MAPPING FOREST STRUCTURE OF DRY MONTANE FOREST LANDSCAPES: A COST-EFFECTIVE THREE-STAGE SAMPLING DESIGN FOR CHARACTERIZING DISTURBANCE DYNAMICS AND STAND DEVELOPMENT

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ABSTRACT

In the dry montane forests of western North America frequent disturbances of variable types and intensities are a source of fine-scale heterogeneity in forest structure. Structural variability reflects complex spatial and temporal interactions between plant growth (e.g., establishment, dispersal, and competition), environmental gradients (e.g., aspect, soil type, or water availability), different types of natural disturbances (e.g., wildfires, windthrow, and insect outbreaks), and various levels of human intervention. New initiatives that attempt to model forest landscape management based on the spatial and temporal dynamics of natural disturbances require detailed maps and field data for a range of parameters across large areas. Traditional two-stage forest inventory based on medium-scale aerial photography and stratified field sampling is not well suited for this task due to limits in photo resolution and the complex requirements for statistical rigor of field sampling. On the other hand, new procedures based on digital remote sensing data and automated image analysis are still limited in their analytical capabilities and general applicability. Consequently, alternative approaches for exploiting existing technologies and refining sampling procedures remain of interest to resource managers and field staff. In this paper I present a novel three-stage approach for mapping the variability of forest stand conditions across mountainous landscapes. It aims to increase the accuracy and efficiency of traditional airphoto-based mapping by combining supplementary high-resolution aerial photography with a sampling strategy developed for regional-scale vegetation inventory. The first stage involves the acquisition and interpretation of 1:2,000-scale small-format aerial photography. Even in steep terrain, existing helicopter-mounted camera boom systems are capable of acquiring continuous strips of stereo images. Helicopter flight lines are purposively located to follow significant topographic or environmental gradients, a sampling design first proposed by Gillison (1985). In the second stage, field plots are systematically placed along these transects to provide empirical data of stand structure and disturbance dynamics, as well as reference data for the measurements on stereo pairs. In the third stage, field data and 70-mm airphotos are used in combination to calibrate and verify the classification key for mapping forest conditions on standard 1:15,000-scale aerial photography across the landscape of interest. I have applied this method in four study areas in the Kamloops Forest Region of southern interior British Columbia, each one covering between 2000 and 5000 hectares. Dry montane forests appear particularly suited for this sampling design as they are influenced by a mix of recurrent, often patchy disturbances of variable severity. Also, stands tend to have less dense and uniform crown closure than moister or cooler forest types. To fully capture fine-scale heterogeneity in vertical and horizontal forest structure, I expanded the structural vegetation classification of O'Hara (1996) to 12 stand structure classes. The resulting maps of forest conditions will form the basis for a quantitative spatial analysis of the influence of topographic gradients on stand structure and natural disturbances.

Keywords: aerial photography, sampling design, forest structure, dry montane forests, vegetation–environment relationships

INTRODUCTION

With the advent of policies for managing forest landscapes in ways that mimic the natural dynamics of stand development and disturbance processes (e.g., British Columbia Ministry of Forests 1995, Swanson et al. 1997) comes the need for a better understanding of interactions between tree growth, environmental conditions, and different agents of natural disturbance at a range of spatial and temporal scales (Swanson et al. 1988, Attiwill 1994, Parminter 1998). The vertical and horizontal distribution of tree canopies, and their changes over time are increasingly recognized as indicators of past and present forest dynamics (Lorimer

1984, O'Hara et al. 1996, Oliver and Larson 1996, Latham et al. 1998). At the stand level, forest structure is mainly a function of tree autecology, tree-to-tree interactions, availability of nutrients, light and moisture, and the site-specific sequence of past disturbances (Cooper 1961, McCune and Allen 1985, Riccius 1998). At the landscape level, large disturbances and broad environmental gradients may synchronize patterns and processes of stand development, overriding, for certain periods of time, fine-scale stand dynamics (Auclair and Bedford 1994). Across a range of scales, the topography of a landscape can act as either a pathway or a barrier for the movement of resource factors and disturbances and thus influence the patterns of forest structure (Swanson et al. 1988).

Given the stochastic nature of many influential ecological processes, the current structure of any given patch of forest is highly site-specific. Consequently, attempts to extrapolate plot-based data of stand structure and natural disturbances to surrounding areas face the complexities associated with the non-deterministic character of environmental heterogeneity (Lertzman et al. 1998, Bunnell and Huggard 1999). An alternative methodology is to map forest conditions across the entire area of interest, using a consistent approach and adequate scale. This provides a first assessment of spatial variation in forest attributes and can be used as a framework for selecting representative locations for intensive field sampling (Bradshaw and Garman 1994).

Many structural parameters of forests, such as species composition, tree height, and crown density can be estimated reliably by stereoscopic analysis of aerial photography (Howard 1991). Medium-scale 1:15,000 imagery, in particular, is well suited for stratifying forest cover into meaningful cover types and detecting stand-replacing disturbances. It is available for most forested areas of North America and forms a common basis for forest mapping and inventory (Aldrich 1979, British Columbia Ministry of Environment 1999).

Despite considerable advances in technologies employing digital airborne or satellite-based imagery, major challenges remain to successfully integrate the full spectrum of human expertise and diagnostic elements available for manual airphoto analysis (e.g., color, size, pattern, and texture) into an automated image interpretation process (Pitt et al. 1997). As a result, visual interpretation of aerial photographs will likely continue to play an important role in forest inventory and management in the near future. During this time, new approaches for airphoto acquisition and analysis can improve traditional procedures with respect to accuracy, efficiency, and thus reduction of direct and indirect costs.

In this paper I present a new approach to landscape-scale mapping of forest structure. This method integrates existing technology and statistical procedures to address the conflicting requirements of fine-scale resolution and large extent of study area. Specifically, it aims to increase the efficiency and accuracy of traditional airphoto-based mapping by combining supplementary high-resolution aerial photography with a sampling strategy developed for regional-scale vegetation inventory.

METHOD DEVELOPMENT

The traditional method of airphoto-based forest mapping and inventory consists of two main stages: (1) Delineation of identifiable stand boundaries on medium-scale aerial stereo photography (approx. 1:15,000) to derive a map of polygons with similar vegetation characteristics; (2) Sampling in the field to provide the photo stratification with quantitative parameters as well as to verify the initial classification (British Columbia Ministry of Forests 1998). The most commonly used type of imagery for this procedure is high quality, true-color imagery acquired with large-format aerial cameras. At a nominal scale of 1:15,000, the common 25-cm by 25-cm print covers approximately 3.5 km by 3.5 km on the ground, an area of 1,225 hectares.

Despite its long and successful application, manual interpretation of medium-scale aerial photography has a number of inherent problems. One of them is the subjective nature of polygon delineation and classification, whose accuracy depends on the experience and care of the photo interpreter, and the optical and spectral resolution of the aerial photograph (Edwards and Lowell 1996). A related aspect is the difficulty of finding the exact location of photo sites in the field, and *vice versa*. Trying to locate on a 1:15,000-scale airphoto a site within a 56.4 m radius—the equivalent of the common 2-ha minimum mapping unit—is challenging, particularly so in dense forests or roadless areas. Nevertheless, accurately relating photo sites to field sites is a very important prerequisite for the collection of reference data.

Deciding on an adequate and statistically robust sampling design, in consideration of direct and indirect costs associated with fieldwork, is another topic of much debate (Howard 1991). A common method in airphoto mapping is to stratify the study area into more or less homogenous classes followed by random or systematic allocation of field sampling locations to each stratum (e.g., British Columbia Ministry of Forests 1998). This procedure requires decisions on criteria for the delineation of strata, often in the absence of field-based information about current forest conditions.

In the ideal case, photo interpretation of large areas would have at its disposal complete photo ground coverage at high spatial resolution as well as data from a large number of randomly placed field sites. In the absence of the ideal case I conducted an intensive search for "the next best" method. I found two procedures, originally developed for quite different goals, which can be integrated in a meaningful and efficient way for landscape-scale mapping of forest conditions. In the following two sections, I describe the basic elements of these procedures—large-scale aerial photography and sampling along gradient-directed transects—that, used in combination, overcome some of the limitations of traditional two-stage airphoto mapping.

Large-scale Aerial Photography

Aerial photography of very large scales (from 1:250 to 1:2,500) has been used in various forest management-related tasks for more than three decades (Aldrich et al. 1959, Lyons 1964, 1967). Stereo images are obtained using 35- or 70-mm camera systems mounted to helicopters or light aircraft. The high ground resolution of a fraction of a meter (Pitt et al. 1997) allows detailed analyses of vegetation and environmental site conditions (Figure 1). Typical applications of this technology include regeneration assessments, fuels inventory, habitat typing, and estimation of tree mortality (Muraro 1970, Croft et al. 1982, Hall 1984, Befort 1986).

In addition to the obvious advantage of more detail, I particularly appreciate two aspects of large-scale photography that are rarely mentioned in the literature: (1) 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 GPS points, even in more dense and uniform stands; (2) At the same time the photographs give a detailed 'birds-eye' perspective of the plot area, thus providing an important link between the visual impression of the stand gained during field sampling and its 'bird's eye' appearance in the stereo model during the subsequent analysis of 1:15,000-scale photography. Since its original conception, specialized equipment

Figure 1. Example of the 70-mm photography used in this study. Kodak Avichrome 200 true-color transparency. 1.8 x enlargement of the original 53 mm by 53 mm image. Photo area approx. 125 m by 125 m. Print scale ~ 1:1,300. Arrowstone Creek study area, Transect B, ~ 1170 meters a.s.l. North is at bottom. Juxtaposition of northeast- and south-east- facing, unmanaged interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) sites. An inactive drainage channel, running West to East (right to left), divides the image area into a mesic Douglas-fir–pinegrass stand (IDF dk1–04; Lloyd et al. 1990) and a drier, open Douglas-fir–bluebunch wheatgrass–pinegrass stand (IDF xh2–04) with a few scattered ponderosa pines (*Pinus ponderosa*). Dominant Douglas-firs in the photo area are up to 30 m tall and between 250 and 350 years old. Partially dead fir crowns are a result of defoliation by Western spruce budworm (*Choristoneura occidentalis)*.

has been developed for large-scale aerial photography to address potentially problematic issues of variable photo scale, image quality, and tracking of ground coverage (Hall 1984, Spencer 1998). Government agencies and private companies operate a number of different systems (Warner et al. 1996, Pitt et al. 1997). In Canada, one of the commonly used systems consists of a 'fixed-base' arrangement of two customized Hasselblad Mk70 cameras, mounted 6.1 m apart, in a 7.2 m long metal boom. The boom is mounted under a Bell 206B Jet Ranger helicopter parallel to the direction of flight (Figure 2; also see Bradatsch et al. 1981, Hall and Aldred 1992). Both cameras are exposed simultaneously, at timed 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. For example, 200 m flying height above ground, using camera lenses with 100-mm focal length, will result in a photo scale of approximately 1:2,000.

Following delivery of the processed films to the interpreter, the rolls of imagery need to be viewed and annotated to match photo pairs and prepare manual interpretation. Several different procedures for film preparation and archival have been described (e.g., Croft et al. 1982, British Columbia Ministry of Forests 1992). For my project, I cut film rolls into sections of five frames and placed each pair of matching strips in 9" by 12.5" transparent album sheets designed for archiving 4" by 10" panoramic photo prints (available at most photo stores). This system allows for convenient handling and viewing of the film, protects the originals from damage, and—provided unambiguous frame annotations are used—prevents mismatching.

The basic equipment for interpretation of 70-mm stereo transparencies consists of a light table, a 2/4–power pocket stereoscope, and a transparent grid overlay (Croft et al. 1982). For precise measurements in three dimensions, micrometer wedges and parallax bars, as well as more sophisticated instruments are available (Hall 1984). As a prerequisite for photogrammetry, the scale of each photo pair needs to be determined. With the Canadian fixed-base system described above, this procedure is straightforward and does not require ground control points or the flying height of the helicopter. The customized Hasselblad cameras expose a regular grid of 25 cross-shaped markings on each image; the distance between any matching pair of crosses viewed in the stereo model is the equivalent distance to the known camera base (i.e., 6.1 m) at ground scale. Since my application of 70-mm technology does not involve stereoscopic photogrammetry, I refer the interested reader to technical discussions in Hall (1984), British Columbia Ministry of Forests (1992), and Warner (1996).

Gradient-directed Transects

One of the most persistent problems for field-based studies of landscape dynamics is the choice of an adequate sampling design (Bourgeron et al. 1994). Study areas with large spatial extent and variable topography incorporate many sources of heterogeneity (Lertzman and Fall 1998) and thus require a large number of sample sites in order to satisfy statistical and ecological considerations, such as replication and representativeness. However, financial and logistical constraints almost always dictate some trade-off between the number of field plots, their spatial location and extent, and the intensity of sampling within each plot. As a consequence, the development of robust sampling designs for inventories of large study areas remains an active field of basic and applied research (Bourgeron et al. 1994, Neldner et al. 1995, Botti et al. 1998).

Figure 2. 70-mm twin camera boom mounted under a Bell 206B helicopter. The system consists of two Hasselblad Mk70 cameras equipped with 100 mm lenses, placed 6.1 m apart. Stereo images are acquired, at timed intervals, by remote control from inside the helicopter.

In many cases, landscape-level studies are initially concerned with accurate characterization of distributional patterns and the range of variability of the biotic and abiotic components of interest. This emphasis is different from traditional ecological studies, which are concerned with unbiased estimation of specific variables and their parametric characteristics (e.g., Fortin et al. 1989). These studies require random sampling strategies that have since become the main criteria for evaluating the credibility of quantitative analyses (Gillison and Brewer 1985). One disadvantage of randomized sampling is, however, that it is biased towards common elements and, unless sampling efforts are very extensive or based on *a priori* stratification, often fails to recover the full range of the variable(s) of interest. In addition, lack of control over sampling locations may greatly increase the unproductive parts of fieldwork, such as locating of and travelling to plot sites.

In mountainous areas, plant communities and their associated agents of natural disturbances are influenced by environmental gradients which modify the availability of primary resources, such as topography, precipitation, and soils (Harmon et al. 1983). In consideration of such non-random distributions of plant communities, Gillison and Brewer (1985) proposed a sampling design that places field plots on belt transects that are aligned with perceived environmental gradients. Delineation of these gradient-directed transects, or 'gradsects', is based on observations regarding potentially significant environmental parameters in 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 lengths of gradsects by the researcher, Gillison and Brewer (1985) provide 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 field work and produced a classification key for vegetation mapping of quality similar to an intensive survey of the whole study area (Gillison, 1985; also see Bourgeron et al. (1994) for independent evaluations of gradsect sampling).

Based on my own research (see Section Application Example below), I believe that sampling along gradsects, in combination with continuous large-scale aerial photography of the gradsect area, has several interesting advantages over traditional sampling methods:

1. In study areas where vegetation communities and natural disturbances are strongly influenced by environmental gradients, gradsect sampling is more likely to capture the full variability associated with it. Where such associations are insignificant or masked by other processes, gradsect sampling is at least at par with random sampling of similar intensity.

2. Gradsect sampling avoids many of the logistic problems associated with designs based on the requirements of randomization, such as field navigation and *a priori* stratification of the study area.

3. Large-scale aerial photography of gradsects provides permanent, detailed records of sampling sites and the transect area in between.

4. The use of continuous belt transects makes large-scale photography more applicable to landscape-scale studies since photo locations are easier to track and delineate on medium-scale airphotos.

APPLICATION EXAMPLE

In my dissertation project, I intend to conduct a GIS-based quantitative analysis of the spatial associations between forest structure, indicators of natural disturbances, and topographic variables. This requires, among other tasks, complete and consistent mapping of current forest conditions across my four study areas. Below, I briefly outline the steps involved in applying the three-stage sampling design in the 5000-ha Arrowstone Creek drainage near Cache Creek, B. C.

1. Using digital elevation data and 1:15,000 color aerial photography provided by the B. C. Ministry of Environment, Lands, and Parks, I selected meaningful locations for six 2 to 3 km long gradient-directed transects. I considered elevation, aspect, slope and the configuration of subdrainages to be the most relevant gradients in this study area. Given a width of about 100 meters, the gradsects cover less than 3 per cent of the Arrowstone Creek watershed (Figure 3).

2. In 1997, we acquired a total of 178 stereo pairs with the 70-mm twin camera system operated by the B. C. Ministry of Forests in Kamloops (Figure 2; Bradatsch et al. 1981). Note that the 1:15,000

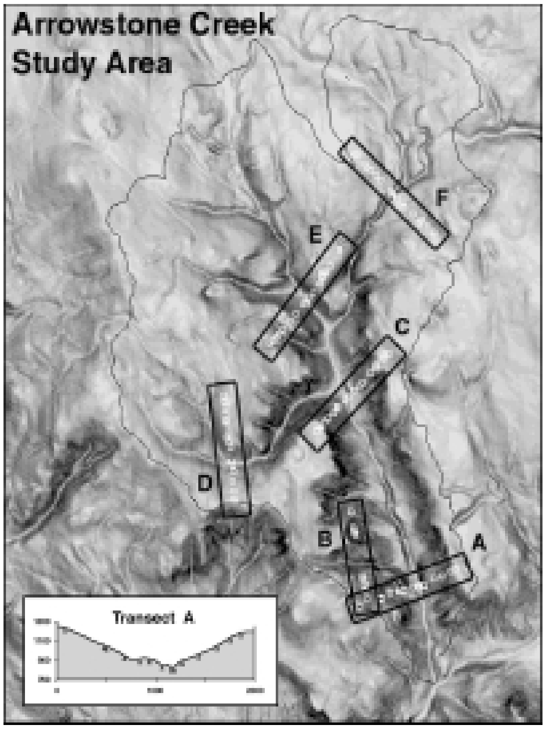

Figure 3. Location of gradient-directed transects (black rectangles) and sampling plots (white squares) in the Arrowstone Creek study area (121º15'W, 50º53'N). Map scale c. 1:67,000. North is at the top. Transect widths and plot sizes are not to scale. Map is based on a GIS screenshot of the digital elevation model, with a gray-scale coding of slope gradient (i.e., the darker, the steeper). The insert shows the elevational profile of Transect A, heading WSW to ENE. Plot locations are indicated by triangles; distances on X-axis in meters, elevations on Y-axis in meters above mean sea level.

airphotos and predetermined compass headings of the transects were sufficient for the helicopter pilot to find and follow the flight lines, eliminating the need for pre-flight marking of transect end-points in the field.

3. With the help of a mirror stereoscope, I transferred the boundaries of about one-quarter of the 70-mm photographs to the 1:15,000 airphotos. Since the photo strips were flown with a constant heading and were timed to achieve a forward overlap of approximately 10 to 30 per cent, this task was more tedious than difficult. The benefits of this procedure are a better understanding of the actual locations of the photo strips and a very helpful airphoto map for on-the-ground navigation in unfamiliar and roadless terrain.

4. In the field, I located sampling plots in the center of each stand intercepted by a transect. Navigation to the plots was accomplished by using 8" by 8" 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 (see Figure 1)—allow for reliable identification of one's position in the photo area. Plot center locations were confirmed by GPS readings (post-processed to about ± 5 m locational accuracy).

5. At each of 90 fixed-radius sample plots, I collected data on stand structure (age, height, dbh, crown class, etc.), community composition, and evidence of past and present natural disturbances. Most of the trees measured in the field (576 out of 611) could be located on the 8" by 8" prints and are thus available for calibration of measurements on the original stereo pairs.

6. The database of the field plots and the large-scale photography together formed the basis for the development of an airphoto interpretation key (Figure 4). For its decision tree I selected three main criteria—relative age, vertical structure, and crown cover—as indicators of significant differences in stand development, site conditions, and natural disturbances. The underlying concept of classifying forest conditions based on ecological processes of stand development (including disturbances) has recently been applied to the forest types of the U.S. Inland Northwest (O'Hara et al. 1996). Given the predominance of old forest types in my study area, I expanded the seven classes defined by O'Hara et al. (1996) to include a greater variety of crown closure types in this age class (Figure 4). A series of tests confirmed that the resulting 12 classes of forest structure can be distinguished reliably on mid-scale aerial photography.

7. Using mirror stereoscope and acetate overlays, I delineated polygons of similar forest types and classified them according to the airphoto interpretation key (Areas with less than 10 per cent crown cover were classified as 'Non-forest'). This was done for the entire study area.

8. GPS data of plot center locations and auxiliary ground control points were used to register scanned files of the acetate sheets with the digital elevation model. Note that the last two steps proceeded at the lower end of the spectrum of available technology. A more sophisticated option would have

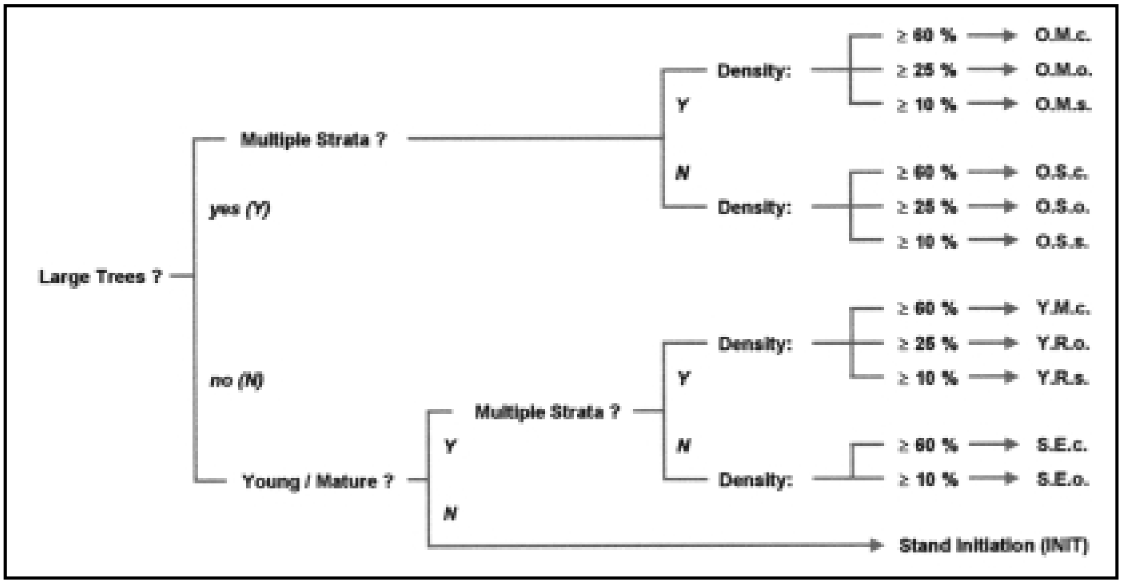

Figure 4. Airphoto interpretation key for forested areas (³ 10 per cent crown cover). The three main criteria of the decision tree—relative age, vertical structure, and crown cover—were selected to capture significant differences in stand development, site conditions, and natural disturbances that can be reliably distinguished on mid-scale aerial photography. Definitions of stand structure classes (see below) are adapted and expanded from Oliver (1981) and O'Hara et al. (1996). Crown cover thresholds are based on British Columbia Ministry of Forests (1998). Note that this interpretation key was defined for dry montane forests, specifically for the Interior Douglas-fir zone (IDF) of south-central British Columbia.

Stand Structure Classes:	**O.M.c.**	Old Forest Multi-Strata, Closed Canopy
	O.M.o.	Old Forest Multi-Strata, Open Canopy
	O.M.s.	Old Forest Multi-Strata, Sparse Canopy
	O.S.c.	Old Forest Single Stratum, Closed Canopy
	O.S.o.	Old Forest Single Stratum, Open Canopy
	O.S.s.	Old Forest Single Stratum, Sparse Canopy
	Y.M.c.	Young Multi-Strata, Closed Canopy
	Y.R.o.	Understory Reinitiation, Open Canopy
	Y.R.s.	Understory Reinitiation, Sparse Canopy
	S.E.c.	Stem Exclusion, Closed Canopy
	S.E.o.	Stem Exclusion, Open Canopy
	INIT	Stand Initiation, Single Stratum

been to conduct on-screen digitizing on top of stereo orthophotos.

The final products of this sampling procedure will be digital thematic layers of forest structure and a database of quantitative parameters associated with each stand structure class found in the gradsect area. These maps will be tested for accuracy by means of an independent sample of randomly selected ground verification sites. Once all necessary adjustments or corrections are completed the polygon maps will be transferred to a raster format to match the format of the digital elevation model. In the subsequent GIS-based statistical analysis, I will test a series of ecological hypotheses about the spatial associations between forest structure, natural disturbances, and topographic variables.

DISCUSSION

When forest managers need complete coverage of baseline data across large areas, it may appear counterintuitive to propose the use of aerial photographs that cover, frame by frame, less than 0.1 per cent of the ground area captured by conventional 1:15,000 photography. More likely, resource specialists would choose digital satellite imagery, such as Landsat-TM or SPOT, as their main data source for mapping (e.g., Harrison and Dunn 1993, Vande Castle 1998). Satellite remote sensing, however, is characterized by comparatively coarse spatial resolution and the limitations imposed by being largely confined to the analysis of spectral information (as opposed to texture, tone, shape, spatial arrangement, etc.). In other words, small-scale satellite imagery (and high-altitude aerial photography) is well suited for projects that 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, small-scale imagery can only be applied as a template for predictive modeling of sub-pixel variability. For direct mapping of fine-scale heterogeneity, high-resolution aerial photography currently remains the only source. The challenge is, therefore, to integrate large-scale photography into landscape-level forest inventory in an effective and efficient way.

Judging by the dates of published literature and the current level of use in British Columbia of the camera boom system, it may appear that the demand for 70-mm photography peaked in the 70s 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 large-scale photography are tedious and expensive; and (3) Non-digital photography and image analysis are outdated technologies.

In the previous sections I have outlined how integrating large-scale photography into a sampling design based on gradient-directed transects can overcome most of the problematic aspects of flight planning and photo tracking. For example, without any previous experience with the application of this technology, I successfully planned, managed, and completed all stages of acquisition and analysis of several sets of 70-mm photography on a small budget.

A particular advantage of this method is that it does not require the acquisition of new equipment or software. Instead, it builds on existing technology and skills and can be conducted by the end users themselves, an important consideration for small field offices and resource specialists in general (Warner et al. 1996, Spencer 1998). 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 hectares (Howard 1991, Gall et al. 1994). In this case, gradsects should be delineated in a nested (i.e., multi-scale) design to capture both watershed-level topographic variability and regional gradients of climate and geology. Other important criteria for evaluating the applicability of this method are the direct and indirect costs associated with its implementation. Assuming that camera system, mirror stereoscopes, and auxiliary equipment for airphoto interpretation are available at no charge, the major sources of expense are the acquisition of 70-mm photography and the time spent on preparations, field work, and airphoto interpretation. If the acquisition of large-scale photography is contracted to a private company the costs per stereo pair (see below) will likely increase by a factor of two or more. However, these additional costs will be partially offset by the delegation of flight planning and operational risks and responsibilities to the contractor (Hall 1984).

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 (see discussions in Hall 1984, Warner et al. 1996). In my study, 609 usable stereo pairs have been acquired to date from three spatially separate watersheds at an average cost of approximately US$ 7.00 per pair. These costs include a total of 5 hours of helicopter time, four 100-foot rolls of Kodak Avichrome 200, and film processing. Using a similar camera system, Gall et al. (1994) reported costs of US$ 8.80 per pair. In addition, I paid an average of US$ 8.30 per print for several hundred 8” by 8” color prints that I used for field navigation and plot layout.

The effects on lab and field expenses of incorporating 70-mm photography and gradsect sampling in 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 actual photo analysis. On the other hand, there are a number of short-and long-term cost reductions associated with less time spent for navigation in the field and the site-specific accuracy of photo plots (see Hamilton 1984, Warner et al. 1996, Spencer 1998).

Gradsect sampling is not suitable for extrapolating averages or variances measured in the transect plots to other sites in the study landscape (for example, the estimation of the mean basal area in stand structure class X). Since the area covered by gradsects is a subjectively chosen subset of the study area, even a randomized placement of plots along gradsects would not correct the bias introduced up front. As argued earlier, however, the lack of equal sampling probabilities (critical to statistical extrapolations) can be an asset if the project's main objective is to characterize the full range of rare and common types of forest conditions. Moreover, the resulting maps of the spatial distribution and configuration of forest types provide a valuable stratification for intensive studies of ecological processes and historical stand dynamics.

Consistent mapping of current forest conditions across large areas, without losing the ability to resolve fine-scale heterogeneity, is a challenging task. The delineation of gradient-directed transects concentrates fieldwork in areas most likely to include the full range of variability in forest structure. Full coverage of the transect areas by large-scale aerial photography provides the means for detailed forest mensuration, easy field navigation, and extrapolation of the visual cues of certain forest structure classes to medium-scale aerial photography that cover the entire area of interest.

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