

# Towards automated segmentation of forest inventory polygons on high spatial resolution satellite imagery

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## ABSTRACT

High spatial resolution satellite imagery, with pixel sizes of one metre or less, are increasingly available. These data provide an accessible and flexible source of information for forest inventory purposes. In addition, the digital nature of these data provides an opportunity for automated and computer-assisted approaches for forest stand delineation to be considered. Specifically, automation has the potential to realize cost savings by minimizing the time required for manual delineation of forest stands; however, inappropriate automation could result in increased costs due to time-consuming revisions of automated delineations. The aim of this research is to present, through example, investigations of an automated segmentation approach for delineating homogeneous forest stands on high spatial resolution satellite imagery. An evaluation of the suitability of IKONOS 1-m panchromatic data for this application is also presented, along with several key issues that must be considered regarding automated segmentation approaches.

**Key words:** forest inventory, segmentation, automation, IKONOS, high spatial resolution satellite, photo interpretation, stand delineation, object

## RÉSUMÉ

Les images par satellite à haute résolution spatiale, caractérisées par des espacements des pixels d'un mètre ou moins, sont de plus en plus disponibles. Ces données procurent une source de renseignements accessibles et souples aux fins d'inventaire forestier. De plus, la nature numérique de ces données offre la possibilité d'étudier diverses approches automatisées et assistées par ordinateur pour effectuer la délimitation des peuplements forestiers. L'automatisation a, plus particulièrement, le potentiel de permettre de réaliser des économies en minimisant le temps nécessaire pour procéder à une délimitation à la main des peuplements forestiers; cependant, une automatisation inadéquate pourrait se solder par une augmentation des coûts en raison de la quantité de temps considérable nécessaire pour effectuer les révisions des délimitations automatisées. L'objectif de cette recherche est de présenter, au moyen d'un exemple, les enquêtes réalisées sur une approche de segmentation automatisée en vue de la délimitation des peuplements forestiers homogènes sur des images par satellite à haute résolution spatiale. Ce document présente également une évaluation du caractère adéquat des données panchromatiques produites par IKONOS 1-m pour cette application, de même que plusieurs questions clés qui doivent être prises en considération relativement aux approches de segmentation automatisée.

**Mots clés :** inventaire forestier, segmentation, automatisation, IKONOS, satellite à haute résolution spatiale, interprétation de photos, délimitation des peuplements, objet



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## Introduction

Typically, a forest inventory is a detailed accounting of the location, spatial extent, and characteristics of forest stands within a forested area. Forest inventories may be represented by many forms; however, in the context of this paper, we refer primarily to forest inventories known as “reconnaissance” or “strategic” inventories, commonly collected at a scale of 1:20 000 (Köhl *et al.* 2006). These inventories are designed to provide an approximation of forest characteristics, location, and spatial extent through the use of aerial photography and field sampling support. These types of inventories are generally completed in two phases: the first is the acquisition, delineation, and interpretation of the air photos, while the second phase involves field sampling based on strata identified in the initial phase of the inventory (Gillis and Leckie 1993). In this first phase, polygons representing homogenous areas of specific forest attributes (such as height, species, age, and density) are delineated on the photos, followed by the interpretation of attributes such as species composition, age, height, and crown closure. In the second phase of the inventory, these polygons are then stratified by a specific combination of attributes, and a sub-sample is selected for field sampling (Gillis and Leckie 1993). The field sampling verifies the estimates of the photo interpreter, and facilitates collection of additional data. These field data are then used to adjust systematic errors in photo interpreter estimates, or to generate new attributes that cannot be calculated based on photo interpretation alone (Kangas and Maltamo 2006). A forest inventory is often the best available characterization of forest resources on the ground; however, it is not without error (Thompson *et al.* 2007).

Aerial photographs are the most frequently used source of information for forest inventory and mapping (Hall 2003), although more recently, high spatial resolution satellite imagery has emerged as a potential data source for forest inventory (Culvenor 2003). Advances in digital camera technology have also made *digital* aerial photography more widely available for forest inventory applications (McRoberts and Tomppo 2007). Despite these advances, however, there currently exists no digital system that can match the spatial resolution, data storage, and hardcopy output capabilities of analog photo systems combined with film scanners (Hall 2003). Furthermore, image processing methodologies commonly applied to digital remotely sensed data are not directly transferable to digital air photos (Tuominen and Pekkarinen 2004, 2005).

Imagery is used to stratify forest land into homogenous stands or sampling units that later serve to spatially distribute the estimates derived from inventory plots. Delineation of homogenous units on air photos has conventionally been completed by photo interpreters, who manually draw the boundaries between units based on the visual differences resulting from variations in tree species, crown closures, and tree heights. However, this process can be slow and costly. Furthermore, skilled and experienced photo interpreters are increasingly rare in the workforce. Recent advances in digital image processing may facilitate delineation by providing photo interpreters with an automatically generated set of stand boundaries, thereby potentially reducing the time required for manual interpretation and digitization (Leckie *et al.* 1998, 2003).

## Image segmentation

Automated image segmentation is the partitioning of a digital image into a set of jointly exhaustive; mutually disjoint regions that are more uniform within themselves than when

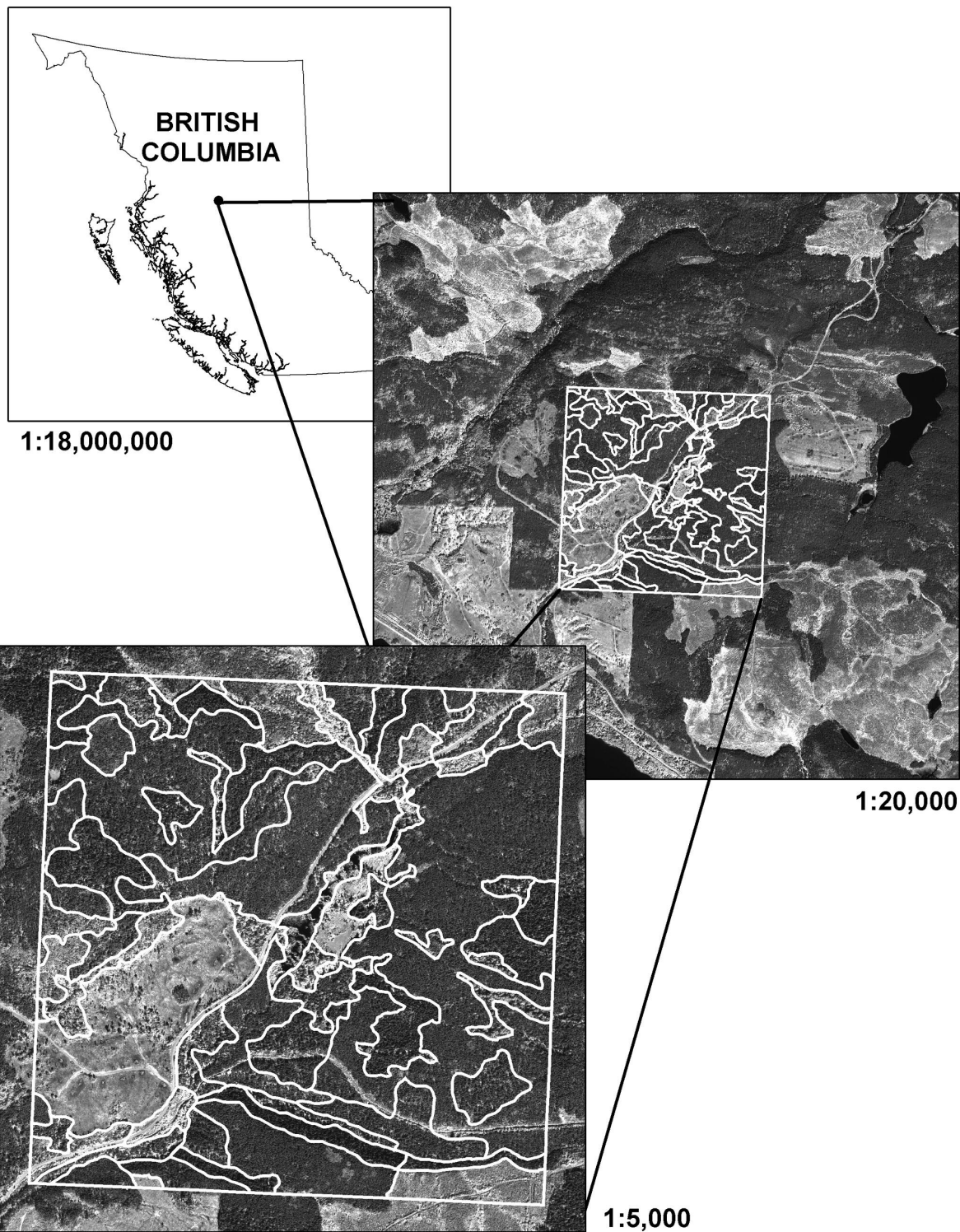
compared to adjacent regions. Uniformity is typically evaluated by a dissimilarity measure(s) upon which the partition itself is constructed (Pal and Pal 1993). Automated segmentation exploits the spatial information inherent in remotely sensed imagery in addition to the spectral information (Cohen *et al.* 1996). There are hundreds of image segmentation algorithms that have been developed not only for remote sensing applications, but also for computer vision and biomedical imaging. The techniques are so varied that there is no up-to-date review in the literature, with the last comprehensive survey undertaken more than a decade ago (Pal and Pal 1993). However, in the context of forest inventory, only a few methods have been applied, including aggregation of individually segmented tree crowns (Leckie *et al.* 2003), wavelet-based segmentation (Van Coillie *et al.* 2006), and the more commonly used region merging (e.g., Hagner 1990, Woodcock and Harward 1992, Baatz and Schape 2000, Pekkarinen 2002). The latter typically consists of the sequential aggregation of adjacent regions according to their similarity until a stop criterion is reached, which can be based on either a similarity or a size threshold. To the best of our knowledge, only one of these methods, the multi-resolution segmentation of Baatz and Schape (2000), has been implemented into commercial software (Definiens 2005).

## Objectives

Research has increasingly focussed on linking satellite remotely sensed data with forest inventory (Franklin *et al.* 2001; Reese *et al.* 2003; Wulder *et al.* 2004, 2008; Remmel *et al.* 2005; Chubey *et al.* 2006; Donoghue and Watt 2006). The objective of this paper is to explore and communicate possible opportunities and limits to the combined use of high spatial resolution satellite remotely sensed imagery and automated segmentation software to generate homogenous forest units, which could subsequently be used to support manual delineation and/or photo interpretation. The intention is not to suggest that human interpreters should be replaced by automated procedures. Rather, this approach is seen as a way of augmenting existing methods and products; thereby, increasing the speed, consistency, and efficiency with which the first phase of a forest inventory could be completed. Additionally, this research is not a trial of a given segmentation software tool, rather, the software is used as an example of the information developed through segmentation. Our goals for this communication are threefold: (i) that segmentation software developers can learn more of the specific information needs of the forest inventory community; (ii) that the forest inventory community can learn more regarding the potential and limits to the use of segmentation for stand delineation, and (iii) that communication between these groups can be enhanced and facilitated, resulting in improved tools and methods to meet increasingly sophisticated inventory demands.

## Study Area

The study area selected for this trial is a 2-km by 2-km Canadian National Forest Inventory (Gillis 2001) photo plot, located approximately 220 kilometres northwest of Prince George in central British Columbia (Fig. 1). The forests in this area are dominated by lodgepole pine (*Pinus contorta*) that are approximately 60 to 80 years of age. Other species include white spruce (*Picea glauca*), black spruce (*Picea mariana*) and aspen (*Populus tremuloides*) (Table 1). Topography in the



**Fig. 1.** Location of study area and sample of IKONOS imagery overlaid with forest inventory polygons.

study area is undulating, with elevations in this area ranging from 740 to 900 metres.

## Data

The IKONOS satellite, launched in 1999, simultaneously collects 1-m panchromatic and 4-m multispectral images with an 11-bit radiometric resolution. The advantages of the IKONOS instrument include its global coverage, consistent acquisition schedule, and its capability to acquire imagery with near nadir viewing angles. The spatial resolution of the sensor is suitable for high accuracy photogrammetric processing and mapping applications (Tao *et al.* 2004). With the robust geometric accuracy of the IKONOS sensor, 1:10 000 scale mapping can be produced without ground control and 1:2400 scale mapping with ground control (Dial *et al.* 2003). Costs for IKONOS imagery vary: to purchase archived imagery costs approximately \$0.07 to \$0.12 C\$/ha for either the panchromatic or the multispectral, or from \$0.10 to 0.17 C\$/ha for both. Tasking the satellite to acquire data in a specific area of interest costs approximately \$0.18 to \$0.20 C\$/ha for either the panchromatic or multispectral, or \$0.25 to \$0.28 for both<sup>4</sup>. Variation in pricing reflects the level of geometric processing, with fully orthorectified products being the most expensive. These costs for IKONOS imagery are only the data costs and do not include costs for processing, classification, or creation of the final deliverables.

The 1-m panchromatic IKONOS image used for this study was acquired on August 6, 2003 with a sensor view angle of 17°, and was delivered georeferenced with a positional accuracy of approximately 15 metres (Dial *et al.* 2003) (Fig. 1). This data set was selected for its similarity in spatial resolution to panchromatic aerial photography that is commonly used in British Columbia for forest inventory applications. Radoux and Defourny (2007) used IKONOS imagery to generate stand delineations that corresponded to 1:20 000 scale map specifications and recommended an optimal spatial resolution of 2 m to 3 m for delineation in temperate forest conditions. QuickBird data, with a spatial resolution of 0.67 m (panchromatic) and 2.7 m (multispectral), is another commercially available remotely sensed data source with demonstrated utility for forestry applications (Coops *et al.* 2006, Hyde *et al.* 2006, LeBoeuf *et al.* 2007).

## Methods

### Manual delineation

The manual delineation and interpretation of the IKONOS panchromatic imagery was undertaken by a certified<sup>5</sup> and experienced photo-interpreter who had local knowledge of the study area. Delineation was conducted as per standard operational inventory procedures (Natural Resources Canada 2004).

### Automated delineation

The automated delineation tool used in this study, the *Size-Constrained Region Merging* (SCRM) algorithm (Castilla 2003, Castilla *et al.* [In press]) has previously been applied to the segmentation of forest scenes (Hay *et al.* 2005). SCRM automatically segments an orthorectified aerial or satellite image (single or multi-channel) into a series of homogenous

Table 1. Properties of forest species in the study area

Leading species	Proportion of study area (%)	Average height (m)	Average age (years)
AT	1.14	9.6	22
PL	76.00	23.6	59
SB	1.47	22	2.3
SW	11.30	29.4	145
Non-Forest	10.09	N/A	N/A

AT = aspen; PL = lodgepole pine; SB = black spruce; SW = white spruce.

segments. The automated delineation resembles the work of a human interpreter. This delineation may then be used as an initial template in the task of the interpreter, whom simply needs to aggregate (and sometimes correct) pre-delineated regions by software supported drag-and-click operations.

SCRM starts the region merging sequence from an initial partition derived from a morphological process. This partition consists of *blobs*, i.e., tiny homogeneous regions in the image, darker, brighter or of different hue than its surroundings. Blobs correspond to the area of influence of local minima in a *gradient magnitude image* (i.e., an edge image) computed from a filtered version of the original image. Filtering is conducted with an edge-preserving smoothing algorithm. These initial regions are then aggregated sequentially by increasing dissimilarity until they all exceed the size of the minimum mapping unit (MMU). The dissimilarity measure between a pair of adjacent regions is simply their absolute difference in mean brightness value. In each iteration, the two adjacent regions that merge are those best fitting (i.e., those having the least dissimilarity distance). After a merge, the brightness value of the new region is the weighted (by size) mean of the signatures of the two merged regions. Finally, the labelled image containing the final partition is converted into a vector layer in ESRI shapefile format.

To run the SCRM algorithm, the user must define at least one of the following four parameters: the desired mean size of output polygons (in hectares); the minimum size required for polygons, or MMU (in hectares); the maximum size allowed for mergers (in hectares); and finally, the minimum distance between vertices in the vector layer, or minimum vertex interval (in metres). Bights and ledges (convolutions in the linework) smaller than the minimum vertex interval are removed and generalized into a smooth cartographic line.

### Comparison and evaluation of manual and automated delineations

The photo interpreter who conducted the manual delineation also evaluated the automated delineation produced by the SCRM algorithm and where possible assigned attributes to the automatically delineated polygons. The photo interpreters' comparison of the two delineations was largely qualitative, as per Leckie *et al.* (2003). A recent study by Radoux and Defourny (2007) identified a quantitative method for comparing two delineations; however, the authors use a manual delineation as truth, and all measures of error are made relative to the manual delineation. A shortcoming of such an approach is that manual delineations are based on subjective criteria and as a result may vary substantially from one interpreter to the next (Kadmon and Harari-Kremer 1999, Culvenor 2002), undermining user confidence in the quanti-

<sup>4</sup>Estimated costs as of December 2, 2007.

<sup>5</sup>[http://www.for.gov.bc.ca/hts/vri/contractinfo/rpt\\_all\\_certified.pdf](http://www.for.gov.bc.ca/hts/vri/contractinfo/rpt_all_certified.pdf)

**Table 2. Relative advantages and disadvantages of manual delineation and automated segmentation.**

Method	Advantages	Disadvantages
Manual delineation	<ul style="list-style-type: none"> <li>• Established standard</li> <li>• Delineation and attribution can be achieved in a single step</li> </ul>	<ul style="list-style-type: none"> <li>• Slow</li> <li>• Costly</li> <li>• Scarcity of skilled interpreters</li> <li>• Prone to show inconsistencies between different interpreters or even the same interpreter at different times</li> <li>• Highly subjective and hence not well suited for monitoring</li> </ul>
Automated segmentation	<ul style="list-style-type: none"> <li>• Faster</li> <li>• Cheaper</li> <li>• More consistent</li> <li>• Less subjective and more repeatable and hence better for monitoring.</li> </ul>	<ul style="list-style-type: none"> <li>• Likely to require manual correction of some linework/polygons</li> <li>• Efficiency rapidly decreasing with the amount of manual tweaking required</li> <li>• Undesired results in areas with low contrast or where different appearance does not imply different meaning</li> </ul>

tative assessments. Communication of the nature of the validation data and the accuracy assessment methodology is critical to assisting the user in interpreting the validation findings. For the exploratory purposes of this study, the primarily qualitative comparisons made are sufficient to satisfy the stated objectives.

## Results and Discussion

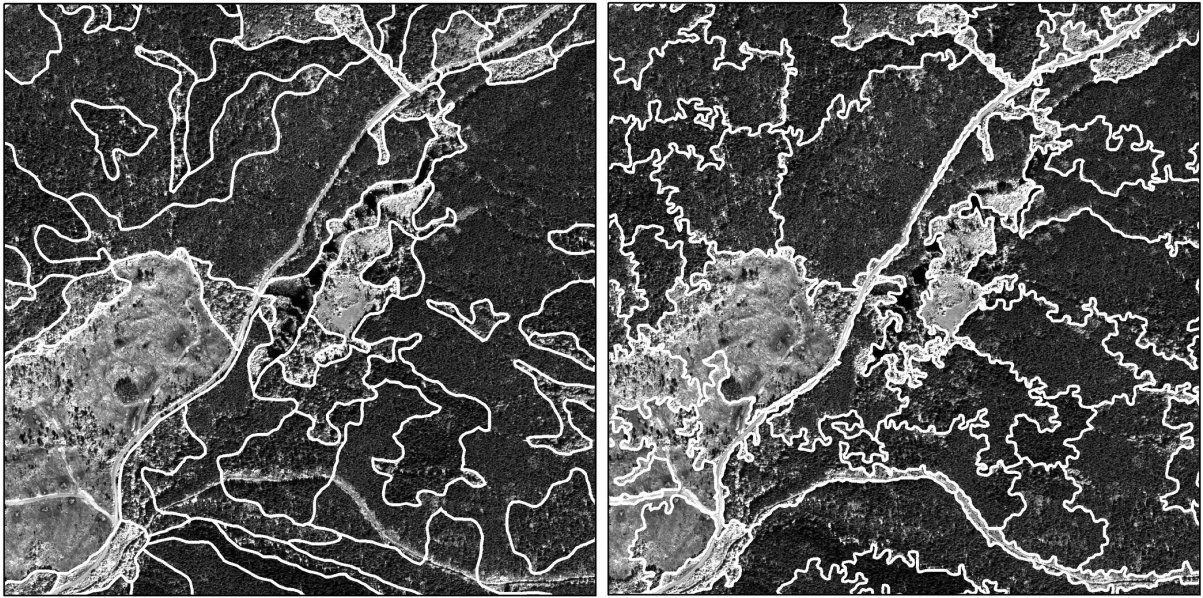
The segmentation results from SCRM were generated using only the radiometric distance between region centroids (i.e., mean value of inner pixels), whereas a human interpreter uses a number of criteria (i.e., shape, size, tone, texture, pattern, location and associations of objects), in addition to external information sources, such as personal experience, knowledge of the ecological relations of the vegetation in the specific region being studied, and other ancillary data. Differences between automated and manual delineations will likely be greatest in those locations where the interpreter uses delineation criteria that have no radiometric context, such as proximity, or where boundaries are delineated that artificially demarcate transitions. In these situations, automated delineations would require manual adjustment of stand boundaries to capture the necessary criteria. Depending on the level of adjustment required, the automated process may still provide time savings and improve the consistency of delineation. Alternatively, a mixture of manual and automated delineations may be selected for a project that covers large areas of homogenous forest in addition to more complex, heterogeneous forests. In this scenario, automated segmentation may be deployed over the homogenous forest, while the efforts of the photo interpreters are focused on the more complex forest areas. To provide a more synoptic perspective, the relative advantages and disadvantages of manual and automated delineation are presented in Table 2.

The results of the manual delineation and automated segmentation procedures applied to a sample of the IKONOS study area are shown in Fig. 2. Upon visual inspection, several differences in the linework are evident. Of particular note are the amount of detail and the convoluted nature of the linework from the automated segmentation lines relative to the more generalized manual delineation. This difference is reflected in the mean perimeter of the polygons generated from the two processes: the SCRM output has a mean polygon perimeter that is approximately 14% greater than the

perimeter of the manually delineated polygons, while the mean polygon size for the SCRM polygons is approximately 20% less than the manual polygons (Table 3). The manual polygons have a much greater range in polygon sizes, with a standard deviation that is more than double that of the automatically delineated polygons. When the photo interpreter typed the polygons delineated with SCRM, only those polygons that the photo interpreter deemed reasonable (i.e., not requiring any modification) were assigned an attribute. Table 3 indicates that 40% of the SCRM polygons, representing approximately 50% of the total NFI photo plot area, were deemed suitable and assigned attributes by the photo interpreter. The remaining 60% of segments required either minor modifications to the linework (17%), or were not appropriate for reasons that we discuss in detail in the following section.

The photo interpreter inspected and assessed the quality of the linework generated from the SCRM algorithm, with the objective of characterizing the SCRM linework in three contexts: (i) locations where the SCRM segmentation performed well, (ii) locations where the SCRM segmentation did not perform well, and (iii) locations where the SCRM linework could be easily and quickly modified to produce a logical polygon. Examples of the first context, where the SCRM algorithm produced polygons that were ready for typing without any manual alteration, are provided in Fig. 3. These polygons represent locations with homogenous texture and tone, which have relatively uniform species composition, age, and height—demonstrating the ability of automated segmentation routines to perform well in uniform stand conditions.

Conversely, Fig. 4 illustrates examples of where the automated segmentation did not perform well. In polygon A, the road has been included within a larger vegetated polygon. The rules for including roads within the bounds of typed polygons are subjective and interpreters often make the decision on whether or not to include a road based on the context of the surrounding forest conditions and the width of the road. Typically, if a road (or other linear feature such as a pipeline or a power line right of way) is greater than 30 metres wide, it will be delineated as a separate polygon. In the manually delineated polygons in Fig. 2, there are examples where stands having similar attributes are bisected by a road that is less than 30 metres wide. In these examples, the interpreter has delineated these as a single polygon, with the portion of road separating the two stands included within the polygon.



**Fig. 2.** Comparison of manual (left) and automated (SCRM) (right) polygon delineation.

**Table 3. Properties of delineated polygons.**

Attribute	Manual	Automated
Total # of polygons	66	82
Attributed polygons <sup>a</sup>	66	34
Mean polygon size (ha)	6.06	4.87
Minimum polygon size (ha)	0.26	0.10
Maximum polygon size (ha)	77.55	24.57
Standard deviation polygon size (ha)	11.30	5.10
Mean polygon perimeter (m)	1418.31	1614.45
Minimum polygon perimeter (m)	249.82	134.59
Maximum polygon perimeter (m)	11 317.00	5669.40
Standard deviation polygon perimeter (m)	1553.76	1181.79

<sup>a</sup>Only those polygons which had “reasonable” linework in the opinion of the photo interpreter were assigned attributes.

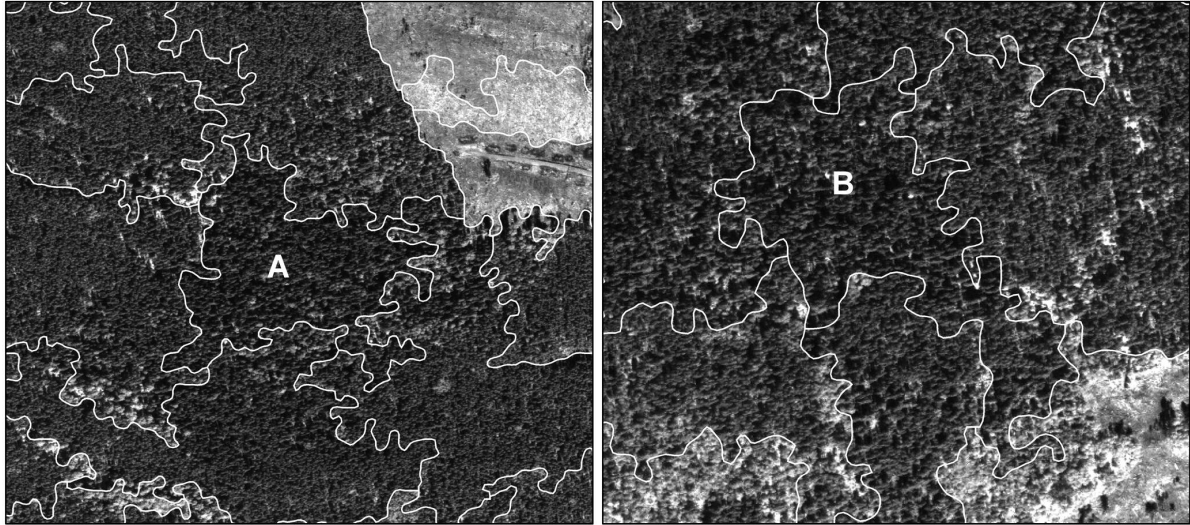
In the second example depicted in Fig. 4, polygon B is a complex polygon that combines vegetated and non-vegetated areas, and the segmentation has partitioned non-vegetated areas that appear to have tone and textural characteristics. The examples in Fig. 4 indicate that the SCRM automated segmentation did not perform well in complex areas where there was an amalgamation of both forest and non-forest areas. In these examples, the polygons would require a large amount of manual editing before they could be interpreted. Lastly, the photo interpreter identified examples where the automatically generated polygons required only minor editing to facilitate interpretation. In Fig. 5 two examples are illustrated where the addition of a single line was effective at separating the polygons into interpretable units.

Table 4 provides a summary of the distribution of forest species in the NFI photo plot as represented by each method of delineation. The bottom portion of Table 4 provides a more reasonable comparison between the two delineations, since it

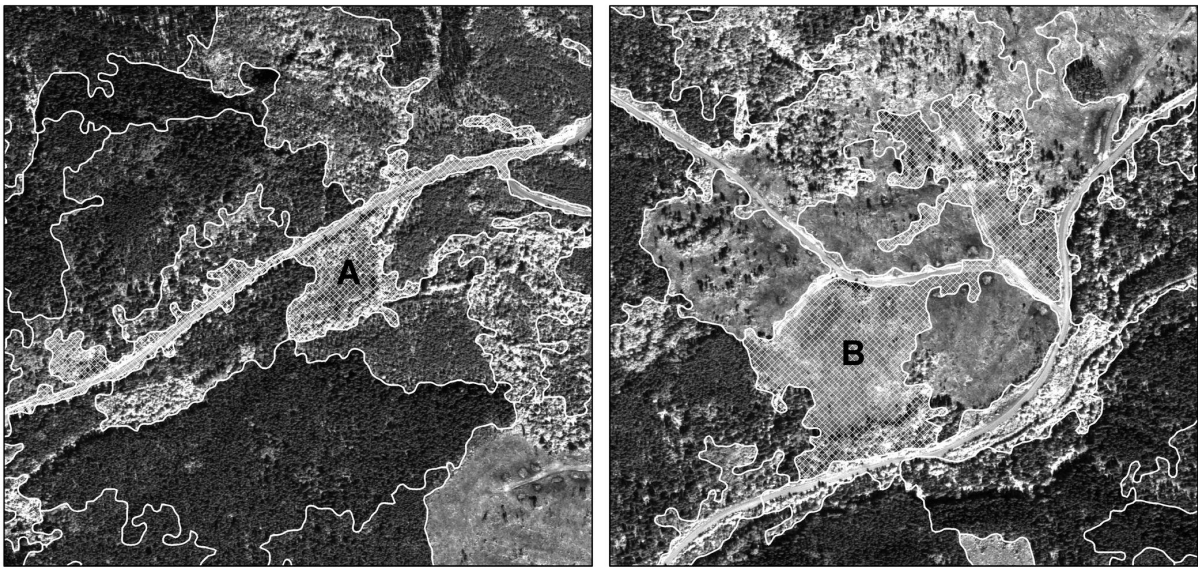
represents the coincident spatial area where both delineation versions have attributes assigned to the polygons. Table 5 provides a spatially explicit comparison of this coincident area in the form of a cross-tabulation matrix. From this we can see that although the total area of lodgepole pine differs by 12%, the manual delineation resulted in pine as leading species in only 84% of the area that was attributed as pine from the automated delineation. The discrepancies identified in Table 5 result primarily from the differences in the delineation of polygon boundaries.

The photo interpreter noted several trends in the SCRM polygons: scattered treed areas that appeared to be wet or flooded were often merged with upland areas of grass, shrub, and treed areas; coniferous stands of pine and mixed coniferous stands of pine and spruce were not distinguished satisfactorily; and stands of aspen were frequently (and erroneously) merged with non-treed cut block areas. In general, the linework generated by the SCRM was considered by the photo interpreter to be too complex, compared to the typical generalized linework produced by manual delineation. However, we note two items: (i) the complexity of the boundaries produced through segmentation can be regulated, either as an output option (in the case of SCRM) or through post-processing in GIS software; (ii) the perceived complexity of boundaries can also be seen as a beneficial feature, due to the fit between source imagery and resultant polygons, with enhanced management opportunities emerging.

The results of this trial suggest that the automated segmentation approach, while promising, would require some improvements before it could be used in an operational context. In some portions of the study area, the automated segmentation performed very well and produced polygons that the photo interpreter considered suitable for interpretation, without any modification. However, for other stands, the automated delineation required some modification by the



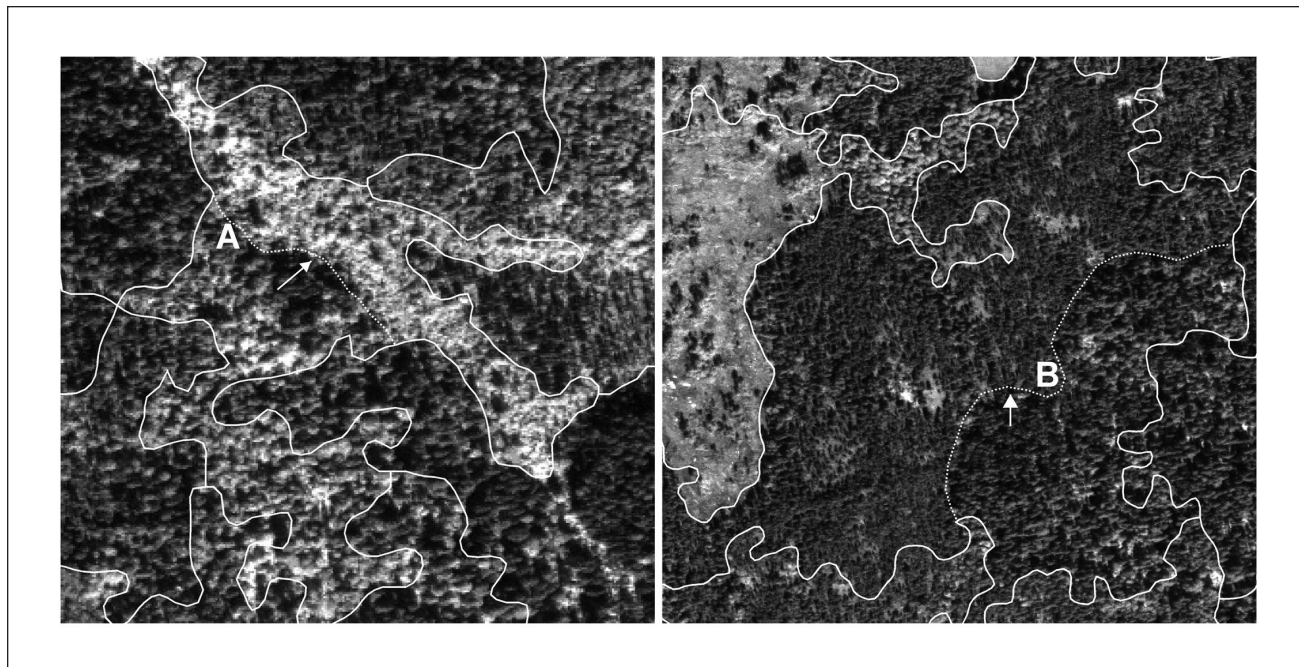
**Fig. 3.** Examples of where automated segmentation performed well, resulting in polygons that required no manual tweaking prior to interpretation. Polygon A is a homogenous stand with consistent texture and tone throughout. Polygon B has consistent species composition, age, and height throughout the stand. The finger of polygon B that extends to the south could be separated and grouped into a separate polygon.



**Fig. 4.** Examples where the automated segmentation did not perform well. Polygon A is a combination of non-vegetated road and vegetation south of the road. Polygon B is a complex polygon that fails in three areas: the treed area in the southernmost extent of the polygon was not separated from non-treed area; areas with similar tone/texture were separated unnecessarily; and roads were included within vegetated polygons.

photo interpreter. This underscores the unparalleled ability of human interpreters to consider a wide range of structural and contextual cues to produce a delineation that has utility for forest management, although it should not be expected that an automated approach can integrate as readily the same broad range of experiences and management intentions as a

experienced interpreter where many interpretation clues are context-, not image-, based. Further trials of the SCRM algorithm under a range of different forest conditions (particularly in areas with a heterogeneous species composition) would be required to make conclusive statements regarding the algorithm's performance for automated stand delineation.



**Fig. 5.** Examples where the automated segmentation could be altered with a few additional line segments. An additional line in polygon A separates the deciduous and coniferous stands. In polygon B, a single line segment separates the approximately 100-year-old lodgepole pine leading stand to the east from the 185-year-old white spruce leading stand to the west

**Table 4.** Distribution of leading forest species over the total NFI photo plot area, and then only over the spatially coincident area where both the manual and automated delineations were attributed.

Tree Species	Manual ha	Automated ha	Difference	
			ha	%
<b>Total area of the NFI photo plot</b>				
Aspen	72.58	7.91	64.67	10.89
Common paper birch	7.97	0.00	7.97	100.00
Lodgepole pine	239.49	163.32	76.17	31.81
Black spruce	1.66	0.00	1.66	100.00
White spruce	71.59	25.72	45.87	64.07
<b>Area where both the manual and automated polygons have attributes</b>				
Aspen	9.59	7.91	1.68	17.51
Common paper birch	4.51	0.00	4.51	100.00
Lodgepole pine	145.89	163.32	-17.43	-11.94
Black spruce	0.00	0.00	0	0.00
White spruce	36.95	25.72	11.23	30.39

**Table 5.** Matrix showing the spatial correspondence (by ha) in the distribution of leading species, as interpreted using the manual and automated delineations.

Leading Tree Species	Automated Segmentation					Total Area (ha)
	AT	EP	PL	SW		
AT	3.46	0.00	4.76	1.37	9.59	
EP	4.00	0.00	0.39	0.13	4.51	
PL	0.12	0.00	136.71	9.08	145.90	
SW	0.34	0.00	21.47	15.15	36.95	
Total Area (ha)	7.91	0.00	163.32	25.72	196.96	

AT = aspen; EP = common paper birch; PL = lodgepole pine; SB = black spruce; SW white spruce.



The future of automated segmentation for forest inventory delineation may be linked to the incorporation of other spatial and or multispectral data layers into the segmentation process. For example, Radoux and Defourny (2007) found that the impact of shadow was greater on the IKONOS 1-m panchromatic data and that the incorporation of IKONOS 4-m multispectral data may help to alleviate the impact of shadows on the segmentation algorithm. Additional spatial data may be used to stratify areas in order to reduce confusion associated with linear features such as roads and rivers. GIS technology readily facilitates this type of data integration and may increase the contextual intelligence of segmentation algorithms. Although not evaluated in this study, IKONOS imagery may also be viewed in stereo, increasing the interpreter's ability to assess landscape position, discern species, and estimate tree heights.

Segmentation algorithms that consider and incorporate knowledge of forest inventory needs, the spatial structure of forest environments, and traditional forest inventory cues are more likely to produce useful results; however, these characteristics are not trivial to implement in code. While already including controls for scale and polygon sizes, ongoing development of the SCRM algorithm is addressing the inclusion of new components in the dissimilarity metric, including a *boundary saliency measure*, which precludes the merging of similar regions separated by a strong edge (like a narrow road separating two stands of similar characteristics), as well as incorporating measures of the internal texture of regions, possibly at different scales, into the segmentation. Furthermore, a reduction in line complexity can be facilitated by selecting a minimum vertex interval more appropriate to the level of generalization required by a photo interpreter, and based on results in Table 3, polygon size parameters (as inputs to SCRM) could also be selected to better match those of a photo interpreter.

## Conclusions

This trial demonstrated the utility of IKONOS panchromatic imagery for delineation and subsequent typing of homogeneous forest units. The photo interpreter was able to apply all of the standard photo interpretation principles to the high spatial resolution satellite imagery, and was comfortable discriminating coniferous and deciduous species in both mixed and pure stands. For programs like Canada's National Forest Inventory, the utility of high spatial resolution satellite imagery may be greatest in inaccessible areas such as in the north of Canada, where there is a paucity of pre-existing forest inventory information and where logistical barriers to air photo acquisition exist. Further encouraging the use of segmentation and satellite data in these remote locations is the lack of confounding elements such as harvested areas, landings, and roads.

It is anticipated that suitable potential has been demonstrated for automated segmentation to warrant further development and investigation with a goal of increasingly augmenting the manual delineation and interpretation processes and facilitating the production of timely and consistent map products. With this in mind, automated approaches must be inexpensive and simple to apply, and must not substantially alter the mapping workflow, nor involve inordinate fine-tuning by the interpreter (Leckie *et al.* 1998). From the lessons

learned from this research, it is clear that segmentation software developers need to consider the information needs of the forest inventory community and focus development on a robust delineation that can help to facilitate the work of human photo interpreters, rather than attempting to develop algorithms that replicate and/or supplant human delineation.

At this time, forest managers should consider automated segmentation as an emerging tool for forest inventory, particularly where there are large areas of relatively homogenous forest conditions to be delineated. In addition, high spatial resolution panchromatic satellite imagery ( $\leq 1$  m) should be considered as a potential data source for manual delineation and interpretation of forest inventory attributes and should be the subject of further research.

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