. Curvy lines indicate the major network of streams, draining south. Plot locations in Panel A for simple random sampling (○) and gradsect sampling (●), and in Panel B for line-plot sampling (○) and random-transect sampling (●). Note: Stratified random sampling is visually indistinguishable from simple random sampling and is therefore not included here.

- ➤ For the three designs with plot clusters, we set the distance between plots to 150 m, the average of between-plot distances of the six original gradsects. A systematic placement of plots was easiest to implement in this simulation though it may not be the most desirable (e.g., Fortin et al. 1989).

- ➤ Only forested areas could receive a sample plot. For the random designs without clusters, nonforested plot locations were replaced with randomly chosen forested ones. For the designs with clusters, additional plots were located at the outer extremes of a cluster of plots to account for nonforested areas within the cluster.

- ➤ Each sampling design was repeated five times, with replacement of plot locations.

Specific procedures for implementing the three designs with plot clusters were as follows:

- ➤ Five sets of line-plot arrangements, with 18 plots in three parallel lines confined to a 1 km^2 grid. Distance between lines was set to 300 m. Starting points for each cluster, with random offsets in E and N directions, were randomly selected from a list of 55 UTM 1 km^2 grid areas that fell completely within the study area (Figure 2b).

- ➤ Six transects with 15 plots each, with randomly located starting points and direction. Only transects that had all their plots within the boundaries of the study area were retained (Figure 2b).

Instead of using the single set of six gradsects used in the Arrowstone Creek study, we specified a set of rules that aims to emulate the general process of choosing gradsect locations. These rules incorporate a random element, as described below, thus allowing us to run several iterations of gradsects with nonidentical outcomes. Our main reason for shifting the position of sampling locations (6 gradsects with 15 plots each) between simulation runs lies in the subjective nature of selecting starting points and dimensions of gradsects; the same set of environmental gradients allows for several valid combinations of gradsects (Gillison and Brewer 1985). In other words, we reason that our imposed variability between sets of gradsects replicates the expected variation of results if different researchers were to decide on a gradsect design for the Arrowstone Creek drainage.

For our formal, though simplified, emulation of locating gradsect, we divided the drainage network of the Arrowstone Creek study area into six major segments. For each stream section, one gradsect midpoint was randomly chosen from a list of predetermined valley bottom locations spaced ≈100 m apart. Then each gradsect received seven plots each in the two directions perpendicular to the valley bottom (Figure 2a).

While the initial focus of this comparison was on the map of stand structure classes, we also included three topographic variables, since their distributional properties are similar to those of numerical variables often obtained in forest inventory (see *Simulation Results*). For ease of comparison, we recoded the three topographic variables into categorical variables. For each iteration of a simulated sampling design, the list of plot locations was first computed by a spreadsheet macro and then transferred into the GIS. Standard overlay functions were used to extract the values of the four variables—stand structure class, elevation, aspect, and slope—for each plot.

Measures of Comparison

Comparisons of sampling designs generally consider three main criteria (Shiver and Borders 1996, p. 7–11, Johnson 2000, Chapter 2):

- ➤ Accuracy: sample estimates should be unbiased and precise with respect to the population parameters; the estimated variance or standard errors of each estimate should be stated.
- ➤ Completeness: sample plots should recover the entire range of variability in the attributes of interest.
- ➤ Cost-effectiveness: direct and indirect costs should be kept at a minimum.

There is a well-established literature on formal methods for judging the efficiencies of different sampling designs (e.g., Taylor 1998, Johnson 2000). However, since gradsect sampling does not satisfy the requirements of probability sampling—i.e., known inclusion probabilities *sensu* Stehman (2001)—there is no basis for a theoretical comparison of bias and precision in the estimates. Instead, we used the simulated plot samples to compute simple metrics of *achieved* efficiency for each of the three criteria listed above.

As a measure of difference in achieved accuracy, we computed the mean deviation about the true proportion of all classes in each of the four variables. For the criterion of completeness, the average number of classes recovered by a sampling design was used to compute the likelihood of placing at least one sampling plot in each class (i.e., number of classes sampled divided by total number of classes). Finally, cost-effectiveness, here restricted to costs of field sampling, was estimated by finding the shortest Euclidean distance between all plot pairs and summing the results to the minimum total distance to be traveled between sampling locations. Each measure was calculated separately for each simulation run so that both bias and precision were evident for the comparison.

Simulation Results

Subjectively allocating sampling plots, as implemented in gradsect sampling, results in loss of accuracy in estimating class proportions of stand structure types (Figure 3a). Deviations from true class proportions are smallest for simple and stratified random sampling, though stratification of random sampling by aspect class did not improve on random sampling. The three designs with plot clusters show similar unsatisfactory estimates of proportions of stand structure classes with respect to bias and precision (Figure 3a).

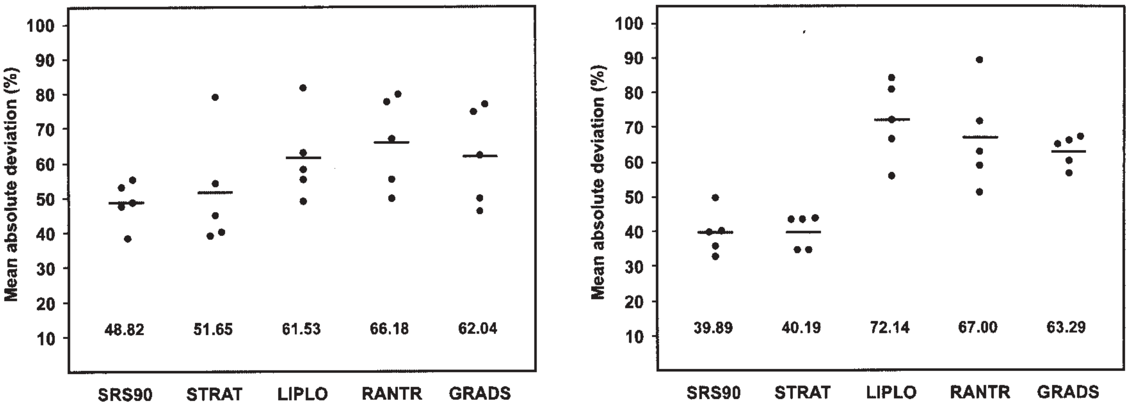
For the topographic variables, bias and precision in estimating class proportions differ substantially both within and among sampling designs (Figure 3b–d). Only simple and stratified random sampling provide fairly accurate estimates of the distribution of altitudes in the study area (Figure 3b). This is probably a result of strong autocorrelation in elevation in this landscape; low altitudes are confined to narrow valley bottoms whereas midelevations are aggregated along the steep side slopes (Figure 1). Therefore, any sampling design with plot clusters is likely to miss sections of the distribution of elevation classes; the tighter the cluster, the higher this likelihood will be.

The misrepresentation of aspect classes apparent in stratified random sampling is a logical result of using slope direction as the variable for stratifying the sampling effort (Figure 3c). While stratification by aspect did not lead to the desired improvement in accuracy with respect to stand structure classes, it resulted in the best relative accuracy for estimating proportions of slope classes (Figure 3d). Apparently, the approximately uniform distribution of aspect classes resulted in an increased level of accuracy in estimating the skewed distribution (skewness = 0.886) of slope classes. This unexpected result emphasizes the potential impact of causal and spurious correlations between sample variables on decisions about stratification and clustering of sampling.

Slope class distributions appeared difficult to accurately estimate with any of the designs besides stratified random sampling (Figure 3d), likely a result of a combination of autocorrelation (of flat to gently sloping areas) and rare classes (i.e., very steep slopes). With the exception of aspect, gradsect sampling consistently failed to provide accurate estimates for the topographic variables. This is to be expected, given that the topographic variables at least partially determine the locations of gradsects and thus interfere with unbiased estimation of distributional parameters.

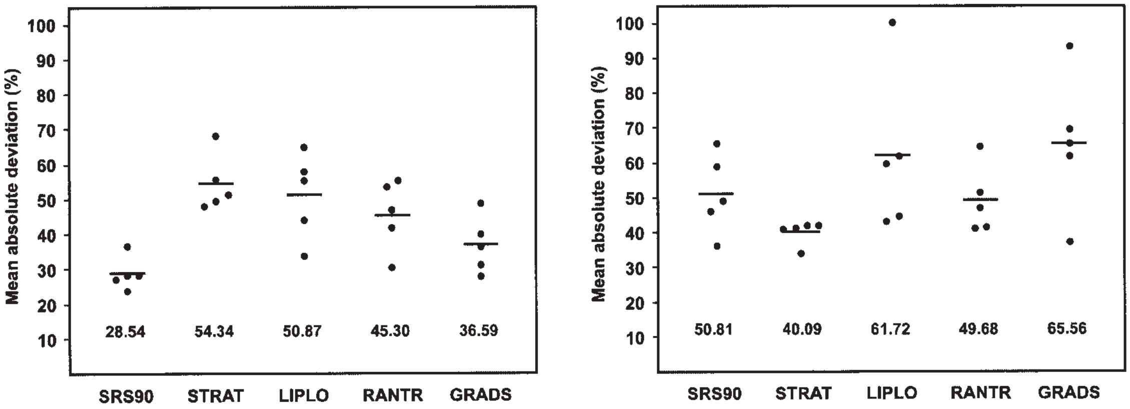
The results for the criterion of completeness in sampling effort lead to a different ranking of sampling designs. Gradsect sampling is as likely as simple random sampling to place plots in all stand structure types and slope classes, though the difference to the other designs is small (Figure 4a and d). Again, the three sampling designs with plot clusters—line-plot sampling, random transects, and gradsects—were sensitive to spatial autocorrelation in the elevation model, resulting in a reduced likelihood of sampling all classes, though gradsect sampling performs better than the other two designs (Figure 4b). Several iterations of line-plot sampling and gradsect sampling failed to place plots in 1 or 2 of the 12 aspect classes (Figure 4c). Overall, gradsect sampling appears to be the most consistent of the cluster designs to allocate at least one plot in each class.

The comparison of cost-effectiveness of field sampling results in the expected distinction between dispersed and clustered placement of sampling plots (Figure 5). Random-transect and gradsect sampling have the lowest minimum distances between plots. Because of its tighter clustering of plots, line-plot sampling is slightly less efficient and more variable between replications than other designs. As expected, simple random sampling is a bad choice for minimizing travel distances between plots, more than doubling total distances between plots. How-



(a) Stand structure type (15 classes)

(b) Elevation (11 classes)



(c) Aspect (12 classes)

(d) Slope (15 classes)

Figure 3. Lack of accuracy of simulated sampling designs in estimating class proportions of the Arrowstone Creek study area. Each black dot represents the average absolute deviation from true class proportions for one simulation run (i.e., sampling of 90 plots). Horizontal dashes indicate means for the five model runs per design, with values listed near the bottom of each panel. Data of equal or similar value are jittered horizontally. The five sampling designs compared are (from left to right): simple random sampling, stratified random sampling, line-plot sampling, random-transect sampling, and gradsect sampling.

ever, the more uniform plot allocation imposed by stratified random sampling makes the latter the least efficient of the five designs with respect to travel cost.

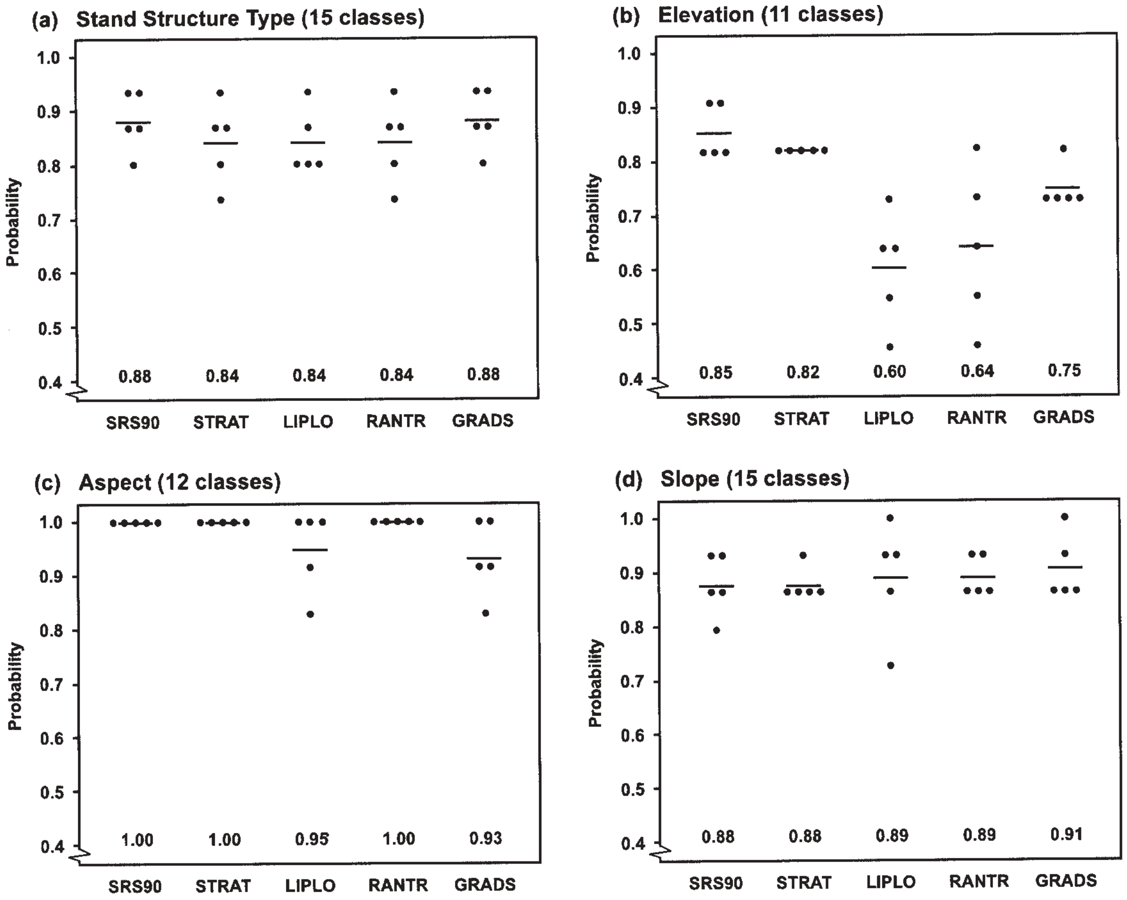
Obviously, a comparison of field costs based on plot spacing alone is incomplete; other factors to consider include cost of travel to and from the nearest access route, and the time spent within each plot (Johnson 2000, Chapter 17). Based on the results of this comparison, it could be argued that simple random sampling is efficient enough that the number of plots allocated could be lowered to reduce field costs, while the design's performance would remain at least as accurate and complete as the types of cluster sampling considered here. To test this hypothesis, we conducted a sensitivity analysis with respect to the number of plots allocated by simple random sampling. For example, reducing the number of plots by 33% (i.e., n = 60) lowered the average total travel distance by 26% (mean minimum total distance: 41,598 m; compare Figure 5) while decreasing accuracy and completeness (as defined above) to levels similar to those achieved with gradsect sampling. Considering variability among simulation runs, random sampling would have to allocate a minimum of 65 plots to have comparable accuracy to that of gradsect sampling.

A cost factor specific to gradsect sampling is the initial stage of mapping environmental gradients and locating gradsects. In most cases, hardcopy topographic maps and midscale aerial photography will be available and presampling time and information requirements will differ little from other multistage sampling designs. However, the additional costs for acquiring high-resolution aerial photography (see *Evaluation of High-Resolution Aerial Photography*), if implemented as described here, needs to be weighed against the cost savings with regard to field travel. Note that we consider incorporating high-resolution photography essential for our specific sampling design but not essential for gradsect sampling in general.

Discussion

Effectiveness and Utility of Gradsect Sampling

Some of the results of our comparison were easy to predict. Obviously, clustering of plot locations greatly reduces travel costs, and the inefficiency in this regard of probability designs with dispersed plots (Figure 5) is well known (Shiver and Borders 1996, p. 230–231). Similarly, the often-stated loss in accuracy of parameter estimates when implementing subjective instead of probability sampling holds true in the case of the five designs investigated


(a) Stand Structure Type (15 classes)

(b) Elevation (11 classes)

(c) Aspect (12 classes)

(d) Slope (15 classes)

Figure 4. Completeness of simulated sampling designs in placing at least one sampling plot in each stand structure or topographic class of the Arrowstone Creek study area. Each black dot represents the mean probability (i.e., classes sampled/total number of classes) for one simulation run (i.e., sampling of 90 plots). Horizontal dashes indicate means for the five model runs per design, with values listed near the bottom of each panel. Data of equal or similar value are jittered horizontally. Sampling designs as in Figure 3.

(Figure 3). It is interesting to note, though, that the two probability designs with plot clusters did not perform better than our implementation of subjectively placed gradsects.

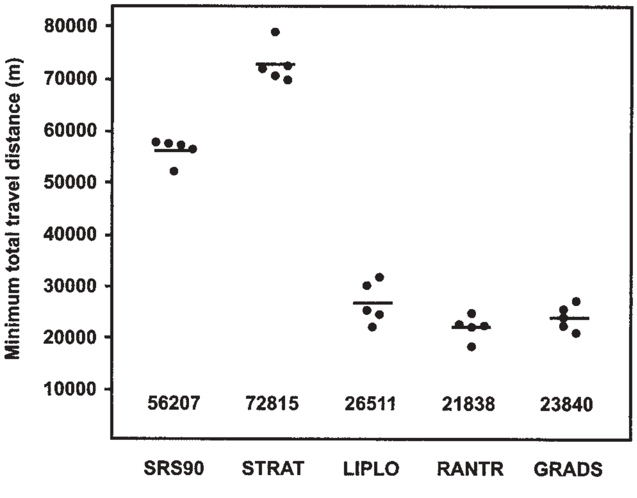


Figure 5. Travel costs for simulated sampling designs, estimated as the minimum total distance (m) between the 90 field plots of each sampling design. Total distances are the sum of Euclidean distances between pairs of nearest neighbors. Horizontal dashes indicate means for the five model runs per design (i.e., sampling of 90 plots). Data of equal or similar value are jittered horizontally. Sampling designs as in Figure 3.

Perhaps less expected are the problematic aspects of implementing plot clusters in the presence of strong autocorrelation in the sample variables. Depending on the particular disturbance history and topographic configuration of a landscape, ecological and physiognomic characteristics of its forests will tend to change gradually in some areas (e.g., on plateaus and along valley bottoms) and more abruptly in other areas (e.g., avalanche tracks or cutblock boundaries). Plot clusters are more likely to be confined to areas with similar characteristics unless they are aligned—deliberately or by chance—perpendicular to the direction of strongest autocorrelation in the parameter of interest. For example, consider the differences in the performance of designs shown in Figure 4. Our simulated gradsects are located at right angles to a stream section and extend from valley bottom to opposite ridges (Figure 2). They are therefore more likely to capture all of the elevation classes than randomly placed line-plots or transects (Figure 4b). However, due to our simplistic emulation of gradsect sampling, each gradsect is likely to be confined to just two slope directions—the opposite slopes of a subdrainage—resulting in a reduced likelihood of sampling all aspect classes (Figure 4c). Note that in our actual implementation of gradsects in the Arrowstone Creek study area we included aspect as a main criterion for gradsect placement and therefore did place at least one plot in each aspect class.

In a design-based sampling strategy, the spatial distribution and covariance of the population will not influence estimates of mean and variance because the estimators are free of assumptions regarding independence of observations (see discussions in Gregoire 1998, Stehman 2001). However, this postulate only holds true if the inclusion probabilities are known for all elements in the sample. In our case, the estimates of class proportions for the elevation data (Figure 3b) are unbiased for the simple random sampling design because the design makes no assumptions regarding the spatial structure of elevation classes in the Arrowstone study area and we know the inclusion probabilities to be equal. On the other hand, clustering of plots in the presence of spatial autocorrelation and without *a priori* knowledge of inclusion probabilities has undesired consequences. For example, if we had collected forest data that are strongly correlated with elevation, such as species composition, line-plot or random-transect sampling would have greatly decreased the accuracy of estimates regarding the proportions of species in the study landscape. Furthermore, if the sample data were used to compute parametric statistics, such as testing hypotheses about relationships among variables by means of correlation coefficients, presence of spatial autocorrelation in the data would violate the assumption of independence of observations for the test of significance and affect its outcome (Fortin et al. 1989, Legendre et al. 2002).

The implementation of gradsect sampling as proposed here aims to provide a complete representation of variability in forest structure in a cost-efficient manner. The results of our simulation exercise lead us to draw the following three general conclusions: (1) simple and stratified random sampling give the most accurate and complete estimates of sample parameters but are the most costly to implement; (2) sampling designs with plot clusters are affected by spatial autocorrelation; and (3) gradsect sampling is an effective alternative to line-plot and random-transect sampling if gradsects can be located along gradients in autocorrelation.

Despite these conclusions, the subjective nature of gradsect sampling will likely be the primary concern in a debate regarding its general applicability for forest sampling. In addition to the lack of formal procedures to estimate statistical parameters, the process of locating gradsects appears to be vague and difficult to reproduce. It has been suggested that gradsect sampling is simply a variant of stratified random sampling if field plots within the gradsects are placed at random (Bourgeron et al. 1994). This statement is based on the assumption that any study area can be stratified into a number of nonoverlapping gradients, similar to stratification by any other set of criteria. However, we are not aware of any study that has tested this assumption and personally doubt that it is reasonable.

Perhaps a better starting point for discussions is to clearly distinguish between tasks where subjective sampling has potential for being beneficial and those where it should be avoided. In the case of forest resource inventories, we would distinguish between applications where the plot data themselves provide the basis for further analysis or management decisions, and applications where plot data are intended primarily as reference for mapping of forest characteristics. In the former case, the sampling design needs to provide accurate estimations of the population mean and sampling error. Since plot data will be extrapolated to the inventory unit, subjective or haphazard placement of plots in the field will have direct influence on the overall accuracy of the sampling effort.

In the case of a mapping project, the quality of the final product is a function of the position of polygon boundaries, the identification of rare forest types, and a representative sample of field data to estimate average conditions within individual polygons (Gross and Adler 1996, Næsset 1999). Consequently, the sampling design should attempt to minimize all three possible sources of error. Simple or stratified random sampling will recover rare forest types, given a large enough sample size. However, as the results of our simulation indicate, gradsect sampling can achieve a comparable success rate at one-half to one-third the cost of field travel.

A further point to consider with respect to gradsect sampling is its assumption of consistent and strong correlations between environmental gradients and vegetation composition and structure. Even in mountainous terrain, the dynamics of natural or anthropogenic disturbances may weaken or mask existing environment–vegetation correlations. However, the occurrence of large-scale disturbances and their impact on the forest are generally easy to detect and can potentially be incorporated in a gradsect framework—perhaps as a gradient of disturbance severity. In general, gradsect sampling will be inadequate in landscapes where vegetation and environmental gradients vary either very gradually (e.g., in coastal plain or lowland boreal forests) or at very fine scales, such as the patch dynamics observed in southern boreal forests by Frelich and Reich (1995).

Some of the shortcomings of gradsect designs mentioned above could be addressed in a variety of ways. First, additional studies should evaluate differences between a number of sampling designs in the context of forest sampling, based on real and simulated landscapes, similar to the studies of Gillison and Brewer (1985), Wessels et al. (1998), or Legendre et al. (2002). Simulation exercises are relatively easy to conduct and have the potential to provide very instructive and pragmatic results regarding improvements to current sampling designs (e.g., Taylor 1998). For example, our simulation study indicates that randomly placed transects may not necessarily be inferior to gradsect sampling, as concluded by Gillison and Brewer (1985). A more detailed simulation with a higher number of model runs and variable sampling intensity would provide a better basis for definite conclusions.

Second, the choice of environmental and topographic variables for delineating gradsects should extend beyond indirect factors of vegetation composition and development (Austin et al. 1984), such as elevation, aspect, and watershed configuration. Direct factors, such as solar radiation and moisture availability have been shown to exhibit stronger correlations between landscape structure and vegetation attributes (Franklin 1995, Stephenson 1998), since they more directly influence ecological processes of plant growth, competition, and disturbances. However, automated procedures for site-specific estimation of energy or water budgets in mountainous landscapes are very complex and only recently have become more generally available (e.g., Fu and Rich 1999, Wood 1999, Tarboton 2000).

Third, the process of locating and delineating gradsects needs to become more formal and transparent, perhaps through an automated process within the framework of a GIS. A number of different approaches can be envisioned, including variants of the method we used in emulating a gradsect layout, multivariate procedures as referenced in Neldner (1995), and algorithms that trace "paths" of strongest gradients or weakest autocorrelation. Obviously, numerical variables will be easier to integrate into these approaches than context-related aspects, such as configuration of subdrainages or access to sampling sites.

In summary, we recommend considering gradient-directed transects as a sampling scheme for forest inventory and mapping if the following conditions are met:

- Consistent maps of the entire study area are available, particular to, but not limited to, topographic variability. High quality maps may be desirable for accurate placement of field plots but are not necessary for the initial selection of gradsects.

- Consistent correlations between environmental gradients and the forest variables of interest are known to exist or reasonable to expect.

- Environmental gradients exhibit considerable variability across the study area. Gentle, unbroken terrain is less likely to have a strong influence on spatial heterogeneity in forest variables, thus making gradsect sampling an ineffective or inappropriate choice.

- Statistical estimation and extrapolation of sampled data are *not* the primary goal of the inventory, as gradsect sampling does not allow determining the inclusion probabilities for the sample observations.

Evaluation of High-Resolution Aerial Photography

When forest managers need complete coverage of vegetation data of large areas, it may appear counterintuitive to advocate a type of aerial photography that covers, frame by frame, less than 0.1% of the ground area captured by conventional 1:15,000 airphotos. More likely, they would look toward small-scale aerial photography or satellite imagery as a data source for mapping (Harrison and Dunn 1993). Small-scale photography, however, is characterized by comparatively coarse spatial resolution, and digital imagery is largely confined to the analysis of spectral information in two spatial dimensions (as opposed to pattern, shape, three-dimensional structure, etc.). In other words, these types of remotely sensed data are well suited for projects that only require coarse-grained characterizations of landscape patterns. If the mapping project needs to be able to resolve fine-scale variability in forest conditions, such as fuel loading, vertical structure, or small canopy gaps, high-resolution aerial photography currently remains the better choice (Pitt et al. 1997). The challenge remains to integrate it with landscape-level forest inventory in an effective and efficient way.

Judging by the dates of published literature about high-resolution aerial photography and its current level of use in North America, it appears that the interest in this technology peaked in the 1970s and early 80s and has since stagnated. This is perhaps due to a number of common misconceptions about this technology, such as: (1) large-scale aerial photography is limited to small, specialized projects; (2) flight planning, acquisition, and analysis of high-resolution photography are tedious and expensive; and (3) nondigital photography and image analysis are outdated technologies.

In previous sections we have outlined how integration of high-resolution photography into a sampling design based on gradient-directed transects can overcome most of the technical disadvantages of flight planning and photo tracking. In addition, we believe that a specific advantage of high-resolution, small-format photography is that it does not require the acquisition of new equipment or software. Instead, it builds on existing technology and skills and can be directed and conducted by the end users themselves (Spencer 1984, Warner et al. 1996, Chapter 12). All of the office-based stages of flight planning and photo interpretation can be achieved with hardcopies of maps and airphotos. The individual components of this sampling design can easily be adjusted to address differences in study objectives and logistical constraints. With the general availability of differential GPS, opportunities exist for extending the basic three-stage sampling design to satellite data or high-altitude photography, especially if study areas extend over more than 10^4 ha (e.g., Howard 1991, p. 345–350, Gall et al. 1994). In this case, gradsects and flight lines might be delineated in a nested (i.e., multiscale) design to capture both watershed-level topographic variability and regional gradients of climate and geology (Nielsen et al. 1979).

Direct and indirect costs are important criteria for evaluating the general applicability of a proposed technology. Assuming that camera system, mirror stereoscopes, and auxiliary equipment for airphoto interpretation are available free of charge (to government agencies), major sources of expense will be the acquisition of 70 mm photography and the time spent with preparations, field work, and airphoto interpretation. If the acquisition of photography is contracted to a private company, the costs per stereo pair will likely increase by a factor of two or more. However, these additional costs could be partially offset by the delegation of flight planning and operational risks and responsibilities to the contractor (Hall et al. 1991).

The actual costs for the 70 mm imagery will vary with the distance of airport from photo sites, arrangement of transects, camera system, and other factors (Hall et al. 1991, Warner et al. 1996, Chapter 5). In our study, we acquired 609 usable stereo pairs from three spatially separate watersheds at an average cost of approximately US$7 per pair. These costs include a total of 5 hr of helicopter time, four 100-ft rolls of Kodak Avichrome 200, and processing of all films. Using a similar camera system, Gall et al. (1994) reported costs of

US$8.80 per pair. In addition, we paid an average of US$8.30 per print for several hundred 20 × 20 cm color prints that we used for field navigation and plot layout.

The effects on lab and field expenses of incorporating 70 mm photography and gradsect sampling into a mapping project are more difficult to gauge. Costs will be incurred through the additional steps involved in planning flight lines, preparing and annotating photographs, and the analysis of 70 mm photography. On the other hand, the results of our comparison of sampling designs suggest that at least some of the costs of field sampling will be significantly reduced. Since only a limited number of the 70 mm stereo pairs are used for developing the interpretative key (i.e., those that contain a field plot), the remainder are available for an independent assessment of the accuracy of the mapping effort (*sensu* Congalton and Green 1997). A simple grid overlay is sufficient to measure area-based values of the three threshold criteria—crown cover of dominant trees, proportions of vertical strata, and crown closure—thus eliminating the need for additional field plots. However, since gradsects comprise a subjective subset of the study area, an accuracy assessment based on aerial photography of the gradsects is not necessarily valid for the study area as a whole. This limitation can be avoided by acquiring several additional random flight lines at the same time as the gradsect flight lines (at little additional cost) and using a random subsample of those stereo pairs for accuracy assessment instead.

The conventional approach to forest mapping—delineation of stand types followed by stratified random placement of field plots—separates airphoto interpretation from data collection and assumes that an unbiased sample of field data will be sufficient to overcome potential inconsistencies in polygon delineation (Gillis and Sundstrom 1999). However, if the mapping process fails to minimize variability within polygons, due to either misplacement of boundaries or an inadequate classification key, even probability sampling procedures may result in maps with low accuracy. The successful application of our three-stage design leads us to conclude that an integration of field sampling and airphoto interpretation, enhanced by supplementary high-resolution photography, can improve on the efficiency and accuracy of conventional procedures.

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